TWENTY-THIRD
HANFORD LIFE SCIENCES SYMPOSIUM

Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields

October 2-4, 1984
Richland, Washington U.S.A.

Sponsored by
the United States Department of Energy,
the Electric Power Research Institute
and Battelle Memorial Institute's
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Twenty-Third Hanford Life Sciences Symposium

PREFACE

Although background levels of atmospheric electric and geomagnetic field levels are extremely low, over the past several decades, human beings and other life forms on this planet have been subjected to a dramatically changing electromagnetic milieu. An exponential increase in exposure to electromagnetic fields has occurred, largely because of such technological advances as the growth of electrical power generation and transmission systems, the increased use of wireless communications, and the use of radar. In addition, electromagnetic field generating devices have proliferated in industrial plants, office buildings, homes, public transportation systems, and elsewhere. Although significant increases have occurred in electromagnetic field strengths spanning all frequency ranges, this symposium addresses only the impact of these fields at static and extremely low frequencies (ELF), primarily 50 and 60 Hz.

Electromagnetic fields, which may extend far beyond their sources, are mostly imperceptible to people. Nevertheless, research and clinical experience have shown that biological effects from such fields are not precluded simply because they are not perceived. There has been considerable controversy as to whether biological effects exist at all in the ELF portion of the electromagnetic spectrum, let alone whether they pose a hazard to health. Recent data, however, seem to confirm some of the earlier reports that ELF fields do cause changes in certain biological systems. Thus, it is both reasonable and important to evaluate possible interactions between the modern electromagnetic environment and living organisms, including humans, and to investigate whether such interactions are beneficial or detrimental, transient or permanent.

Over the past two decades, research programs throughout the world have greatly expanded in scope and depth to address such questions. Significant progress has been achieved, both in defining the way living organisms interact with electric and magnetic fields and in describing biological effects, both actual and potential, from such fields. Much of this effort has been directed toward electric fields at power frequencies. However, more recently, frequencies other than 50 and 60 Hz have been examined, and research efforts have been expanded to include magnetic as well as electric fields.

This volume contains the proceedings of the Twenty-Third Hanford Life Sciences Symposium entitled "Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields," which was held in Richland, Washington, October 2-4, 1984. The purpose of the symposium was to provide a forum for discussions of all aspects of research on the interaction of static and ELF electromagnetic fields with biological systems. These systems include simple biophysical models, cell and organ preparations, whole animals, and man. Dosimetry, exposure system design, and artifacts in ELF bioeffects research were also addressed, along with current investigations that examine fundamental mechanisms of interactions between the fields and biological processes.

The symposium included discussions of research that is directly related to contemporary problems associated with electric power transmission and use (both ac and dc). In addition to the 50 technical papers presented, two lively panel discussions were held in consideration of the fact that the subject of ELF bioeffects has become one of public as well as scientific interest. The first panel dealt with "Sources and Structure of Magnetic and Electric Fields in the Home"; the second addressed the "Impact of Electric and Magnetic Field Exposure on Human Populations."

This symposium was sponsored by the U.S. Department of Energy, Office of Health and Environmental Research; the Electric Power Research Institute; and Battelle, Pacific Northwest Laboratories. We also acknowledge the encouragement and cooperation of Kenneth Klein in the U.S. Department of Energy Office of Electric Storage and Distribution. Special thanks go to the session chairmen: Tom Tenforde, Lawrence Berkeley Laboratory; Robert Kavat, Health Effects Institute; Ron McKnight, National Bureau of Standards; Dan Bracken, T. D. Bracken, Inc; Mike Marron, Office of Naval Research; Greg Lotz, Naval Aerospace Medical Research Laboratory; H. B. Graves, Consultant; Bob Banks, Robert S. Banks & Associates; Dick Phillips, U.S. Environmental Protection Agency; and Marv Frazier and Mel Sikov, Battelle-Northwest. We also extend our appreciation to the members of our discussion panels: Bill Kaune, Battelle-Northwest and Bill Wisecup, W/L Associates, as moderators; Don Deno, General Electric; Kjell Hansson-Mild, Swedish National Board of Occupational Safety and Health; Brian Maddock and John Bonnell, Central Electricity Generating Board, U.K.; Ray Vincent, Stanford Research Institute; Tom Budinger, Donner Laboratory, University of California; Nancy Wertheimer, University of Colorado; and Sam Milham, Washington State Department of Social and Health Services. Our appreciation is extended to the many scientists who took the time to prepare their manuscripts for inclusion in these proceedings. We are indebted to Dev Felton and Ray Baalman, and the publishing staff of Battelle-Northwest, whom we credit for making this volume available to all interested parties in research, industry and government throughout the world. Finally, we award special recognition to Patty Bresina, Symposium Secretary, and Glenn Horstman and Ed Blanton, Arrangements Committee, who (with the help of volunteers from the Battelle staff) managed the symposium while we concentrated on its technical content.

L. E. Anderson
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Contents

OPERATION OF AN ION COUNTER IN THE GROUND PLANE UNDER A MONOPOLAR HIGH-VOLTAGE LINE

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ABSTRACT

Studies have been made of the operation of an ion counter with the inlet located in the ground plane near a monopolar high-voltage line. Electric-field values at the ground plane ranged between 14.8 kV/m and 29.8 kV/m, while ion current densities varied from 0.1 to 0.43 $\mu A/m^2$. An observed variation in measured ion density with volumetric flow rate through the counter appears to be primarily due to losses in the duct between the ground-plane opening and the ion-counter inlet.

Ion counters are devices which have been used by atmospheric scientists to measure unipolar ion densities in studies of the earth's electrical properties and, in some specialized applications, to provide estimates of the mobility spectrum of the small ions under investigation (Chambers, 1967; Tammet, 1970). More recently, these instruments have also been used to provide information about the electrical environment around high-voltage direct current (HVdc) transmission lines and in biological exposure systems intended to simulate certain aspects of the transmission line environment (Bracken et al., 1978; Weigel and Kaune, 1981).

Except in storm conditions, ion counters used in atmospheric research are in surroundings where the ambient electric field is less than 1 kV/m and where ion densities are less than 1000 cm^3 (Israel, 1971). By contrast, electric fields near an HVdc transmission line may be as large as 25 kV/m, and unipolar ion densities are greater than 10^5 ions/cm^3. In addition, the distribution of ions near the ground under a transmission line is highly nonuniform and predominantly unipolar (Comber and Johnson, 1982).

Because of the large difference between the ambient atmospheric and HVdc transmission-line environments, the operation of an ion counter under these conditions must be investigated to determine the sources of error associated with ion-counter measurements and to provide estimates of accuracy for these measurements. In contrast to the situation for electric-field meters, for which calibration techniques have been determined, there are no "standard" ion sources or calibration facilities for ion counters. Two systems useful as sources of ions for investigating different measuring devices have been described in the literature (Misakian, 1981; McKnight and Cotter, 1983). The work discussed below was undertaken to provide information about the effects of external electric fields on the operation of ion counters.

METHODS

The experimental configuration used in the present study is similar to that used in an earlier investigation in which the ion counter was located above the ground plane (McKnight and Fulcomer, 1984). The purpose of the arrangement shown in Figure 1 is to provide electric-field measurements and current densities at the ground plane similar to those near an HVdc transmission line. The monopolar line, which was 4 m long and 2 m high, was connected to a variable high-voltage power supply. A table, 1.2 m on a side and 0.3 m high, was erected under the line and served as a local ground plane. The table, which was covered with aluminum, was 1.7 m from the line. As indicated, an ion counter was located under the table with an inlet located in the ground plane. Other instrumentation included a field mill for measuring the electric field and surface-mounted current sensors for determining the vertical current density. These current sensors were located on either side of the ion counter inlet and, along with the field mill and ion counter inlet, were colinear with the line.

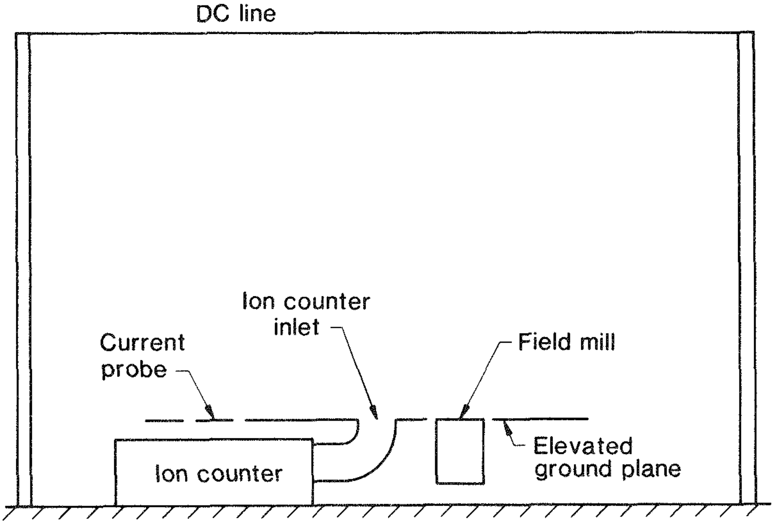

Figure 1. Experimental Configuration (Schematic). Elevated ground plane is located on a table. Relevant dimensions are in text; drawing is not to scale.

The experiments were performed in a laboratory in which there was limited temperature and humidity control. During the experiments, the temperature varied from 21 to 27°C, and the relative humidity ranged from 55 to 70%. The value of the electric field and current density could not be independently varied but were determined (for fixed geometry) by the line operating voltage.

In order to clarify the technical problem under consideration, consider the diagram of an ion counter, shown in Figure 2. For purposes of illustration, a parallel-plate geometry is shown, although the discussion applies to a cylindrical geometry as well. These instruments operate on an aspiration principle, i.e., a continuous air stream containing ions is drawn into the instrument opening. Inside the ion counter, ions are precipitated from the air stream by internal electric fields which are produced by polarizing potentials. Depending on the relative polarity of the electric field and ions, positive (or negative) ions impinge on collector plates and result in a current to ground, which can be measured. The motion of the ions is determined by the air stream, the internal electric field, and the mobility of the ions. Some ions will be collected, others will pass through the device. It can be shown that all ions with mobilities greater than that known as the "critical mobility" will be collected; for less-mobile ions, only a fraction will be collected (Hoppel, 1970). The critical mobility is determined by the construction and operating conditions of the ion counter being used. For the ions collected, a value for space charge density in the air being sampled is given by

$$\rho = I/M, \tag{1}$$

where I is the measured ion current and M is the volumetric flow rate through the ion counter. This space charge density, which has units of coul/m^3, is usually converted to an equivalent ion number density by assuming that each ion is singly charged, an assumption which is reasonable for the small ions of interest here. The space charge density, ρ, may also be obtained from simultaneous measurements of the electric field, E; vertical current density, J; and an estimate of the average ion mobility, k. The relationship among these quantities is given by

$$J = \rho k E. \tag{2}$$

In the discussion below, and on the figures, the value of charge density determined using Equation 2 will be denoted as ρ_0. For all the calculations, the average value for ion mobility was taken as 1.4 x 10^{-4}m^2/Vs and 1.8 x 10^{-4}m^2/Vs for positive and negative ions, respectively.

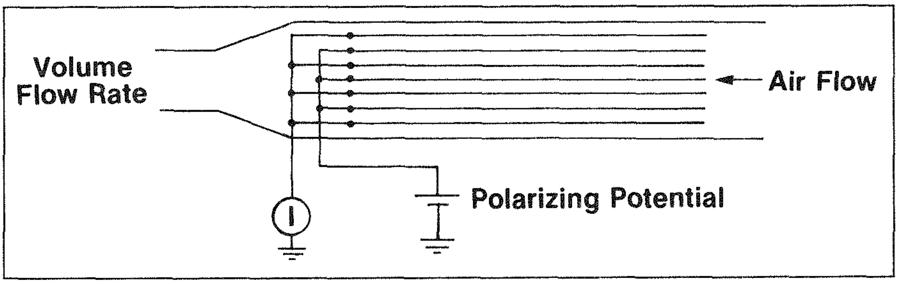

Figure 2. Parallel-Plate Ion Counter Similar to that Used in Reported Study.

Of concern in the present experiment is the influence of the electric field external to the counter, which, along with the air flow, determines the motion of ions near the inlet to the ion counter. The results of an earlier study, described by McKnight and Fulcomer (1984), indicated a strong external field effect for an experiment in which an ion counter was located above the ground plane under a monopolar line. For such a geometry, the external field is substantially enhanced but is not directly measurable. With the inlet to the ion counter located in the ground plane, there is no enhancement, although the field is perturbed in the vicinity of the opening to the ion counter.

The table shown in Figure 1 was constructed with a movable center section so that the field and current densities along the line could be mapped for different operating conditions. This was done to determine the uniformity along the line and to insure that the results were not dependent on precise locations of sensing elements. For line operating voltages of 28, 36, and 47 kV, the electric field and ion current densities along a 0.7-m distance were uniform to within ± 3% for both positive and negative line voltages. For these operating voltages, the nominal electric field had values of 14.8, 20.8, and 29.8 kV/m, respectively. The corresponding vertical current densities were 0.1, 0.21, and 0.43 $\mu A/m^2$. Slightly lower values were observed for negative voltage. In practice, the line voltage was adjusted to give the same electric field at the surface of the table for both positive and negative voltages.

For a given line operating condition, the air flow through the ion counter was varied, and the ion density was determined using Equation 1. The flow rates were measured using a turbine flow meter. Polarizing potentials were such that, for all flow rates, there was complete collection of small ions. During these measurements, the electric field and the current to the sensing elements on either side of the counter inlet were also recorded and used to determine ion density, ρ_o, using Equation 2. The results of one set of measurements are shown in Figure 3. This figure illustrates clearly a dramatic dependence on flow rate, a situation which was also observed in earlier experiments. Measurements were made for both line polarities and were repeated under different, although not intentionally varied, laboratory conditions.

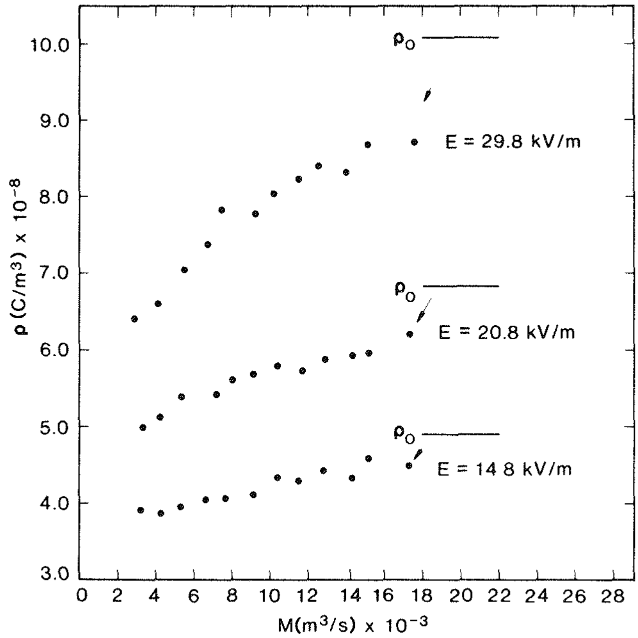

Figure 3. Space Charge Densities Determined for Different Volumetric Flow Rates, M, Using the Ion-Counter Measurements Described in Text.

RESULTS

Although the decrease of ion density with decreasing flow rate is suggestive of an external electric-field effect causing loss of ions, there are systematic corrections to be applied to the data. The charge density is unipolar; as a result, there is considerable loss in the ductwork leading from the inlet in the ground plane to the ion counter. In order to estimate the loss in the duct, the general theory of ion transport described by Kaune et al. was used (Kaune et al., 1983a; Kaune et al., 1983b). The result of adapting this theory for the particular experimental condition described above is summarized in Equation 3,

$$\frac{\rho}{\rho_o} = \left[1 + \frac{\rho_o k}{\varepsilon_o} \; \frac{\ell}{v}\right]^{-1} \tag{3}$$

where ρ_o is the ion density at the inlet, ε_o is the permittivity of free space, k is the average ion mobility, ℓ is the length of the pipe connecting the ion counter and the inlet, and v is the average speed of the ion moving in the tube (determined from the duct diameter and the measured flow rate). The initial value of charge density, taken to be ρ_o, was obtained using the independently measured values for the electric field and vertical current density and the assumed value for average ion mobility. The results of this calculation are plotted in Figure 4, along with the observed ion density. It is clear that the change in observed ion density with flow rate is primarily due to duct losses. In order to validate this conclusion, an additional length of tubing was inserted in the duct, increasing its length to 0.6 m, and the loss measurements were repeated. Although not shown here, the results of this second measurement confirmed the first: the losses appeared to be duct losses.

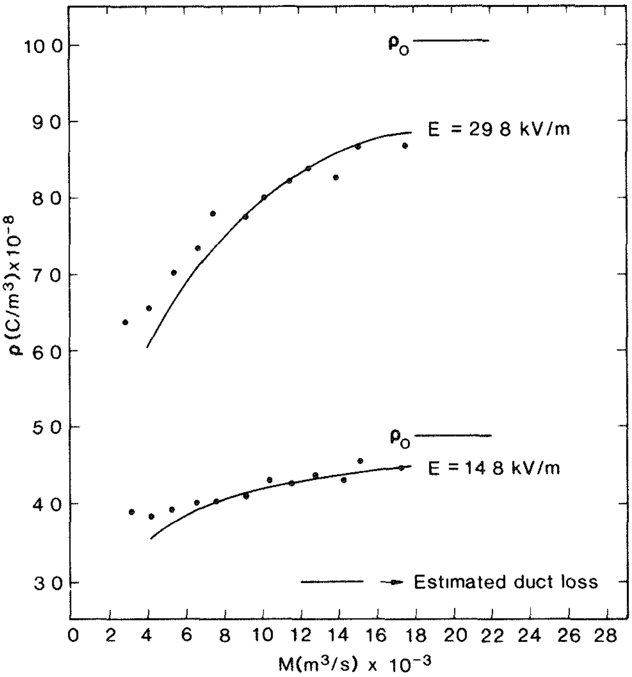

Figure 4. Comparison of Experimental Results (Solid Circles) and Estimates of Duct Losses (Solid Line), Calculated as Outlined in Text.

Although it is encouraging to note that for this configuration there do not appear to be any substantial external electric-field effects for the values considered here, the situation is not entirely clear. Figure 5 shows the results of measurements of air speed made 0.5 cm above and along a diameter of the opening in the ground plane for several flow rates. Superimposed on these curves are the speeds of ions (with the average mobilities given above the curves) moving in the electric fields used in the study. The motions due to the electric fields are a substantial fraction of the air speeds and, in some cases, exceed the air speeds. (The effects of the external field may be overestimated in the figure because the perturbation due to the ion counter opening was ignored.) For this reason, these fields would be expected to produce observable effects. Duct losses cannot explain the similar variation observed for the aboveground location of the ion counter in the earlier study (McKnight and Fulcomer, 1984), since the duct length there was insignificant.

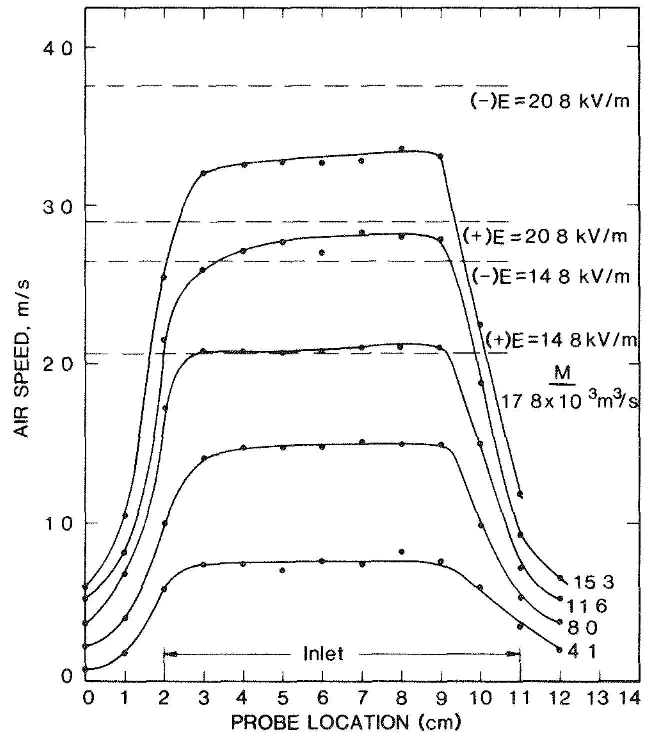

Figure 5. Measurements of Air Speed, Made 0.5 cm Above Ion-Counter Opening, for Different Volumetric Flow Rates, M. Also shown are ion speeds resulting from movement in constant electric fields, as indicated. Probe location relative to inlet opening is shown.

CONCLUSIONS

For the experimental configuration of an ion counter with its inlet located in the ground plane and for the electrical conditions described, there appear to be no substantial effects on ion counter operation resulting from external electric fields.

Observed losses which depend on flow rate can be accounted for as duct losses. This result is not obvious, since the external electric fields result in ion motions which are comparable to those due to air motion. Further investigations are planned using the parallel-plate system described by Misakian (1981). Modeling, using realistic flow fields and external field distributions, would also be very helpful in providing a qualitative view of ion motion, but actual three-dimensional modeling would require substantial time and effort because of the complexity of the problem.

ACKNOWLEDGMENT

The effort described in this communication was sponsored by the Electric Energy Systems Division, U.S. Department of Energy. Special thanks go to Andy Secula, without whose help the experiment would not have been completed.

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AN EXPOSURE SYSTEM WHICH SIMULATES THE HVdc TRANSMISSION-LINE ENVIRONMENT

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ABSTRACT

The electrical environment beneath high-voltage direct-current (HVdc) transmission lines is unique in that there is a high concentration of small air ions moving under the influence of a large, static electric field. To assess the possible biological effects of this environment, a small-animal (rodent) exposure system was constructed that generates these two factors up to 21 hr/day for long durations. The system consists of four exposure units, each containing 14 individually housed animals in specially designed glass cages. The four units are in a single room where temperature, relative humidity, and other environmental factors are controlled, and air is HEPA-filtered to reduce particulates. The room is divided into two identical, electrically shielded areas, each containing two exposure units. At the start of each experiment, one area is arbitrarily selected to be the exposure side; the other contains sham-exposed animals. On a weekly basis, the exposure/nonexposure condition of each side is interchanged, with a concomitant change of animals to balance any possible uncontrolled variables in the room. Electric fields up to ± 100 kV/m and concentrations up to 5×10^5 ions/cm^3 (either polarity) can be generated. A computer monitoring system collects data on the electric field, current density, temperature, relative humidity, light cycle and the conditions of all electrical equipment. Final characterization of the system is now being performed. Animal occupation of the cages for up to 7 days did not seriously degrade the performance of the system. Uniformity of the exposure variables throughout the cages was good, with some variability near the walls.

The environment in the vicinity of high-voltage direct-current (HVdc) transmission lines is marked by above-normal concentrations of air ions of both polarities moving under the influence of high-strength static and slowly varying electric fields. Other conditions found under these lines are small static or magnetic fields, corona noise, and radiofrequency (RF) interference. Public concern over possible health consequences of electrical power transmission, including the use of HVdc lines, led to a series of projects to investigate these concerns. In one such project at Pacific Northwest Laboratory (PNL), small laboratory animals are to be exposed to a simulated HVdc environment. This paper describes the design of the exposure system which will be used in these investigations.

Other projects (Charry et al., 1982; Kreuger and Reed, 1976) have investigated the presence of space charge, and the electric field was only incidental to the generation or presentation of the ions. Our approach is to simulate both the large space charge and the high-strength electric fields beneath HVdc lines. Our simulation is preferable because it more closely duplicates the actual HVdc environment. In such an environment effects may be due to synergistic relationships between fields and ions, or delivery of ions to a site of interaction may depend, in some way, on the presence of the large electric field.

The design goals of the exposure system were to provide exposure capability for large numbers of small animals for long durations to fields and space-charge densities *similar to those beneath an operating HVdc transmission line.*

GENERATION OF EXPOSURE PARAMETERS

Electrodes

Generation and control of the electrical environment is performed by four, 1-m^2, parallel-plate electrodes (Figure 1). Air ions are generated by placing into corona a number of fine wires (0.003 in.) strung onto the frame of the corona electrode. Most of the air ions are captured by one of the three remaining electrodes: the cap electrode, the regulating electrode, and the field electrode. Captured ions form a current which flows to ground through a pair of resistors. The resulting voltage drop across these resistances energizes the three electrodes. The larger of the resistors (hundreds of megohms), R_f, connects the field and ground electrodes, generating the voltage needed to produce the electric field in the exposure zone. The resistor between the field electrode and the other two electrodes (which are electrically connected), R_r, is much smaller ($<$10 MΩ), generating a small voltage which regulates the space-charge concentration in the exposure zone. To obtain a specific combination of electric field and space-charge density, both the magnitude of the corona current and the values of the resistances are adjusted empirically until the correct levels are obtained.

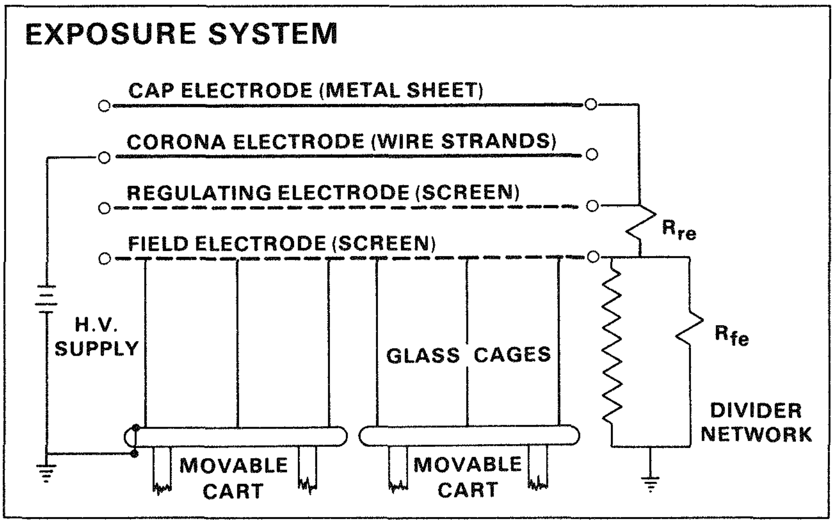


Figure 1. Diagram of the Components of an Exposure Module. R_{re} and R_{fe} are resistances in megohms. Connections between divider network and metal strips on cages are not shown.

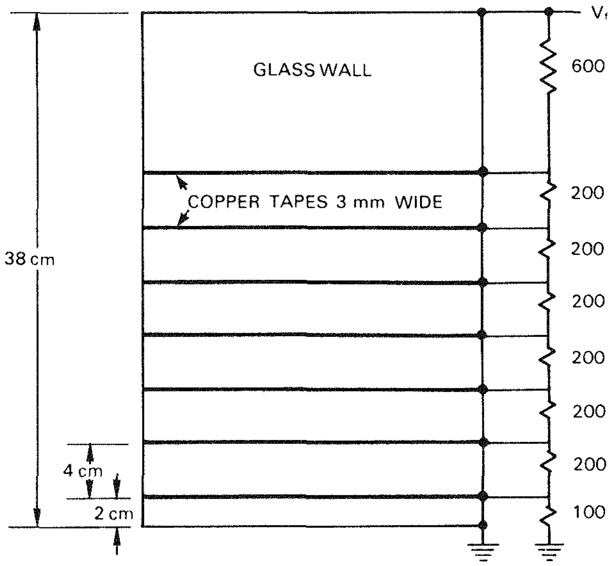
Animal Housing

Caging is the most critical aspect of a system designed to expose animals to uniform, steady levels of air ions. A method is required which restricts the movement of the animals without distorting the electrical environment.

Many cage designs use plastic materials for the cage walls; however, this is generally inappropriate for an ion exposure system because of the extremely high resistivity of the material. The first ions to impact on the wall will be unable to move to ground rapidly, and their presence on the wall will generate an electric field, changing the path of the ions moving within the cage. If this charge accumulation is large enough, ion densities can be reduced or eliminated in the exposure zone. Our cage walls are made of glass, a more conductive material than plastic. Plastic may have bulk resistivities of greater than 10^{16} Ω/cm, but glass is approximately four orders of magnitude more conductive. The glass walls of the animal cages span the distance between the field electrode and ground and are in electrical contact with both. A small current flows through the glass and on its surface, producing a uniformly decreasing potential gradient on the walls which matches the space potential within the cage. Theoretically, space charge will be neither attracted nor repelled from the wall but will move vertically to ground. This technique was originally suggested by Frazier and Preache (1980).

Using the walls to actively stabilize the nearby space potential will be effective only if the bulk and surface conductivities of the glass are uniform and constant with time. Surface conductivity can be affected by changes in relative humidity (Holland, 1964) or by contamination of the surface. For long-term animal studies, such contamination will result from animal wastes and secretions. This would effectively short out the potential gradient on the wall near the ground surface, where contamination would be greatest, decreasing the electric field in the region closest to the wall. To prevent this problem, we have included in the cage design a method of actively controlling the wall's potential gradient instead of depending solely on the electrical properties of the wall. We have mounted a number of conducting copper strips on the outer surface of the cage; they surround the cage at equally spaced intervals. Each strip, which is connected to a unique location on a voltage divider network, is energized to a voltage equal to the theoretical space potential appropriate to its height above the ground plane. If a 50-kV/m field is to be generated in the cages, then the strip 6 cm from the bottom of the cage, for example, carries a voltage of 3 kV. Figure 2 illustrates the placement of the "guard" strips and the configuration of the voltage divider. The voltage at the top of the divider, V_f, is obtained by connecting it to the field electrode.

A cage unit is assembled by placing eight individual cages in a 4 x 2 configuration. Each cage is 23 cm square and 38 cm high and is surrounded by the set of guard strips. The cages are fixed to a mobile cart as a single unit, and two carts are placed beneath each set of parallel plate electrodes. Figure 3 is a sketch of a complete exposure module.



ALL RESISTANCES MΩ

Figure 2. Location of Metal Tapes and Values for Voltage Divider Network. V_f is the voltage on the field electrode which is in contact with the top of the cage.

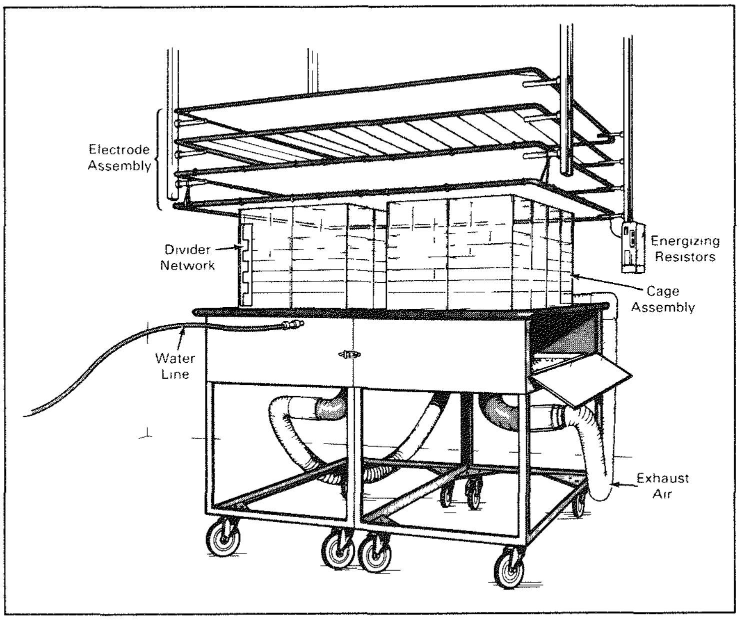


Figure 3. Sketch of a Complete Exposure Module. Note the open access door to the waste catch pan, and the connections for water and exhaust air. The energizing resistors correspond to R_{fe}. The field electrode is suspended above the cages by rigid rods at the rear end and, at the front, straps that allow the electrode to be lifted in order to remove the cages.

SYSTEM CONFIGURATION

Room Layout

The entire exposure suite is contained in a 15-ft x 40-ft room which has been divided into four separate areas by walls of Lexan sheets with a metal mesh overlay (Figure 4). Two of the exposure modules (electrodes and two carts) are in each of the two largest areas, which is 10 ft x 20 ft. These two areas are separated so that one area can be operated in a sham-exposure condition while the other is the exposure side. A more complete description of sham-exposure considerations is given in the next section. The control room and two entry ways are outside the exposure areas. The control room contains the data acquisition equipment and logging computer, the power supply units and system interlock.

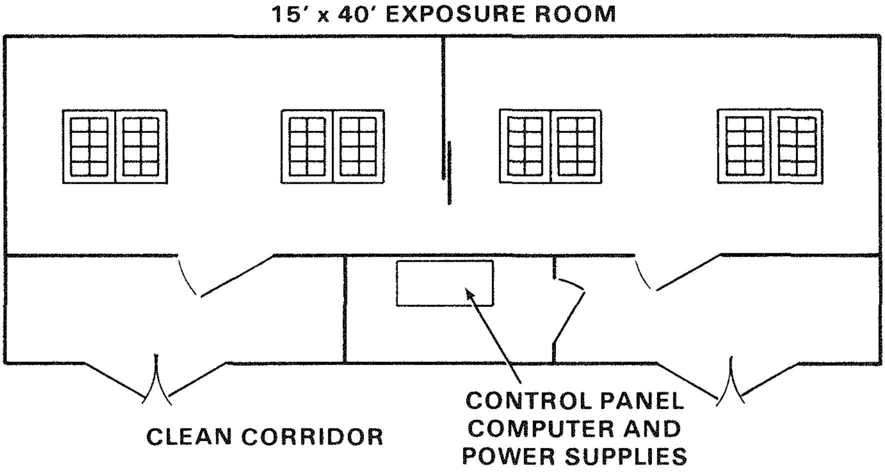


Figure 4. Layout of Exposure Suite. There are two identical exposure zones, each containing two exposure modules. Either side can be used for exposure while the other is used for sham-exposure.

Sham-Exposure Provisions

It is our intention to conduct experiments in a blind condition, where half of the animals are exposed and the other half are under identical environmental conditions except for the electric field and enhanced air ion concentration. To meet these conditions, we chose to keep both sets of animals in the same room, separated only by a partial wall constructed of metal mesh and Lexan. This eliminates differences in room conditions, i.e., room temperature, relative humidity, light levels and sounds. However, small differences may still exist between sides of the room. For exposures of long duration, therefore, we will exchange exposure sides, as well as animal groups, once a week. In addition, the side of the room to be exposed first will be chosen arbitrarily. Thus, exposure modules on both sides must have identical capabilities. An additional advantage of our design is that the exposures can be conducted with only the system operator aware of which is the exposure side, eliminating the possibility of bias in handling or testing the animals.

High-frequency noise is a problem unique to an exposure system that generates ions by corona. This noise is in the range of 10 to 60 kHz (Frazier and Preache, 1980), where rats have acute hearing. The presence of such noise only on the exposure side would compromise our sham-exposure conditions. We have therefore developed a scheme of energizing the electrodes to create comparable noise on the sham-exposure side without introducing into the exposure zone either electric fields or air ions. The technique employed is to ground both the field and regulating electrodes while energizing the corona electrode to a much lower level than in the exposure condition (Figure 1). The exact voltage level is chosen by adjusting the power supply until the captured corona current is the same as the corona current in the normally operating exposure modules. Measurements will be made to insure that the noise levels and frequency components are indeed similar in the sham-exposure and exposure sides.

System Capabilities

The complete system is capable of individually housing a total of 56 rats; at a given time, half would be exposed, and the other half would be sham-exposed. The system has been designed for long-term exposure, with food and water provided *ad lib*.; there is no restriction on the maximum length of exposure. Water is delivered via a pressurized water system to Lixits® (Edstrom Industries, Waterford, WI) mounted beneath the floor of the cage. Food is obtained through a 2-cm slot at the bottom of the outside wall of each cage; the slot leads to a specially constructed trough mounted to the wall. Daily animal care requires that the system be shut down for a minimum of 3 hr; that period can be extended for scientific procedures.

An extensive range of exposure levels can be attained. Although the full range of capabilities has not been tested, especially at the lowest levels, electric fields between 10 and 100 kV/m have been demonstrated. Space-charge densities in the range between 5×10^3 and 5×10^5 ions/cm^3 have been obtained, although the allowable level depends, in part, on the magnitude of the electric field desired. That is to say, the highest ion concentrations are difficult to obtain in our system if the electric fields are at the lower levels.

ENVIRONMENTAL CONTROLS AND SYSTEM MONITORING

Room Environment

Air quality in an air ion exposure system must be well-controlled. Particulates, especially, can be a problem in maintaining constant ion concentrations since they, and also aerosols, can become multiply charged, reducing the concentration of small ions (Chalmers, 1967). Two methods are used to control the number of particulates in the exposure zone. The air supply to the room is HEPA-filtered, keeping particulate counts in the empty room to approximately 300/cm^3. In addition, animals will introduce particulates such as dander and food particles. This source of contamination is partially prevented by housing them on a 2 x 2-mesh, 16-gauge stainless-steel welded cloth so that wastes, food particles, and spilled water fall into the supporting cart, where they are collected on paper-lined waste pans. To further enhance air quality in the cages, the room's air exhaust system is used to draw air down through the cage floor (Figure 3). This keeps the deposited material in the waste pan from drifting back into the exposure zone and draws fresh room air through the cages.

Temperature and relative humidity in the exposure zone are essentially identical to room levels since the air in the cages is exchanged at least 50 times/hr. During a 2-wk period when temperature and relative humidity were monitored every 30 min, temperature averaged 24.2° C, and relative humidity averaged 42%.

Monitoring System

To insure that a stable environment exists during exposures, a small computer monitors and records room temperature and relative humidity every 30 min and light levels every hour (Figure 5). In addition, we measure ozone levels and room particulates to insure that they remain at levels measured prior to the introduction of the animals to the room and the onset of the exposure. The small computer that performs the 30-min measurements also provides a permanent record (Figure 5).

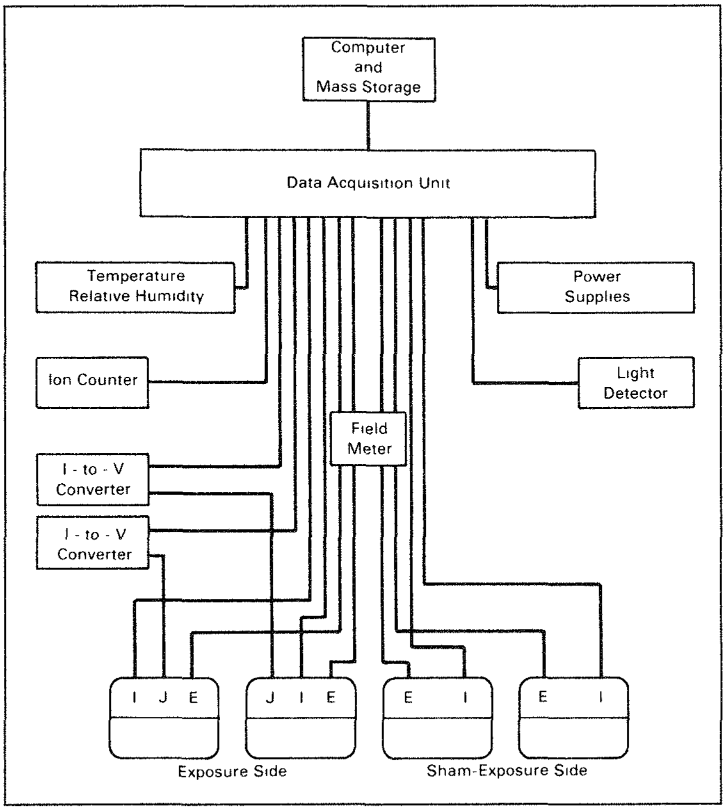


Figure 5. Computer Monitoring System for Measuring Electrical Parameters, Room Temperature and Relative Humidity. Light detector signals the status of room lights: on or off. I is the corona current captured by the electrodes; J, current density, is measured only on exposure side; E is electric field, measured in unoccupied cage.

The computer also monitors and records the following electrical parameters: electric field in each exposure system, current density in each system when generating exposure levels of ions, total corona current generated by each system and the output voltage of each power supply. The electric field and current density readings are taken every 10 min. Since these measurements have a great deal of natural short-term variation, six readings are taken at 2-sec intervals, and the average of these readings is taken as the 10-min value. In addition, space-charge density is calculated, using the relationship $J = \mu \rho E$, where the values for J and E are determined sequentially (less than 0.05 sec difference). Again, the recorded value for space charge is the average of the six calculated values. The other electrical parameters mentioned above are recorded once each hour.

The field and current density probes are in the ground plane of an unoccupied cage. The field probe is a vibrating-element type (Model 171, Monroe Electronics, Inc., Lyndonville, NY) and the current probe is an isolated segment of a copper-clad circuit board ($\sim$180 cm^2), connected to the virtual ground input of a picoammeter (Model 480, Keithley Instruments, Inc., Cleveland, OH).

SYSTEM PERFORMANCE

The success of our cage design depends on whether the cage walls can maintain a stable electrical environment as the cleanliness of the walls decreases during animal occupation. How long the cages can be used before requiring cleaning is unknown; to start, our cages will be changed at least once each week. The following tests were performed to observe the effects of animal occupation on the system's electrical performance.

Test Protocol

A test was developed to measure the electric field and current density in various parts of the cages following increasingly longer periods of occupation. A cart was specially modified to allow a detailed ground-level scanning of the electrical parameters. The ground screen was removed from the cart and replaced with eight removable metal squares (22.5 cm x 22.5 cm) slightly smaller than the floor of a cage. With the eight-cage unit resting on this cart, the metal squares were individually replaced with a modified metal square divided into removable quadrants. A square of copper-clad circuit board that had an electric field probe and current-sensing area (10 cm^2) mounted on it was inserted in one quadrant of the modified metal square (Figure 6A). By rotating both the small square with the sensors and the larger, cutout square, a total of 16 measurements could be taken at various points within the cage. Figure 6B illustrates the locations of the readings on the ground plane of a cage using this technique.

Electrical measurements of cages were made at four times: 1 day after cage cleaning in the standard cagewasher; after 4 days of animal occupation (one male rat/cage); after 4 days of animal occupation; and one day after recleaning the cages. Before making measurements the cage unit was removed from its standard cart and placed on the scanning cart described above. After all eight cages were scanned, the unit was returned to the original cart and, if appropriate, the rats were returned to their original cages. The 1-day delay before performing the scans on newly cleaned cages allowed them to dry thoroughly and equilibrate with room conditions. Scans on soiled cages were performed immediately after the rats were removed and as soon as the cages were shifted to the scanning cart.

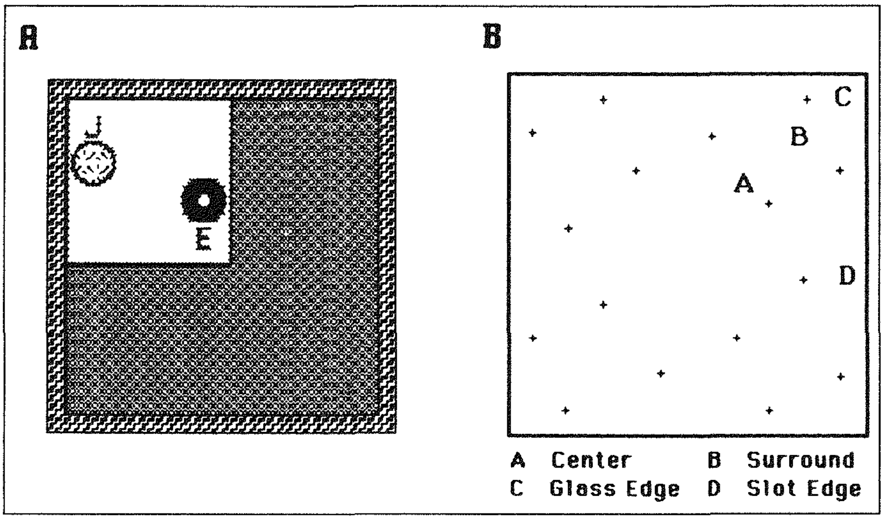


Figure 6. A. Diagram of Scheme for Scanning Electrical Parameters, Showing Location of Current-Density Probe (J) and Electric Field Probe (E). The light-colored square is removable and can be rotated. By locating the quadrant and probes in the four orientations allowed for each, 16 separate scan locations are obtained. B. Plus Sign Shows Locations Obtained by Rotating Inner and Outer Squares Described in 6A. Data are organized by regions, as illustrated.

The resulting data have been organized by regions, as illustrated in Figure 6B. Since we expected contamination of the glass surfaces to have the largest effect on the ground-level electrical environment nearest the glass, 50% of the data points were located within 2 cm of the cage walls. These data have been separated into two regions: the glass edge (C) and the slot edge (D). The slot edge refers to the one wall of the glass cage which ends almost 2 cm above the ground plane to provide access to the food troughs. The remaining data are categorized as from the center (A) or from the area surrounding the center (B).

The results of the electric-field measurement are presented in Figure 7A; the plot of the current-density measurement is given in Figure 7B. In both plots, the results of the scan are plotted by area, as discussed above. For each area, the average for the eight cages has been plotted under the four tested conditions. Exposure conditions with the cages removed from the cart were: electric field, 35 kV/m; current density, 45 nA/m^2.

As shown in Figure 7A, the electric field is quite stable and uniform throughout the cage. The largest change was near walls with glass reaching to the ground plane. In the area near the slot edge, the electric field was always higher than the average reading. This was because the lowest guard strip, which was 3 mm above the slot edge, caused this edge to be slightly higher than the corresponding space potential.

The current density levels (Figure 7B) were also maintained quite well over the period of the tests, although current density was not always uniform within 2 or 3 cm of the walls. This was most apparent at the slot edge, where the higher electric field caused an ion-free region beneath the glass. This variation in current density levels will be factored in when determining average exposure levels experienced by animals in the cages.

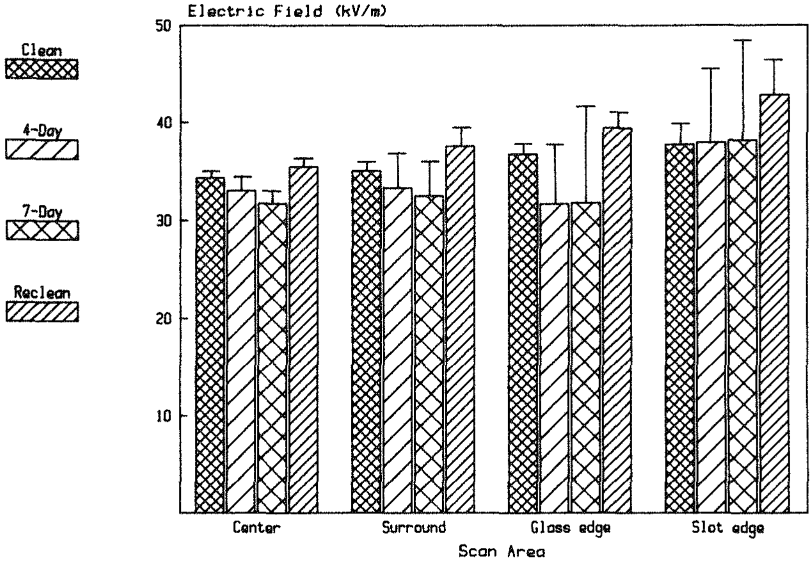


Figure 7A. Electric-Field Levels Within the Cages During a 7-Day Test with Animals. (Without cages, field strength was 35 kV/m.) The data are reported by the regions shown in Figure 6B. 4-Day and 7-Day bars refer to total time animals were in cages. Values are averages for eight cages (four readings/cage). Mean ± SD also shown.

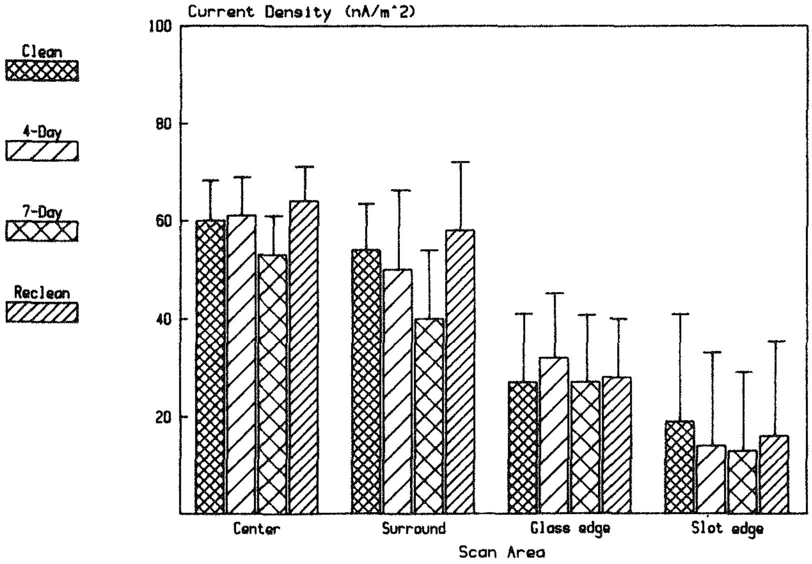


Figure 7B. Current Density Inside Cages During the 7-Day Test with Animals. Without cages, current density was 45 nA/m².

ACKNOWLEDGMENT

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MEASUREMENT OF NEUROTRANSMITTER RELEASE AND UTILIZATION IN SELECTED BRAIN REGIONS OF RATS EXPOSED TO DC ELECTRIC FIELDS AND ATMOSPHERIC SPACE CHARGE

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ABSTRACT

With the advent of high-voltage dc transmission lines there has been increased interest in possible biological effects of exposure to dc electromagnetic fields and atmospheric space charge. In our experiments, male Holtzman rats were exposed to positive or negative space charge (corona generated small air ions: 5.0 x 10^5 ions/cm^3), to dc electric fields of the same polarity and magnitude as that measured in the presence of space charge (3.0 kV/m), or to ambient conditions for periods of 2, 18, or 66 hr. The concentrations and utilization of serotonin (5HT), norepinephrine (NE) and dopamine (DA) in discrete brain regions were evaluated by sensitive and specific high-performance liquid chromatography/electrochemical detection methods. Exposure to space charge in the form of small air ions or to static electric fields did not significantly affect the concentration or utilization of these biogenic amine neurotransmitters in this rat strain.

Although there has long been interest in the possible behavioral and biological effects of exposure to atmospheric space charge in the form of small air ions, only in recent years has consideration been given to the possibility that the electrostatic fields associated with atmospheric space charge in the form of small air ions might have biological effects apart from any influence of air ions *per se*.

As part of our ongoing investigation of the biological significance of air ions, we evaluated this possibility in a series of experiments in which we measured the release and utilization of catecholamine and indoleamine neurotransmitters in rats that were exposed to air ions or to dc fields of the same magnitude as that measured with exposure to air ions. The original reports (Charry and Bailey, 1985; Bailey and Charry, in press) should be consulted for additional details.

METHODS

Figure 1 shows the exposure system used in these studies. Air was filtered and passed through the exposure system at controlled temperature (23 ± 1°C) and relative humidity (50 ± 10%). A complete description of the exposure system and its performance can be found in Charry, Bailey, Shapiro et al. (1986). Male Holtzman rats were exposed to air ions or dc electric fields for 2, 18 or 66 hr. The concentration of air ions was 5.0 x 10^5 ions/cm^3; the dc electric field strength was 3.0 kV/m.

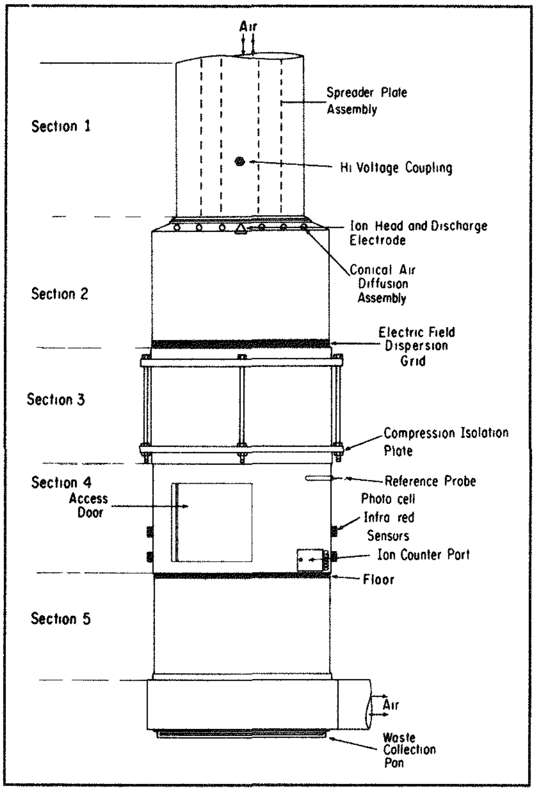

Figure 1. **System for Exposing Rats to Positive or Negative Space Charge (Concentration, 5.0×10^5 Ions/cm^3) dc Electric Fields (3.0 kV/m) or Ambient Conditions.**

The release and utilization (turnover) of norepinephrine (NE) and dopamine (DA) neurotransmitters were measured at the conclusion of the exposure period in the hypothalamus, brainstem, hippocampus and amygdala, frontal cortex, and striatum. Turnover measurements were compared for two groups of rats within each experimental condition. One group of rats served as controls; the other group was injected, 2 hr prior to sacrifice, with 250 mg/kg of the catecholamine synthesis inhibitor d,l a-methyl-p-tyrosine methyl ester (AMPT). Turnover was calculated from the differences in catecholamine concentration between control and AMPT-injected groups, expressed in percentages. The release and utilization of serotonin (5-HT) within each brain region was measured by comparing the concentration of 5-HT to the concentration of 5-hydroxyindoleacetic acid (5HIAA), the major metabolite of 5-HT (i.e., the ratio 5HIAA/5-HT). For both catecholamine and serotonin measures of neurotransmitter turnover, increases or decreases in the calculated percentage differences that are reported correspond to increases or decreases in the release and utilization of these neurotransmitters. The neurotransmitters and their metabolites were measured by high-performance liquid chromatography and electrochemical detection (Charry and Bailey, 1985; Bailey and Charry, in press).

RESULTS

Exposure to positive air ions, negative air ions, or to dc electric fields failed to significantly affect the concentration of NE or DA in any of the five brain regions examined after exposure for 2 hr (Tables 1 and 2), 18 hr (Tables 3 and 4), or 66 hr (Tables 5 and 6). This was the case whether or not catecholamine synthesis had been blocked by the administration of AMPT prior to sacrifice.

TABLE 1 Regional Turnover of Dopamine in Rat Brain Regions for 2-Hr Exposure to Air Ions and DC Field Conditions

		Dopamine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	332.5 ± 26.7	340.0 ± 22.0	373.7 ± 38.2	389.9 ± 75.0	320.0 ± 28.1
	AMPT[a]	110.7 ± 6.9	111.7 ± 6.0	105.4 ± 10.6	127.1 ± 11.0	104.1 ± 8.6
	%	-66.7	-67.2	-71.8	-67.4	-67.5
Brainstem	Control	122.9 ± 4.6	122.3 ± 4.5	124.6 ± 7.2	124.4 ± 4.6	121.1 ± 8.0
	AMPT	36.0 ± 1.8	34.3 ± 1.6	38.5 ± 3.1	36.2 ± 2.4	34.5 ± 4.1
	%	-70.7	-72.0	-69.1	-70.9	-71.5
Hippocampus/amygdala	Control	83.7 ± 7.5	76.4 ± 5.4	74.8 ± 6.4	79.0 ± 4.1	75.9 ± 9.4
	AMPT	32.0 ± 3.4	33.5 ± 5.5	29.5 ± 4.4	28.7 ± 2.4	32.1 ± 6.4
	%	-61.8	-56.2	-60.6	-63.7	-57.7
Frontal cortex	Control	77.1 ± 6.9	87.2 ± 9.1	87.9 ± 10.6	89.9 ± 7.3	94.4 ± 11.6
	AMPT	32.0 ± 3.3	38.1 ± 5.1	39.8 ± 5.0	40.3 ± 6.8	47.4 ± 6.5
	%	-58.5	-56.3	-54.7	-55.2	-49.8
Striatum	Control	8195.8 ± 537.3	8879.5 ± 690.2	8072.8 ± 719.2	8443.9 ± 735.9	7564.1 ± 715.2
	AMPT	4225.7 ± 377.1	4275.1 ± 344.5	4508.4 ± 762.0	4348.6 ± 1574.6	4763.9 ± 682.0
	%	-48.4	-51.8	-44.2	-48.5	-37.0
		(14-15)[b]	(14-15)[b]	(7-9)[b]	(14-15)[b]	(6-7)[b]

[a] d,l a-methyl-p-tryosine methyl ester a catecholamine synthesis inhibitor
[b] Number of samples analyzed

TABLE 2 Regional Turnover of Norepinephrine in Rat Brain Regions for 2-Hr Exposure to Air Ions and DC Field Conditions

		Norepinephrine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	1528.6 ± 87.2	1646.1 ± 97.0	1629.1 ± 77.5	1664.9 ± 154.1	1563.4 ± 169.9
	AMPT[a]	1239.5 ± 63.8	1182.9 ± 51.6	1224.9 ± 120.4	1263.5 ± 74.7	1166.6 ± 115.9
	%	18.1	-28.1	-24.8	-24.1	-25.4
Brainstem	Control	568.0 ± 17.1	578.8 ± 28.8	556.7 ± 31.5	562.6 ± 26.8	583.8 ± 46.6
	AMPT	403.4 ± 19.5	397.8 ± 15.2	416.8 ± 20.1	396.3 ± 14.5	400.6 ± 23.7
	%	-29.0	-31.3	-25.1	-29.6	-31.4
Hippocampus/amygdala	Control	336.5 ± 15.8	326.3 ± 23.2	336.0 ± 22.3	323.6 ± 14.8	336.7 ± 19.2
	AMPT	228.7 ± 15.6	222.5 ± 13.6	203.7 ± 13.6	221.2 ± 11.7	218.6 ± 20.6
	%	-32.0	-31.8	-39.4	-31.6	-35.1
Frontal cortex	Control	313.9 ± 40.7	302.9 ± 31.1	277.4 ± 13.6	316.1 ± 39.7	381.4 ± 98.1
	AMPT	171.1 ± 6.8	168.1 ± 8.8	160.9 ± 17.8	159.5 ± 7.6	166.6 ± 10.2
	%	-45.5	-44.5	-42.0	-49.5	-56.3
		(14-15)[b]	(14-15)[b]	(7-9)[b]	(14-15)[b]	(6-7)[b]

[a] d,l a-methyl-p-tryosine methyl ester, a catecholamine synthesis inhibitor
[b] Number of samples analyzed

TABLE 3 Regional Turnover of Dopamine in Rat Brain Regions for 18-Hr Exposure to Air Ions and DC Field Conditions

		Dopamine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	391.9 ± 20.0	362.8 ± 18.0	338.0 ± 17.2	355.2 ± 15.3	396.6 ± 28.2
	AMPT[a]	137.4 ± 6.3	138.1 ± 9.2	126.4 ± 17.3	130.1 ± 11.2	121.3 ± 9.6
	%	-64.9	-61.9	-62.6	-63.4	-69.4
Brainstem	Control	134.9 ± 6.1	130.6 ± 2.8	133.5 ± 6.4	133.6 ± 3.0	135.1 ± 6.3
	AMPT	40.9 ± 2.7	40.1 ± 1.4	42.8 ± 1.9	40.2 ± 1.8	37.3 ± 3.8
	%	-69.7	-69.3	-67.9	-70.0	-72.4
Hippocampus/amygdala	Control	90.0 + 14.3	90.2 ± 13.4	74.3 ± 15.8	89.1 ± 11.7	94.7 ± 16.9
	AMPT	25.1 ± 3.8	29.0 ± 4.1	38.0 ± 6.8	27.3 ± 4.7	19.8 ± 3.5
	%	-72.1	-67.8	-48.9	-69.4	-79.1
Frontal cortex	Control	111.5 ± 11.0	96.6 ± 12.7	137.5 ± 22.4	98.8 ± 11.9	107.8 ± 13.4
	AMPT	50.5 ± 7.9	27.6 ± 3.5	42.9 ± 7.4	37.6 ± 6.1	32.5 ± 6.3
	%	-54.7	-71.4	-68.8	-61.9	-69.8
Striatum	Control	8923.3 ± 510.4	8478.1 ± 356.2	8548.3 ± 457.6	8255.2 ± 560.2	8501.9 ± 412.4
	AMPT	4893.7 ± 285.4	5166.7 ± 410.8	5152.0 ± 549.9	5086.5 ± 250.6	4514.2 ± 526.8
	%	-45.2	-39.1	-39.7	-38.4	-46.9
		(11-15)[b]	(13-15)[b]	(6-7)[b]	(13-15)[b]	(6-8)[b]

[a] d,l a-methyl-p-tryosine methyl ester, a catecholamine synthesis inhibitor

[b] Number of samples analyzed

TABLE 4 Regional Turnover of Norepinephrine in Rat Brain Regions for 18-Hr Exposure to Air Ions and DC Field Conditions

		Norepinephrine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	1663.2 ± 54.4	1600.9 ± 49.7	1680.5 ± 98.7	1636.5 ± 64.1	1597.0 ± 86.5
	AMPT[a]	1467.1 ± 108.8	1439.2 ± 99.6	1250.5 ± 159.2	1451.1 ± 97.7	1398.8 ± 173.0
	%	-11.8	-10.1	-25.6	11.3	-12.4
Brainstem	Control	580.3 ± 20.4	575.8 ± 23.5	599.0 ± 39.2	604.4 ± 15.7	575.7 ± 25.7
	AMPT	456.1 ± 19.6	450.3 ± 16.1	422.1 ± 40.5	451.0 ± 17.0	375.5 ± 51.9
	%	-21.4	-21.8	-26.2	-25.4	-34.8
Hippocampus/amygdala	Control	339.6 ± 15.0	320.8 ± 12.1	320.1 ± 11.7	329.2 ± 14.3	333.2 ± 20.2
	AMPT	272.1 ± 11.0	247.0 ± 7.5	241.6 ± 17.1	258.8 ± 12.4	228.1 ± 7.3
	%	-19.9	-23.0	-24.5	-21.4	-31.5
Frontal cortex	Control	274.6 ± 11.8	261.4 ± 10.1	274.7 ± 10.9	273.7 ± 11.3	262.5 ± 10.7
	AMPT	197.1 ± 9.8	196.1 ± 7.2	186.9 ± 18.4	198.0 ± 10.0	191.5 ± 9.2
	%	-28.2	-24.9	-32.0	-27.7	-27.0
		(12-15)[b]	(13-15)[b]	(7)[b]	(13-15)[b]	(6-8)[b]

[a] d,l a-methyl-p-tryosine methyl ester, a catecholamine synthesis inhibitor

[b] Number of samples analyzed

TABLE 5 Regional Turnover of Dopamine in Rat Brain Regions for 66-Hr Exposure to Air Ions and DC Field Conditions

		Dopamine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	338.4 ± 20.8	349.0 ± 20.5	333.4 ± 26.7	358.4 ± 20.4	342.3 ± 27.0
	AMPT[a]	131.0 ± 8.3	136.6 ± 10.0	118.8 ± 12.2	134.1 ± 4.5	143.9 ± 14.1
	%	-61.3	-60.9	-64.4	-62.6	-58.0
Brainstem	Control	126.7 ± 4.3	129.6 ± 5.3	127.1 ± 3.7	136.5 ± 3.9	135.2 ± 8.6
	AMPT	38.3 ± 1.4	41.2 ± 1.7	41.3 ± 2.5	40.4 ± 2.0	45.7 ± 3.0
	%	-70.0	-68.2	-67.5	-70.4	-66.2
Hippocampus/amygdala	Control	65.8 ± 5.7	70.1 ± 8.8	74.3 ± 10.7	68.7 ± 6.3	68.5 ± 14.6
	AMPT	24.5 ± 4.2	28.2 ± 3.7	30.6 ± 6.0	25.0 ± 2.4	34.3 ± 6.8
	%	-62.8	-59.8	-58.8	-63.6	-49.9
Frontal cortex	Control	93.3 ± 9.0	95.2 ± 12.4	109.3 ± 13.9	95.5 ± 15.0	99.1 ± 16.2
	AMPT	41.7 ± 5.3	37.5 ± 3.2	47.8 ± 11.0	49.2 ± 8.7	46.1 ± 11.1
	%	-55.3	-60.6	-56.3	-48.5	-53.5
Striatum	Control	9806.1 ± 687.8	9276.4 ± 659.3	8539.5 ± 1153.1	9249.4 ± 659.6	10441.5 ± 1012.3
	AMPT	5598.4 ± 224.6	5570.1 ± 299.0	5083.4 ± 482.8	5517.2 ± 257.5	6603.4 ± 715.2
	%	-42.9	-40.0	-40.5	-40.3	-36.8
		(14-15)[b]	(14-15)[b]	(8-9)[b]	(14-15)[b]	(5-6)[b]

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[a] d,l a-methyl-p-tryosine methyl ester a catecholamine synthesis inhibitor

[b] Number of samples analyzed

TABLE 6 Regional Turnover of Norepinephrine in Rat Brain Regions for 66-Hr Exposure to Air Ions and DC Field Conditions

		Norepinephrine Concentration (ng/g Brain Tissue ± SEM)				
Brain Region	Injection	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	Control	1640.3 ± 89.1	1626.2 ± 55.6	1758.1 ± 83.1	1630.5 ± 88.5	1600.0 ± 55.9
	AMPT[a]	1325.4 ± 34.7	1326.0 ± 62.1	1282.5 ± 46.5	1393.2 ± 53.6	1490.8 ± 120.9
	%	-19.2	-18.5	-27.0	14.6	-6.8
Brainstem	Control	576.5 ± 25.8	578.8 ± 28.6	600.9 ± 27.5	575.2 ± 18.7	617.5 ± 44.1
	AMPT	451.9 ± 14.2	439.6 ± 14.1	427.1 ± 17.7	440.7 ± 13.8	446.2 ± 13.1
	%	-21.6	-24.0	-28.9	-23.4	-27.7
Hippocampus/amygdala	Control	301.1 ± 13.7	331.5 ± 13.2	302.2 ± 11.0	310.0 ± 10.7	328.9 ± 14.9
	AMPT	225.4 ± 11.4	248.0 ± 15.0	258.1 ± 16.4	249.3 ± 15.9	232.9 ± 10.6
	%	-27.3	-25.2	-14.6	-19.6	-29.2
Frontal cortex	Control	296.3 ± 12.0	266.5 ± 9.5	262.9 ± 14.6	268.3 ± 9.1	268.2 ± 11.5
	AMPT	170.9 ± 6.7	179.1 ± 6.5	181.6 ± 10.1	177.9 ± 6.6	192.6 ± 11.7
	%	-36.5	-32.8	-30.9	-33.7	-28.2
		(15)[b]	(15)[b]	(9)[b]	(15)[b]	(6)[b]

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[a] d,l a-methyl-p-tryosine methyl ester, a catecholamine synthesis inhibitor

[b] Number of samples analyzed

The concentration of 5-HT, its metabolite, 5HIAA, and the ratio of 5HIAA to 5-HT were measured in the same brain regions that were analyzed for catecholamines after exposure periods of 2 hr (Table 7), 18 hr (Table 8), and 66 hr (Table 9). There were no significant differences among the values of these measures across experimental conditions at any of the three exposure durations tested, even when the P value required for statistical significance was relaxed from $P < 0.05$ to $P < 0.10$.

TABLE 7 Concentration (ng/g tissue ± SEM) of Serotonin (5HT) and Its Major Metabolite 5-Hydroxyindoleacetic Acid (5HIAA) in Rat Brain Regions after 2-Hr Exposure to Air Ions and DC Field Conditions

Brain Region	Measure	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	5HT	758.4 ± 43.0	780.4 ± 32.0	823.7 ± 26.3	808.7 ± 55.0	776.5 ± 60.9
	5HIAA	358.9 ± 25.1	349.1 ± 24.6	370.7 ± 26.2	362.4 ± 23.5	335.6 ± 36.7
	5HIAA/5HT	0.366 ± 0.020	0.343 ± 0.019	0.356 ± 0.027	0.351 ± 0.019	0.323 ± 0.033
Brainstem	5HT	782.2 ± 13.7	765.2 ± 16.2	775.9 ± 18.3	763.3 ± 15.8	766.7 ± 11.3
	5HIAA	557.1 ± 24.0	519.9 ± 31.8	526.6 ± 37.7	525.3 ± 20.1	506.9 ± 25.6
	5HIAA/5HT	0.549 ± 0.027	0.521 ± 0.025	0.532 ± 0.034	0.538 ± 0.033	0.494 ± 0.040
Hippocampus/amygdala	5HT	439.8 ± 17.0	431.0 ± 12.6	457.2 ± 12.8	450.1 ± 15.3	466.4 ± 19.2
	5HIAA	251.5 ± 13.5	229.6 ± 16.3	239.3 ± 22.1	241.4 ± 13.3	244.0 ± 19.0
	5HIAA/5HT	0.441 ± 0.022	0.409 ± 0.022	0.406 ± 0.025	0.419 ± 0.028	0.395 ± 0.044
Frontal cortex	5HT	288.5 ± 10.3	287.0 ± 8.7	284.5 ± 7.8	284.3 ± 11.4	304.3 ± 10.1
	5HIAA	179.1 ± 11.1	163.5 ± 12.3	160.8 ± 13.2	161.9 ± 8.8	166.9 ± 9.1
	5HIAA/5HT	0.475 ± 0.022	0.432 ± 0.019	0.442 ± 0.031	0.447 ± 0.031	0.409 ± 0.030
Striatum	5HT	438.4 ± 18.3	446.6 ± 27.3	432.7 ± 29.1	426.8 ± 14.0	440.3 ± 15.2
	5HIAA	431.4 ± 23.6	409.7 ± 32.8	389.5 ± 24.8	403.7 ± 18.7	407.0 ± 19.9
	5HIAA/5HT	0.763 ± 0.040	0.709 ± 0.039	0.726 ± 0.060	0.741 ± 0.047	0.694 ± 0.061
		(15)[a]	(15)[a]	(9)[a]	(15)[a]	(6)[a]

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[a] Number of samples analyzed

TABLE 8 Concentration (ng/g tissue ± SEM) of Serotonin (5HT) and Its Major Metabolite, 5-Hydroxyindoleacetic Acid (5HIAA) in Rat Brain Regions after 18-Hr Exposure to Air Ions and DC Field Conditions

Brain Region	Measure	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	5HT	991.8 ± 30.7	924.6 ± 44.7	922.7 ± 39.6	1012 ± 41.5	945.8 ± 55.8
	5HIAA	440.1 ± 23.4	424.1 ± 31.1	395.8 ± 22.2	459.1 ± 29.2	439.4 ± 39.8
	5HIAA/5HT	0.503 ± 0.033	0.481 ± 0.030	0.459 ± 0.030	0.476 ± 0.030	0.476 ± 0.020
Brainstem	5HT	836.2 ± 29.0	809.0 ± 52.2	763.7 ± 20.4	870.1 ± 44.9	862.0 ± 41.2
	5HIAA	523.4 ± 20.0	499.2 ± 43.6	470.8 ± 17.6	551.5 ± 26.8	525.5 ± 32.8
	5HIAA/5HT	0.661 ± 0.026	0.661 ± 0.038	0.658 ± 0.032	0.670 ± 0.029	0.664 ± 0.024
Hippocampus/amygdala	5HT	527.8 ± 23.8	515.1 ± 34.2	480.4 ± 16.7	539.5 ± 28.0	517.7 ± 26.7
	5HIAA	243.9 ± 11.3	245.9 ± 16.6	235.2 ± 22.5	253.4 ± 16.3	239.4 ± 20.6
	5HIAA/5HT	0.498 ± 0.019	0.493 ± 0.029	0.474 ± 0.023	0.502 ± 0.028	0.500 ± 0.027
Frontal cortex	5HT	383.3 ± 35.7	399.5 ± 38.9	328.2 ± 11.0	391.2 ± 42.1	403.2 ± 38.0
	5HIAA	188.1 ± 21.0	195.7 ± 27.1	149.9 ± 8.8	200.5 ± 26.7	197.1 ± 26.1
	5HIAA/5HT	0.562 ± 0.058	0.525 ± 0.0444	0.491 ± 0.031	0.577 ± 0.052	0.528 ± 0.035
Striatum	5HT	638.0 ± 54.3	557.1 ± 60.2	502.9 ± 51.9	570.4 ± 54.9	712.7 ± 50.6
	5HIAA	438.3 ± 31.3	413.7 ± 43.1	323.0 ± 30.7	424.0 ± 37.9	405.7 ± 48.8
	5HIAA/5HT	0.829 ± 0.091	0.871 ± 0.098	0.706 ± 0.073	0.877 ± 0.098	0.656 ± 0.070
		(17-19)[a]	(12-14)[a]	(14-16)[a]	(13-14)[a]	(13-16)[a]

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[a] Number of samples analyzed

TABLE 9 Concentration (ng/g tissue ± SEM) of Serotonin (5HT) and Its Major Metabolite, 5-Hydroxyindoleacetic Acid (5HIAA) in Rat Brain Regions after 66-Hr Exposure to Air Ions and DC Field Conditions

Brain Region	Measure	Control	Positive ions	Positive Electric field	Negative ions	Negative Electric field
Hypothalamus	5HT	936 9 ± 56 4	910 1 ± 51 0	845 2 ± 87 4	947 0 ± 59 2	916 7 ± 21 6
	5HIAA	393 4 ± 33 4	386 0 ± 26 0	388 5 ± 66 2	418 4 ± 31 8	375 7 ± 19 2
	5HIAA/5HT	0 388 ± 0 021	0 398 ± 0 021	0 410 ± 0 051	0 413 ± 0 020	0 411 ± 0 021
Brainstem	5HT	845 1 ± 44 6	794 8 ± 51 6	830 1 ± 62 5	851 2 ± 38 3	863 2 ± 33 5
	5HIAA	507 1 ± 29 3	483 3 ± 32 8	545 0 ± 61 9	520 9 ± 30 2	495 7 ± 18 5
	5HIAA/5HT	0 541 ± 0 030	0 571 ± 0 025	0 592 ± 0 061	0 569 ± 0 022	0 576 ± 0 026
Hippocampus/amygdala	5HT	501 2 ± 26 4	509 9 ± 25 8	490 1 ± 44 3	504 7 ± 22 2	486 7 ± 17 3
	5HIAA	234 4 ± 14 8	234 6 ± 12 2	256 9 ± 30 6	239 2 ± 13 8	213 6 ± 9
	5HIAA/5HT	0 430 ± 0 023	0 433 ± 0 022	0 472 ± 0 046	0 444 ± 0 022	0 440 ± 0 024
Frontal cortex	5HT	329 4 ± 21 5	339 4 ± 18 1	336 5 ± 38 7	352 5 ± 21 1	322 1 ± 7 3
	5HIAA	161 1 ± 19 4	170 0 ± 16 0	194 3 ± 38 6	177 1 ± 19 6	142 2 ± 8 2
	5HIAA/5HT	0 447 ± 0 035	0 467 ± 0 032	0 508 ± 0 064	0 462 ± 0 033	0 440 ± 0 021
Striatum	5HT	532 8 ± 37 7	525 8 ± 34 0	508 3 ± 42 2	599 2 ± 61 1	599 7 ± 95 5
	5HIAA	375 7 ± 24 8	373 6 ± 19 2	415 5 ± 62 0	408 5 ± 43 6	339 1 ± 20 8
	5HIAA/5HT	0 689 ± 0 065	0 693 ± 0 060	0 757 ± 0 121	0 719 ± 0 067	0 613 ± 0 063
		(14-15)[a]	(15)[a]	(9)[a]	(14-15)[a]	(6)[a]

[a] Number of samples analyzed

DISCUSSION

There have been previous reports in the literature that air ions can produce biological responses in animals which include alterations in whole-brain neurotransmitter levels. The exposure system used in this study permitted close control over the exposure and dosimetry variables that have been identified as potential sources of artifact in previous biological studies. The exposure of Holtzman outbred rats to either positively or negatively charged small air ions (and associated dc electric fields) did not significantly affect the concentration of NE or DA in the various brain regions examined. Nor was there any significant effect of this exposure on the concentration of these catecholamines measured 2 hr after the injection of AMPT, indicating that the turnover of catecholamines which reflects their release and utilization was not affected by exposure to air ions. Nor did the exposure of rats only to dc electric fields of the same polarity and magnitude as that measured in the ionization conditions affect catecholamine turnover. An analysis of serotonin turnover in our experiments also indicated that there was no effect of air ions and/or low-strength dc electric fields on this neurotransmitter system.

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ALTERATIONS IN RAT FLEXOR WITHDRAWAL REFLEX RESPONSE TO A NOXIOUS STIMULUS AFTER EXPOSURE TO ATMOSPHERIC IONS

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ABSTRACT

The flexor withdrawal reflex is inhibited by a descending spinal pathway which includes a medullary serotonergic component originating in the nucleus raphe magnus (NRM). This provides an ideal system in which to test Krueger's serotonin hypothesis, which states that positive ions induce serotonin release, while negative ions cause an increase in the rate of serotonin oxidation. The hypothesis predicts that, in this neural system, exposure to positive ions would produce inhibition of the withdrawal reflex, and negative ion treatment would have the opposite effect. Experiments were conducted on male Long-Evans rats (200 g). The latency of the withdrawal reflex was measured after application of a heat stimulus to the rat's tail. Positive ion exposure (7×10^5 ions/cm^3) for 7 days induced a state of analgesia, increasing the latency of the withdrawal reflex. Negative ion treatment (7×10^5 ions/cm^3) for 7 days produced the opposite effect, as predicted. Naloxone treatment failed to reverse the analgesic effect of positive ions, thereby excluding the opioid system of the periaqueductal gray (PAG) from involvement in this ion effect. Furthermore, the administration of morphine to negative-ion-treated rats failed to reverse their hyperalgesic state, suggesting that the ion treatment had blocked the activity of the descending pathway at a site caudal to the PAG. The serotonin system of the NRM is thus a possible site for mediation of the ion effects observed. The significant changes in whole-brain serotonin levels, which increased following positive ion exposure and decreased after negative ion treatment, provide additional support for Krueger's hypothesis.

A great deal has been written about the relationship between atmospheric ions and the serotonin systems of the body (Krueger and Smith, 1960; Krueger, Andriese and Kotaka, 1963; Gilbert, 1973; Diamond et al., 1980). The scientific merit of many publications in this field is questionable because of conflicting data. The value of some of this work has been criticized (Bailey, 1982) for lack of adequate controls, poor design and inappropriate techniques. However, a body of evidence derived from well-executed experiments forces us to accept the serotonin hypothesis as being heuristically important and in need of further testing. This hypothesis, as defined originally by Krueger, states that positive ions induce serotonin release, while negative ions increase the rate of serotonin oxidation (Krueger and Sigel, 1981). Since many functional responses to atmospheric ion exposure may be linked theoretically to changes in the serotonergic system, much may be learned from rigorous testing of this hypothesis, which we have adopted as the point from which to begin investigations into the biological actions and effects of atmospheric ions. Our first objective has been to test this hypothesis in a well-defined physiological system which is functionally dependent on a serotonergic pathway.

To this end our attention has been directed at the serotonin system of the spinal cord and, in particular, that component of the cord system which originates in the nuclear raphe magnus (NRM). This system has been investigated meticulously (Willis and Coggeshall, 1978; Yaksh and Wilson, 1979) in connection with its role in pain inhibition at spinal cord level. The system inhibits not only the onward transmission of the pain input but also the motor response to the pain stimulus, which is the flexor withdrawal reflex (Basbaum and Fields, 1984).

Björklund and Skagerberg (1982) have distinguished three major components of the descending serotonin system. The pathway involved primarily with inhibition of the flexor reflexes has a dorsal projection originating in the NRM, passing along the dorsolateral funiculus and innervating the dorsal horn. The ventral and intermediate projections originate in other raphe nuclei. Basbaum and Fields (1984), among others, have shown that the processes which drive the final descending serotonin system are complex, and many still require clarification. Their studies have shown, however, that cortical and other higher (diencephalic) brain sites provide significant stimulation to the periaqueductal gray (PAG), where one of three opioid links has been demonstrated. This region is probably the major target for morphine-like compounds (μ-receptor agonists) which comprise a major excitatory input to this descending pathway. The medullary component of the descending pain control system receives input from, among others, the PAG and from collateral fibers arising from the ascending spinothalamic tract. Opioid-mediated input also occurs at this level. Most of this input affects the activity of the NRM, whose serotonergic fibers constitute a vital link between the brainstem inhibitory system and the dorsal horn neurons of the cord. Perturbation of this pathway is likely to cause significant disruption of the whole inhibitory process. The possibility that atmospheric ions may induce this perturbation by altering serotonin metabolism is the hypothesis under investigation.

METHODS

Male Long-Evans rats weighing 200 g were used throughout the study. Water and commercial rat food were available ad libitum, and the quarters were temperature-controlled (24°C). Animals were housed in groups of four to six. The ion-inhalation chambers consisted of four identical cubicles with smooth masonite walls and a stainless-steel grid floor, 25 cm by 35 cm, which was maintained at ground potential. The design of our system was similar to that described by Diamond et al. (1980). Negative or positive ions were generated by a corona discharge ionizer (NEGION 90, Nu-Aire (SA) Pty Ltd., Johannesburg), and their concentration in the chambers was measured with a parallel-plate ion collector (DEV Industries, Inc., Boulder, CO) connected to an electrometer (Keithley Instruments, Inc., Cleveland, OH). The small-ion concentration in all the experiments reported was approximately 7×10^5 ions/cm^3. The physiological parameter measured was the latent period of the tail flexor withdrawal reflex, i.e., the time between the application of a heat stimulus to the tail and the action of withdrawal (D'Amour and Smith, 1941). The pain stimulus used to evoke this response was produced by a hot wire, which was lifted toward the tail on a magnetically damped lever. A switching mechanism activated an electronic timer as soon as the hot wire touched the tail and stopped the timer when the tail moved. The latent period was obtained from the mean of three such readings. Whole-brain serotonin levels were measured by spectrophotofluorimetry according to the method of Udenfriend and Weissbach (1963). Drugs such as morphine and naloxone were administered by subcutaneous route. Data are presented as means ± SD except where indicated otherwise. Student's *t*-test was used to determine the statistical differences between means.

RESULTS

Positive Ions and the Latency of the Flexor Reflex

Twelve male rats were exposed to positive ions for a period of 7 days. The latency of the withdrawal reflex was measured before treatment and again on days 4 and 7. The increase in the latency of this reflex (Figure 1) after the ion treatment was statistically significant on both days ($P < 0.001$).

A number of experiments were conducted to determine the duration of this positive ion response, and it was quickly ascertained that the effect was shortlived, i.e., it lasted less than 2 hr. The rate of decay of this effect was measured in 12 male rats which had been exposed to positive ions for 7 days. The latency of the withdrawal reflex was measured in all animals 10 min after removal from the positive-ion-rich environment and again at successive 15-min intervals. Figure 2 shows that the reduction, with time, of the reflex latent period describes a straight line on a semilog plot. The curve, fitted by regression analysis, is described by the equation $Y = 14.29 - 3.25 \ln X$. The half-life of this decay curve was about 20 min.

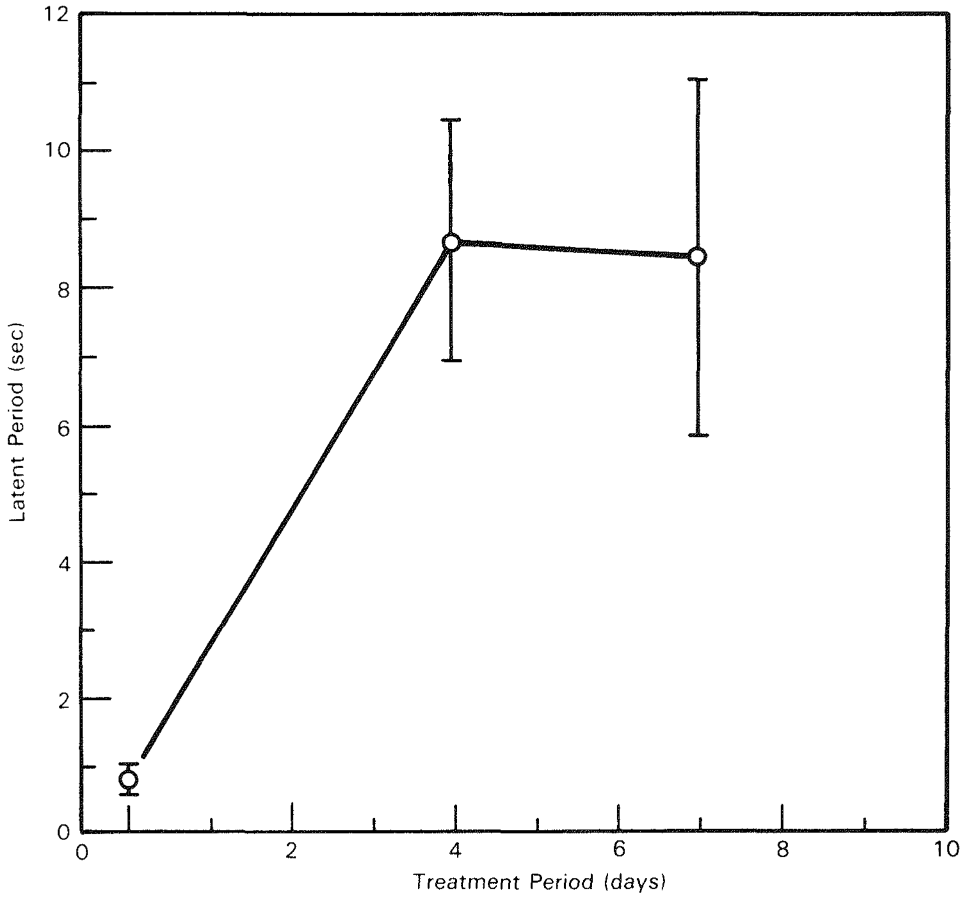

Figure 1. Effect of Positive-Ion Treatment for 7 Days on the Latent Period of the Withdrawal Reflex. Mean latencies were obtained from 12 rats; vertical bars are standard deviation of the means.

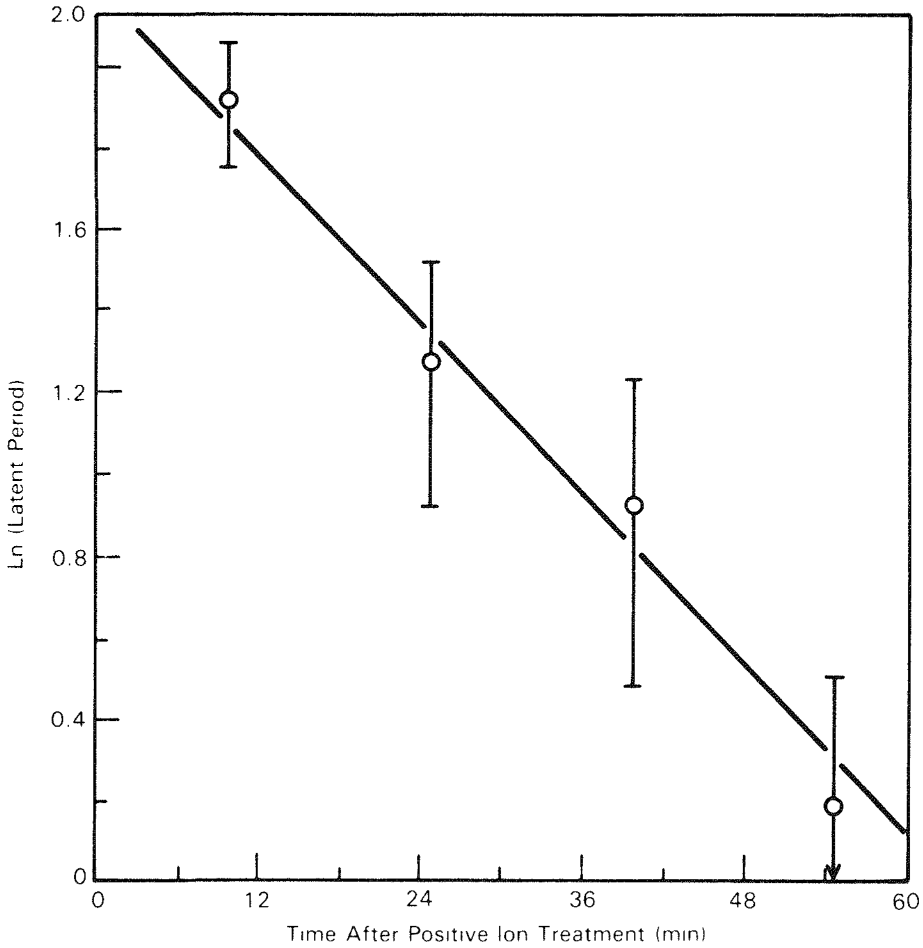

Figure 2. Response of the Positive-Ion-Induced, Elevated Withdrawal Latency to Removal of the Animals from the Ion Environment. Latency measurements (means ± SEM) are expressed on a natural log scale. N = 12.

The Influence of Naloxone on the Flexor Reflex Latency of Positive-Ion-Treated Rats

The possibility existed that positive ions were activating an opioid-mediated neural pathway to cause inhibition of the flexor withdrawal reflex (Basbaum and Fields, 1984; Yaksh, 1979). This hypothesis was tested by administration of naloxone (1 mg/kg) or saline to groups of positive-ion-treated rats. Two groups each of five male rats were housed in the positive-ion environment for 7 days. Latency measurements were made on day 4 and again on day 7; in the latter case on two occasions: 25 and 50 min after the administration of either naloxone or saline. The effect of acute naloxone treatment on the positive-ion-induced increased reflex latency is shown in Figure 3. On the morning of day 4 the reflex latency was significantly elevated and remained so in both naloxone- and saline-treated groups on day 7. In addition, there was no significant difference between the effects of the naloxone and saline treatments on day 7.

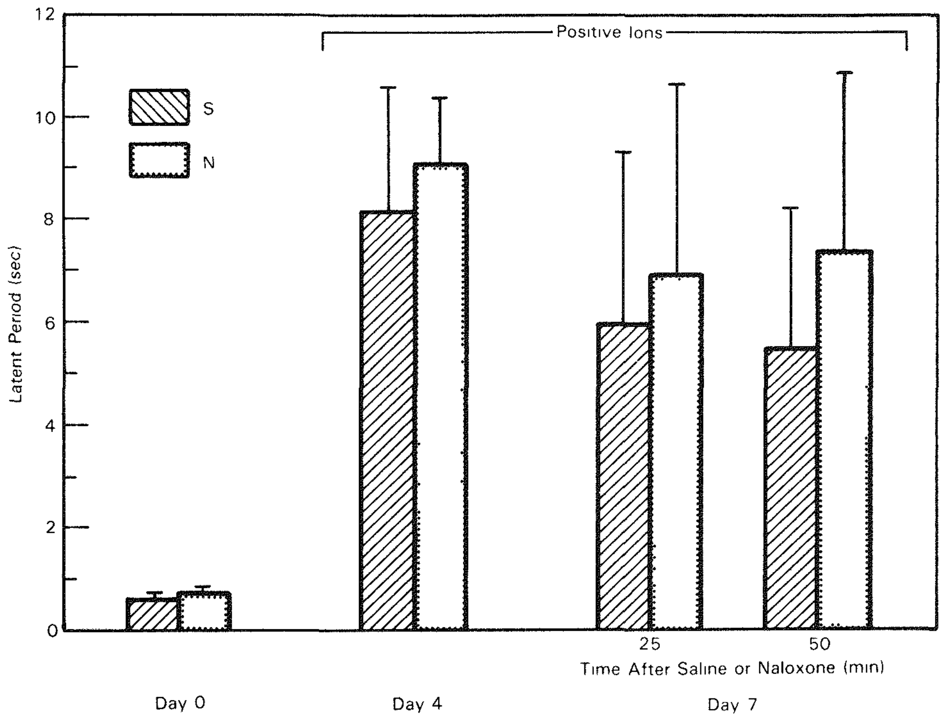

Figure 3 Acute Effect of Naloxone (1 mg/kg Body Weight) Administration on the Positive-Ion-Induced Elevated Latent Period of the Withdrawal Reflex Five rats per group The groups labeled (N) and (S) received naloxone and saline, respectively, 25 min before the first latency measurement on day 7

The Effect of Morphine on the Flexor Reflex Latency of Negative-Ion-Treated Rats

In a number of preliminary experiments, negative-ion-treated rats exhibited reduced reflex latencies (e.g., control group, 0.73 ± 0.12 sec, n = 8, treated group, 0.62 ± 0 11 sec, n = 14; $P < 0\ 025$) Although not all the results achieved statistical significance, the behavior of the ion-treated animals (vigorous flexor responses) suggested that they were in a state of hyperalgesia. Therefore, the effect of morphine on the reflex latencies of such animals was measured to determine the integrity of the pain inhibitory pathway.

In the first experiment, eight rats were exposed to ambient air for 7 days in the inhalation chambers, after which their withdrawal reflex latency responses to morphine sulphate (0.5 mg/kg) were measured. Seven days later, after continuous negative ion exposure, the morphine test was repeated. The treatment order in the second experiment (12 rats) was reversed, with the ion exposure period preceding the control period. In both experiments the negative ion treatment caused a very marked and significant decrease in the reflex latency response to morphine administration ($P < 0.01$; Figures 4 and 5).

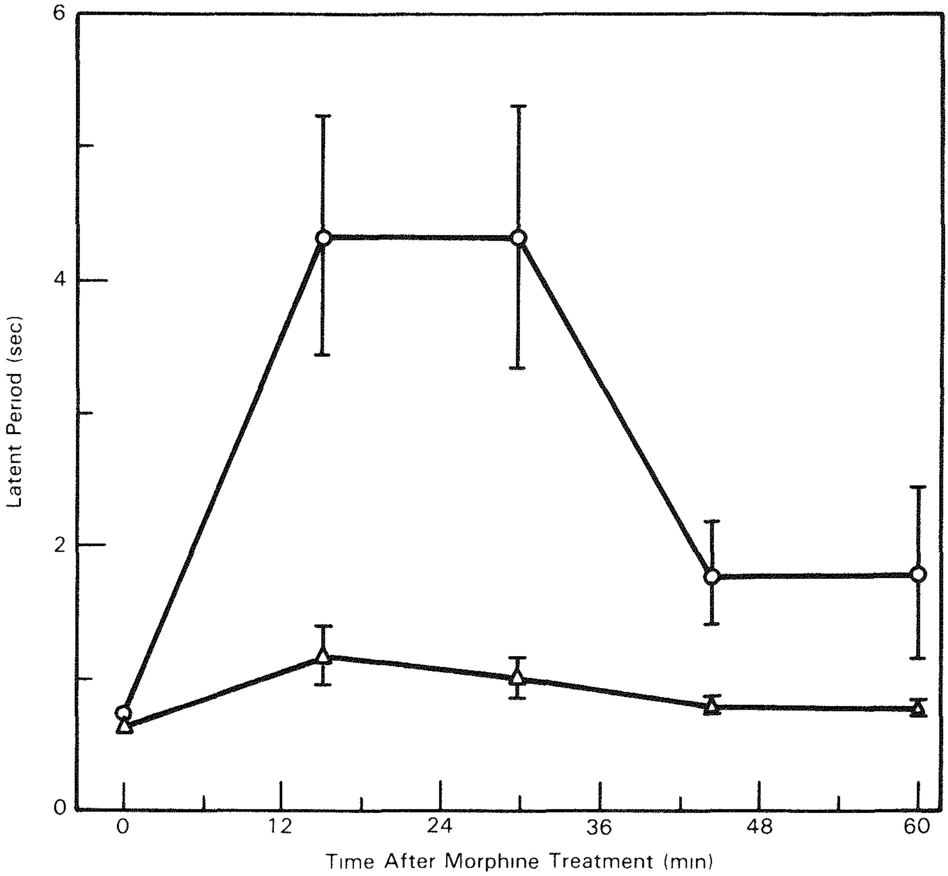

Figure 4. Influence of Negative-Ion Treatment on the Morphine-Induced Increase in the Latent Period of the Withdrawal Reflex. Animals were exposed to ambient air for 7 days, followed by measurement of the withdrawal latency response to morphine (open circles). Exposure to negative ions for 7 days followed, after which withdrawal latency response to morphine was again measured (triangles). The morphine dose was 0.5 mg/kg body weight. Means ± SEM.

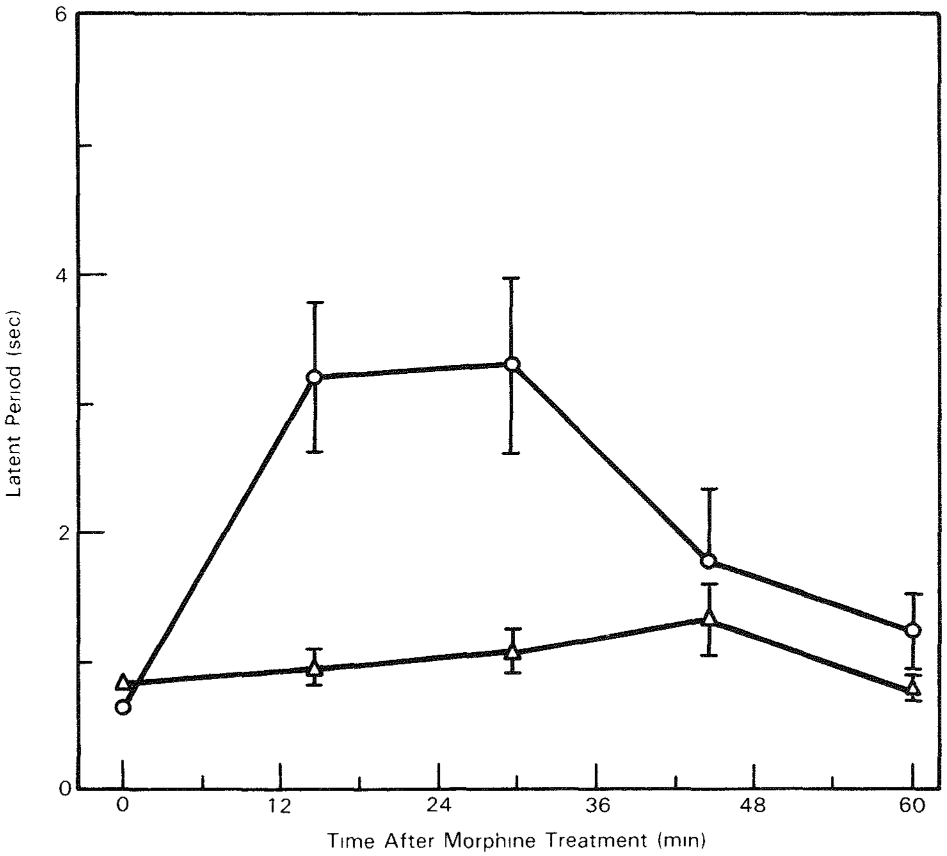

Figure 5. As in Figure 4 Except that Negative-Ion Treatment (Triangles) Preceded that with Ambient Air (Open Circles). Means ± SEM.

Brain Serotonin Measurements

Brain serotonin levels were measured in eight male rats immediately after exposure to positive ions for 7 days. In an additional eight male rats both brain and lung serotonin levels were measured after their exposure to negative ions for 6 days. Expressed as mg/g wet weight, the total brain serotonin concentration was significantly elevated after positive ion exposure and was significantly depressed following negative ion treatment. In the latter case, the pulmonary serotonin levels were also very significantly reduced (Table 1).

TABLE 1. The Effect of Air Ion Exposure on Brain and Lung Serotonin Levels. (Number of animals per group shown in parentheses.)

Tissue	Serotonin Concentration μg/g Control	Ion-Treated − ions	 + ions
Whole Brain (8)	0.93 ± 0.16	0.79 ± 0.12[a]	1.92 ± 1.03[b]
Lung (19)	3.63 ± 1.14	2.61 ± 0.60[b]	3.60 ± 0.78

[a] Significantly different from control, $P < 0.05$
[b] Significantly different from control, $P < 0.01$

DISCUSSION

Exposure to positive ions for a period of 7 days produced a very marked inhibition of the flexor withdrawal or tail-flick reflex, which suggested that some process in the inhibitory pathways had been activated. The latency of the tail-flick reflex provides an index of the animal's response threshold to a noxious stimulus and is therefore considered to indicate its level of tolerance to that stimulus (Hayes, et al., 1978b). The tail-flick latency may be altered by a wide range of environmental (Hayes, et al., 1978a; Ossenkopp, Kavaliers, and Hirst, 1983) and other stimuli (Akil and Mayer, 1972). The mechanism by which these diverse stimuli induce a state of analgesia depends largely upon two descending spinal pathways, the major one of which is opioid-mediated. Naloxone inhibits this pathway. The site of opioid activity and of naloxone antagonism is the PAG (Basbaum and Fields, 1984). In our investigation, naloxone treatment failed to reverse the elevated tail-flick latencies induced by positive-ion exposure, suggesting that the ion effect is mediated either at a site more caudal to the PAG or by an alternative adrenergic pathway. Since the opioid-mediated pathway involved the serotonin neurons of the NRM, which are caudal to the PAG, it would be important in future experiments to determine the effects of lesions of the NRM on the tail-flick latency following exposure to positive ions. If positive ions affect serotonin metabolism in NRM cells, then destruction of this nucleus should abolish their effect.

Negative-ion treatment for a period of 7 days caused the tail-flick latency to decrease, suggesting that the animals were in a state of hyperalgesia that was not reversible by morphine treatment. The action of morphine, insofar as it affects the tail-flick latency, requires the integrity of the NRM (Vogt, 1974; Proudfit and Anderson, 1975). Since morphine is unable to excite the activity of the antinociceptive pathway in negative-ion-treated animals, the implication is, again, that the ion effect is mediated at a site caudal to the PAG where morphine exerts its main effects (Basbaum and Fields, 1984).

The alteration in brain serotonin levels after the different ion treatments produced physiological and behavioral responses which may be duplicated by appropriate pharmacological manipulation of the serotonin system. Thus, the increase in tail-flick latency following positive ion exposure is in accord with the significant elevation in serotonin concentration observed. The experimental elevation of brain serotonin levels following the administration of 5-hydroxytryptophan to rats (Yaksh and Wilson, 1979) also induced a significant increase in the tail-flick latency. On the other hand, the effects of treatment with parachlorophenylalanine (pCPA), which depletes the brain of its serotonin content and effectively blocks the analgesic action of morphine (Vogt, 1974), are precisely mimicked by those obtained after treatment with negative ions. While the magnitude of the serotonin depletion by negative ions is not great, the effect is considerable. This suggests that the negative ions may block the action of this transmitter rather than inhibit its synthesis.

The serotonin hypothesis of Krueger, which states that positive ions increase serotonin release, predicts that positive-ion exposure would increase the activity of the serotonergic pathway of the cord. The inhibitory effect of this pathway on the withdrawal reflex would, in turn, be increased. Furthermore, the hypothesis predicts that negative-ion treatment, which is supposed to increase the rate of serotonin oxidation, would be likely to block the activity of the descending inhibitory pathway, thus producing a state of hyperalgesia. The results presented above tend to confirm these predictions and therefore lend support to this hypothesis, encouraging further investigations into the possible causal relationships between air ions and the activity of the serotonergic system.

ACKNOWLEDGMENTS

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MUCOCILIARY CLEARANCE IN DOGS EXPOSED TO ELECTROSTATIC FIELDS

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ABSTRACT

The effect of electrostatic fields on mucociliary clearance in the canine upper respiratory tract was studied in vivo and in vitro. Tracheal mucous transport velocity was measured by nuclear imaging of radiolabeled particles at field intensities of 150, 275 and 1475 V/cm with both positive and negative orientations. In the tracheal region where the field was applied, clearance was first reversed, then stopped, after an induction period which decreased with increasing field intensity. Effects were field-orientation-sensitive: more significant where the positive electrode faced the airway epithelium. Clearance was normal outside the field. Studies of ciliary beat frequency and clearance were performed on canine tracheal strips in fields normal to the tracheal surface. The beat frequency decreased at a rate dependent on field intensity; particle transport ceased when the beat frequency dropped to about half its control value of 1200 min^{-1}.

Mucociliary clearance is an important mechanism by which the respiratory tract is protected against inhaled viable organisms, particulates, and vapors. This mechanism clears material deposited in the nasal passages and in the ciliated bronchial airways. It is coupled with the alveolar macrophage clearance system to remove substances deposited more distally, in the lungs.

The mechanism by which cilia beat in their fluid medium, both individually and collectively, has been discussed in detail by Sleigh (1977). The nature of the fluids surrounding and driven by the beating cilia are discussed by Lopez-Vidriero et al. (1977). A number of factors are known to alter the rate at which inert particles are cleared from the respiratory tract, including pharmacologic agents, irritant gases, respiratory disease, and temperature. No studies have as yet investigated the effect of electric fields on mammalian mucociliary transport. This paper reports the results of studies that measured the effect of DC electric fields on the mucus velocity of inert particles in the canine trachea.

MATERIALS AND METHODS

Inert, spherical anion exchange resin particles (Biorad A G 1-X8) of 100 to 150 μm in diameter were radiolabeled with $Tc^{99m}\ O_4^{=}$ pertechnetate-ion to a specific activity of 6 μCi/particle in aqueous solution, then washed and dried to be used individually for measuring tracheal transport.

Healthy mongrel dogs were lightly anesthetized and placed in the supine position on a special plastic board over a gamma scintillation camera (Figure 1). The dog's larynx and upper trachea were surgically exposed, and the trachea was severed just below the larynx. The upper trachea was then enclosed in a cylindrical brass electrode (Figure 1), and the severed end was connected to a plastic tube holding moist gauze pads to maintain humidity during tidal breathing. The preconditioning tube was heated by a light bulb to prevent tracheal drying. The other electrode was a 3-mm-diameter metal rod mounted coaxially with the trachea and the outer electrode (Figure 2).

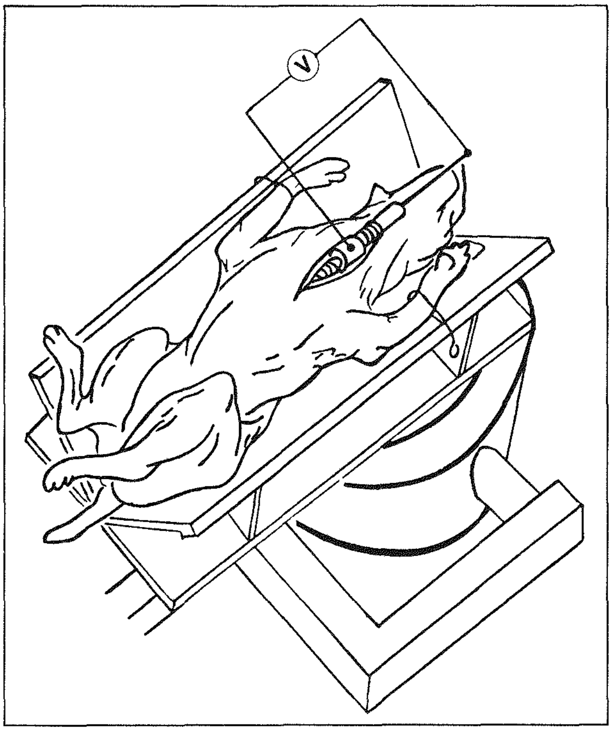

Figure 1. Diagram of *In Vivo* Set-Up for Measuring Tracheal Mucus Transport Velocity (TMTV) in the Tracheas of Dogs Exposed to an Electric Field.

A steady electric field was established along a portion of the trachea enclosed by the outer electrode by applying a DC voltage to the central electrode. The magnitude of the field at the tracheal surface was calculated from the electrode dimensions and the measured tracheal thickness.

In vivo particle-transport experiments were performed by placing a single labeled resin particle, suspended in 1 to 2 μl of water, on the tracheal epithelium proximal to the carina. Serial 15- to 30-sec images of the particle were recorded by the scintillation camera and stored on tape for analysis of particle particle motion. Similar control studies were performed similar without an applied field. The slope of the particle-position-versus-time curve gives the tracheal mucus transport velocity (TMTV).

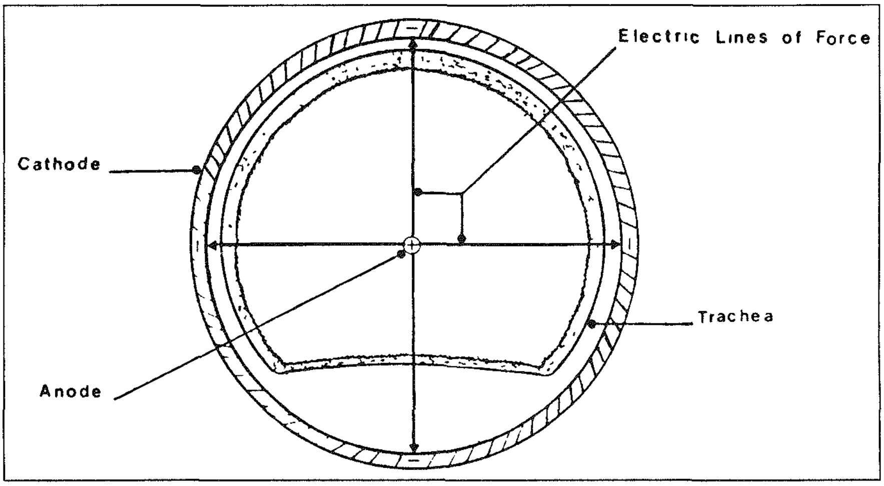

Figure 2. Cross-Section through Electric-Field Exposure Chamber.

In vitro TMTV measurements were performed with excised canine tracheal lengths from similar dogs. The trachea was severed at larynx and carina, connected to plastic tubes at both ends, and ventilated with a steady flow of heated, humidified air. Drying of the tracheal exterior was minimized by applying moist gauze pads. The excised trachea, with the inner and outer electrodes in place was positioned over the face of the scintillation camera. The resin particles were placed at the carinal end, as in the *in vivo* experiments.

In vitro experiments with canine trachea strips were performed in a small chamber, which was designed to maintain an electric field transverse to the strip (Figure 3).

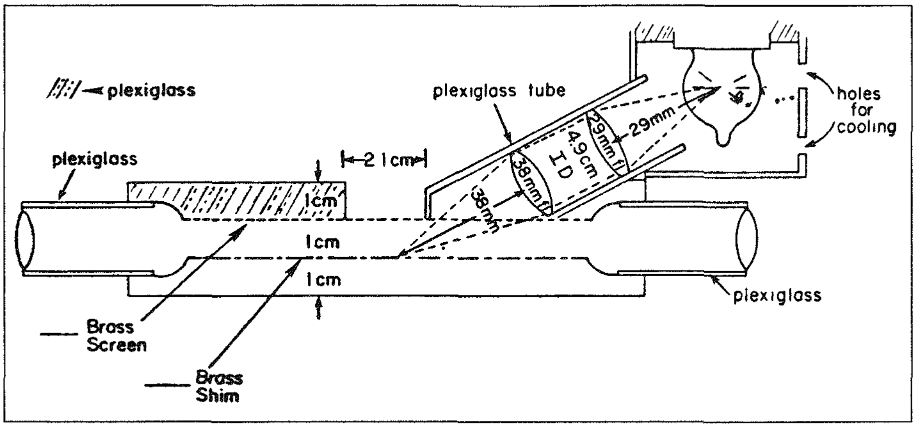

Figure 3. Transverse Section through Parallel-Field Exposure Chamber.

Low-angle illumination of the tracheal strip with a xenon lamp was employed to observe ciliary beating. The upper electrode was a screen with a small hole (2.1 cm), through which ciliary beating could be observed through one eyepiece of a binocular dissecting microscope; a strobe lamp illuminated the strip through the other eyepiece. Humidified air (95% RH) at 34-37°C continuously passed over the strip to prevent drying.

RESULTS

TMTV Studies

Control measurements of TMTV were carried out in three dogs *in vivo* and in three dogs *in vitro*. Typical control results are shown in Figures 4 and 5 for experimental periods of 4 hr. Although the slopes vary somewhat from one trial to the next, all demonstrate smooth movement from carina to larynx; the particles stopped only when they reach the plastic tube. Figure 6 shows an electric-field experiment at a field strength of 147.4 V cm. The first three particles cleared normally, including the third particle, which was "launched" at the beginning of the exposure period. The next particle, however, began moving normally, reversed, resumed forward motion, and stopped, remaining in place for more than 2 hr. Even after the field was shut off, particles placed below the field location cleared to where the field boundary had been and stopped. A particle placed within the region where the tissue had been exposed to the electric field failed to exhibit any motion. Similar behavior is shown in Figure 7 for an *in vivo* measurement at 147.4 V/cm: an induction period, initial reversal, then stasis within the field location, and clearance to the boundary from below. The stasis persisted at least 2 hr after the end of exposure.

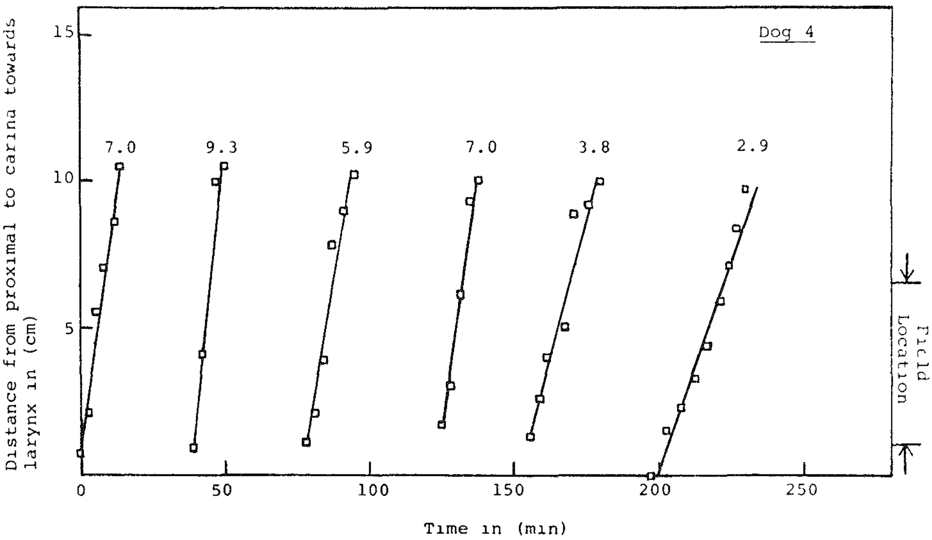

Figure 4. *In vivo* Control Study, Showing Normal Tracheal Mucus Transport Velocity. Slope (mm min^{-1}) is given above each curve.

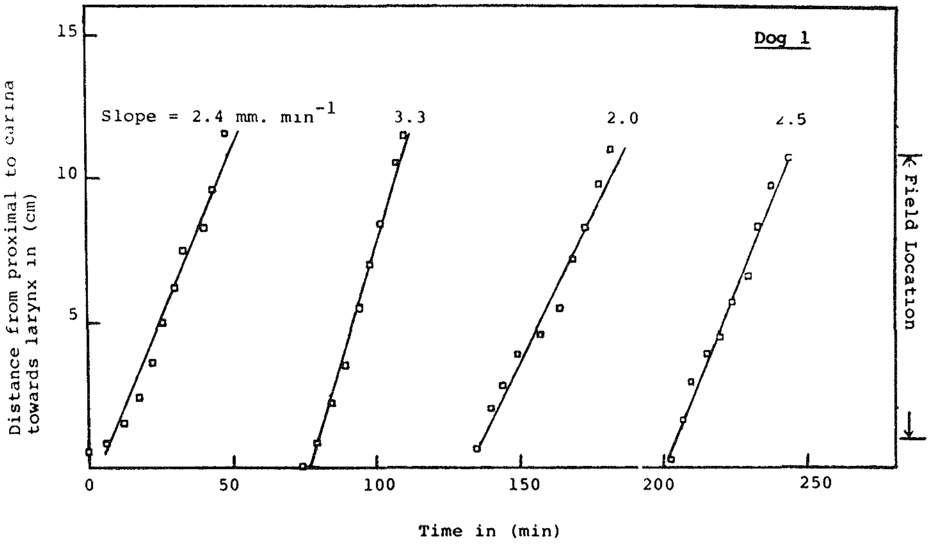

Figure 5. *In vitro* Control Study, Showing Normal Tracheal Mucus Transport Velocity. Slope (mm min^{-1}) is given above each curve.

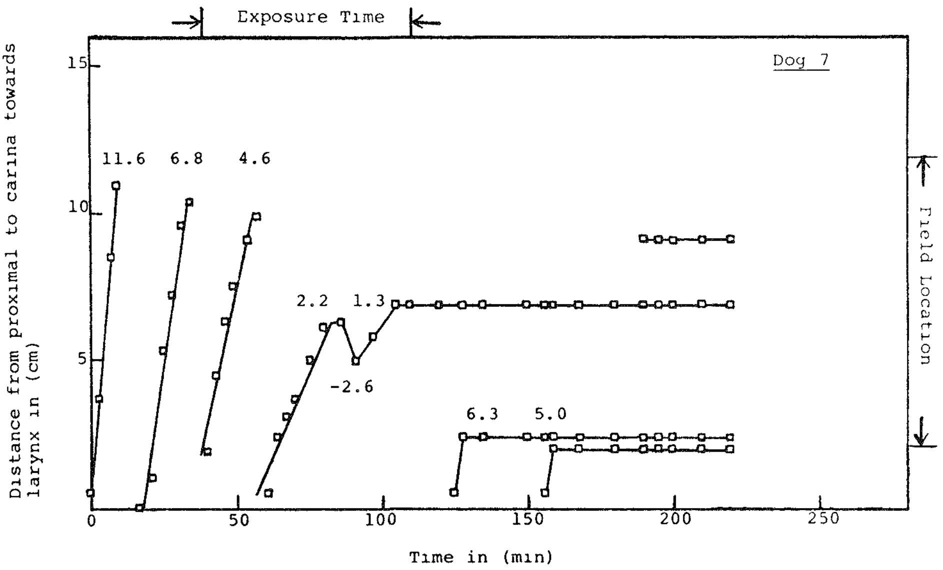

Figure 6. *In vitro* Study of Tracheal Mucus Transport Velocity in a Coaxial Electrostatic Field at 147.4 V/cm (Positive). Slope (mm min^{-1}) is given above each curve.

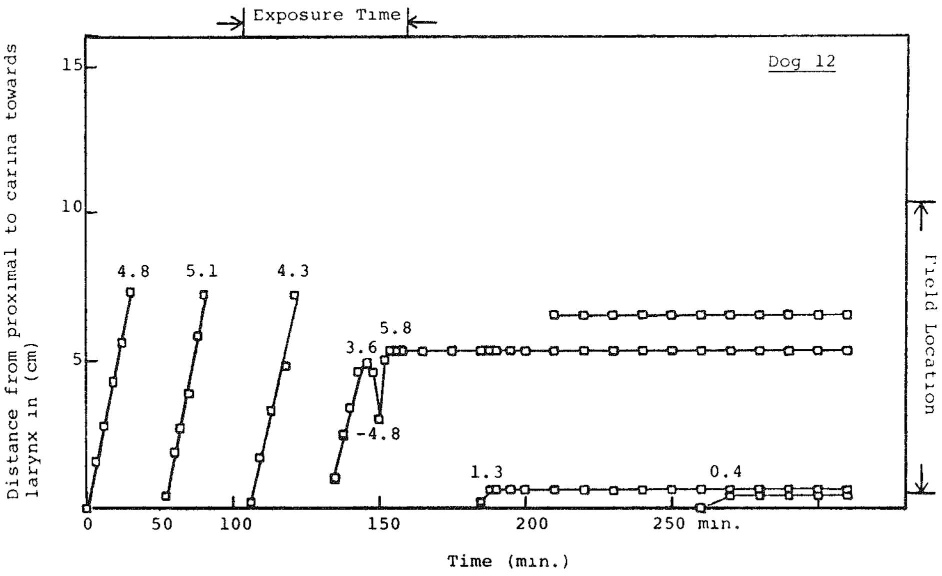

Figure 7. *In vivo* Study of Tracheal Mucus Transport Velocity in a Coaxial Electrostatic Field at 147.4 V/cm (Positive). Slope (mm min^{-1}) is given above each curve.

When the polarity was reversed at the same field strength (negative electrode within trachea), no cessation of clearance was noted, either *in vitro* (Figure 8), or *in vivo* (Figure 9). At a field strength of 271.4 V/cm, with the positive electrode on axis (positive), particles reversed as soon as the field was applied, then moved forward. Subsequently, particles placed at the carinal position cleared only to the boundary.

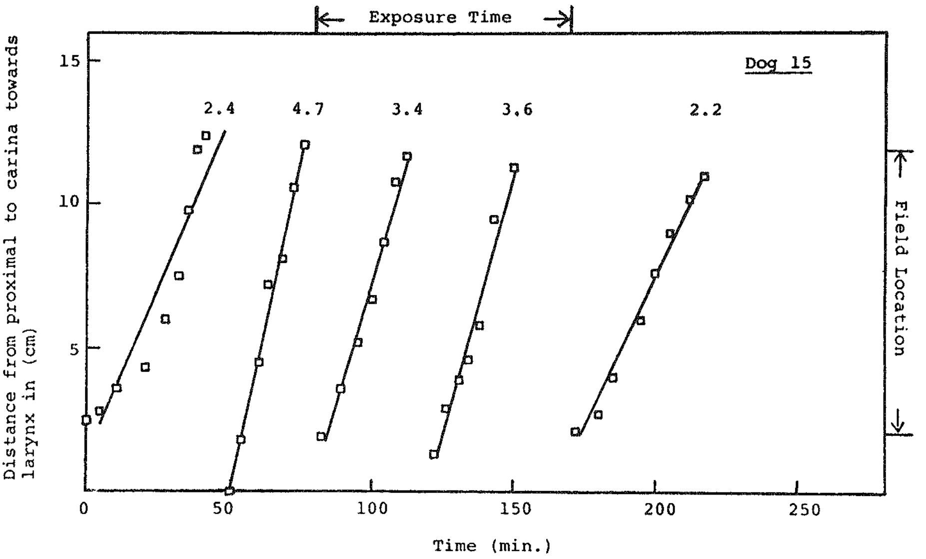

Figure 8. *In vitro* Study of Tracheal Mucus Transport Velocity in a Coaxial Electrostatic Field at 147.4 V/cm (Negative). Slope (mm min^{-1}) is given above each curve.

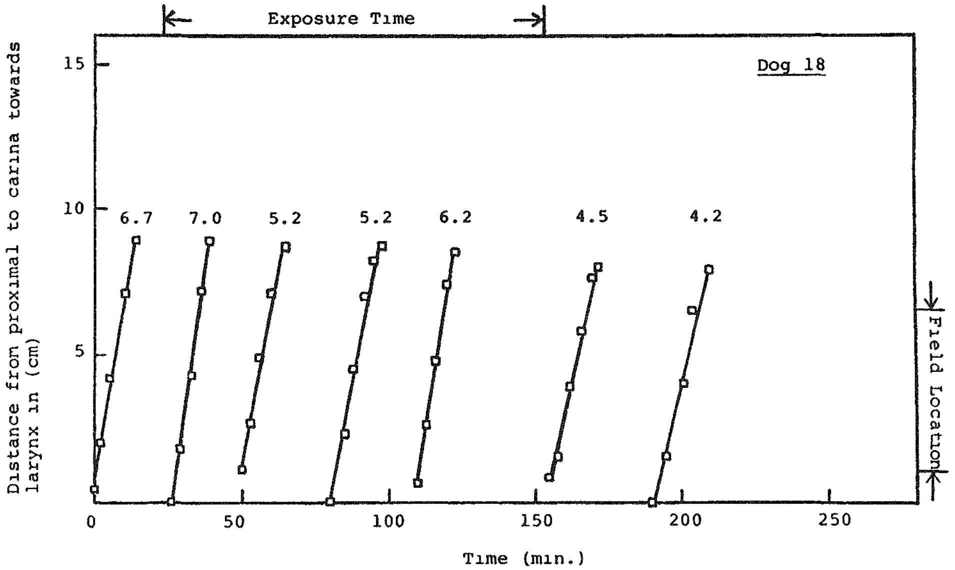

Figure 9 *In vivo* Study of Tracheal Mucus Transport Velocity in a Coaxial Electrostatic Field at 147 4 V/cm (Negative) Slope (mm min^{-1}) is given above each curve

At a field strength of 1474 V/cm, with both positive and negative polarity, particle motion caused shortly after exposure began in both *in vivo* and *in vitro* experiments Figure 10 (positive field *in vivo*) shows a typical result

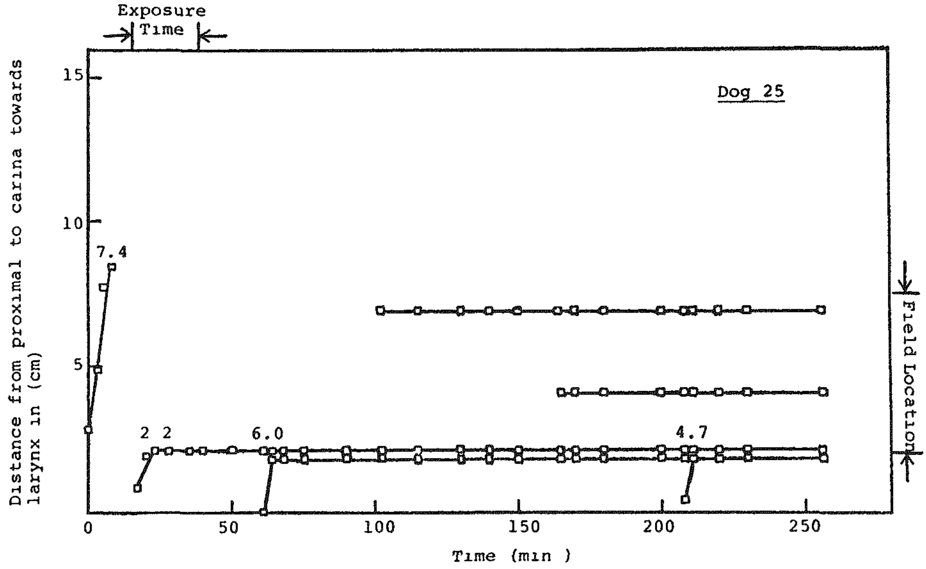

Figure 10 *In vivo* Study of Tracheal Mucus Transport Velocity in a Coaxial Electrostatic Field at 1474 V/cm (Positive) Slope (mm min^{-1}) is given above each curve

Measurement of Ciliary Beat and Mucus Flow on Tracheal Strips

Control studies of ciliary beating and mucus flow were carried out with three tracheal strips over a period of 480 min. The initial frequency (Figure 11) was approximately 1200 beats/min, decreasing linearly to a frequency of 600 beats/min at 6 hr. When the frequency was between 600 and 700 beats/min, mucus stopped streaming, but ciliary beating continued at an undetermined low frequency for at least 8 hr.

When a positive field of 1000 V/cm was applied, the beat frequency decreased much more rapidly, as shown in Figure 12. Mucus streaming stopped at an average frequency of 644 beats/min, 46 min after the application of the electric field; ciliary beating, however, stopped at 124 min.

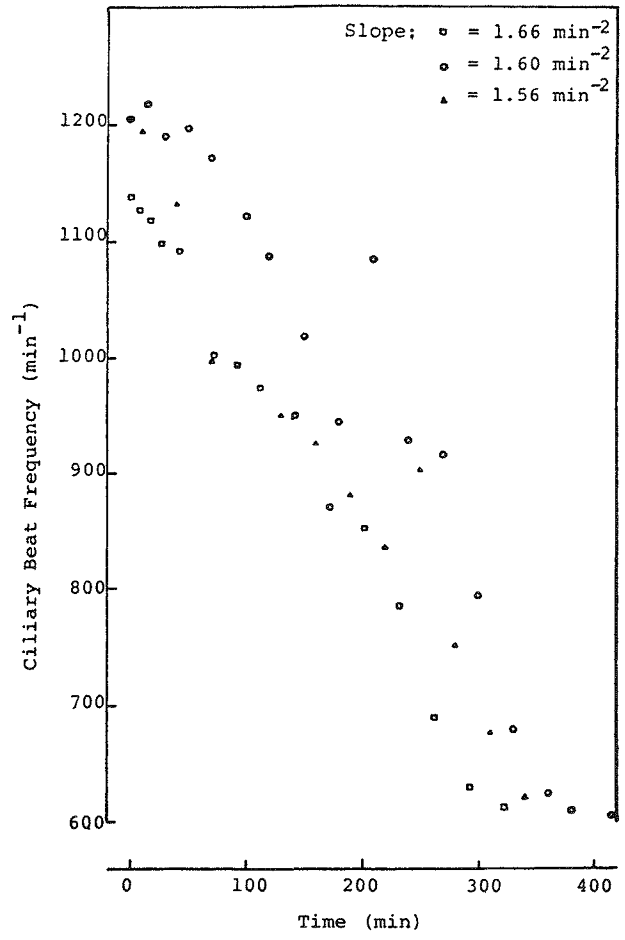

Figure 11. *In vitro* Control Study Showing Deceleration of Ciliary Beat Frequency with Time. Each point represents the mean of eight values.

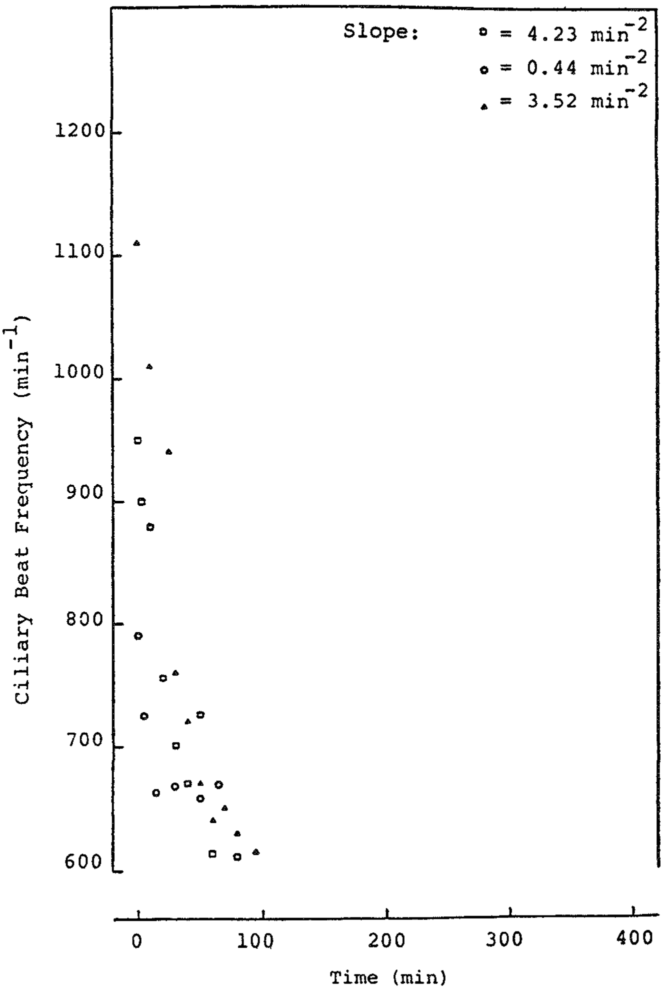

Figure 12. *In vitro* Study of Ciliary Beat Frequency in a Homogeneous Electrostatic Field at 1000 V/cm^{-1} (Positive). Each point represents the mean of eight values.

Experiments were also carried out at 2000 and 4000 V/cm in the positive mode. The trend with increasing field intensity was toward more rapid deceleration of ciliary frequency (Figure 13) and earlier cessation of mucus streaming and ciliary beating (Figure 14).

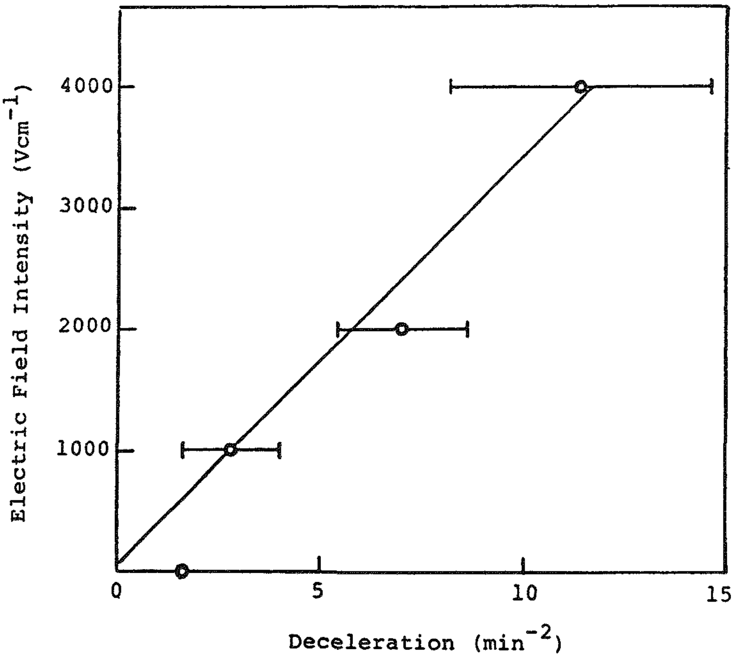

Figure13. Ciliary Frequency Deceleration to Below 600 min^{-1} with Increasing Electrostatic Field Intensity.

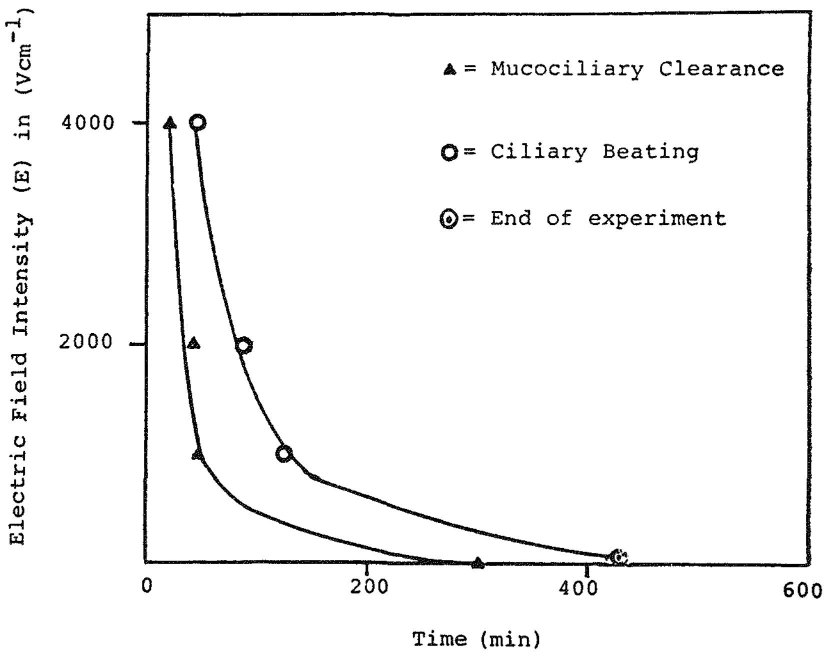

Figure 14. Deceleration of Clearance and Ciliary Beating with Increase in Electrostatic Field Intensity.

DISCUSSION AND CONCLUSIONS

The experiments described above have demonstrated that a static electric field, applied transversely to the ciliated epithelium of the canine respiratory tract, stops mucociliary clearance of particles. Measurements of ciliary beat frequency and mucus streaming on tracheal strips suggest that slowed ciliary beating is the likely cause of this stasis. Such slowing of ciliary beating frequency may be the result of field-induced alterations in the permeability of the ciliary membrane, which alter the concentration gradients of ions and ATP.

It appears that tracheal mucus transport velocity (TMTV) remains constant even though ciliary beat frequency decreases. This occurs until some critical beat frequency is reached, at which point the beating becomes disorganized, with resultant cessation of transport. The application of the electric field brings about a rapid decrease in beat frequency, but the cessation of transport occurs after a measurable induction period, presumably the time required for beat frequency to decrease to the critical level.

The apparently normal mucociliary clearance observed outside the region of the applied field supports the notion that clearance is locally determined; it is inconsistent with the idea of a mechanically continuous "carpet" or "blanket" of mucus. Our observations are consistent with the studies of Smaldone et al. (1979), in which local disturbance of clearance was produced by mechanical trauma (repeated cough), but clearance outside the region was normal.

The observations reported here suggest several follow-up studies with implications for both respiratory physiology and occupational health. Neither the effect of AC electric fields on mucociliary clearance nor the effect of the field orientation to the epithelium is known. We did not investigate recovery of ciliary function following cessation, nor did we study cases in which the field was applied external to the body.

Since respiratory clearance is not the only mammalian physiological process which employs ciliary beating, one would expect that other systems, such as reproduction, might be affected if externally applied electric fields change ciliary function. It is important to pursue the implications of these findings for mammalian species exposed to electric fields.

ACKNOWLEDGMENT

This paper is excerpted from the doctoral thesis of Paul O. Ukpo, "Mucociliary Clearance in Electrostatic Fields," 1980. The technical assistance of William Wells and Thomas Wainwright is acknowledged.

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INTRODUCTION OF COMMERCIAL ±500-kV DIRECT-CURRENT TRANSMISSION LINES: OPERATING CHARACTERISTICS, ENVIRONMENTAL EFFECTS, AND STATUS OF BONNEVILLE POWER ADMINISTRATION RESEARCH

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ABSTRACT

Currently, there are only four commercial direct-current (dc) transmission lines in North America. The first ± 500-kV dc line is scheduled to begin operation in early 1985, when the Pacific Intertie is upgraded from ± 400 kV. There is renewed interest in HVdc, and additional ± 500-kV and lower voltage lines are under construction or have been proposed. The Bonneville Power Administration (BPA) has initiated a program to obtain long-term data on dc lines; included is a project to monitor the electrical environment of the Intertie at ± 400 kV and, later, at ± 500 kV. The dc environment is more complex and variable than that of an alternating-current (ac) line because of the presence of air ions generated by corona on dc conductors. Electrical parameters will be monitored on and off *the Intertie right-of-way from fall 1984 through at least 1985. A literature review was conducted* which indicated that adverse biological effects are unlikely from a ± 500-kV dc line. However, few laboratory or environmental studies have been done that are directly applicable to such lines, so additional research is warranted. Because of the difficulties associated with simulating the HVdc environment in a laboratory, studies are also needed that involve plants and animals living near dc lines under natural conditions. A program has been designed to obtain needed information on livestock and crops raised near a ± 500-kV dc line that would supplement recently initiated HVdc laboratory studies.

The ± 400-kV Pacific dc Intertie (Celilo-Sylmar line), the first commercial HVdc transmission line constructed in North America (Figure 1), extends 1360 km from The Dalles, Oregon to near Los Angeles, California. The dc Intertie, with a transmission capacity of 1600 MW, provides surplus electrical energy to the Pacific Southwest during periods of the year when energy needs are low in the Northwest and when adequate water for generation is available. This project has been a substantial success technically and financially and has resulted in millions of dollars of benefits in reduced power rates to consumers in both regions.

When the Intertie was energized in 1970, few concerns were expressed about potential environmental effects of dc lines. The line is located mostly in remote areas, and it was constructed prior to passage of the National Environmental Policy Act, so no environmental impact statement was prepared.

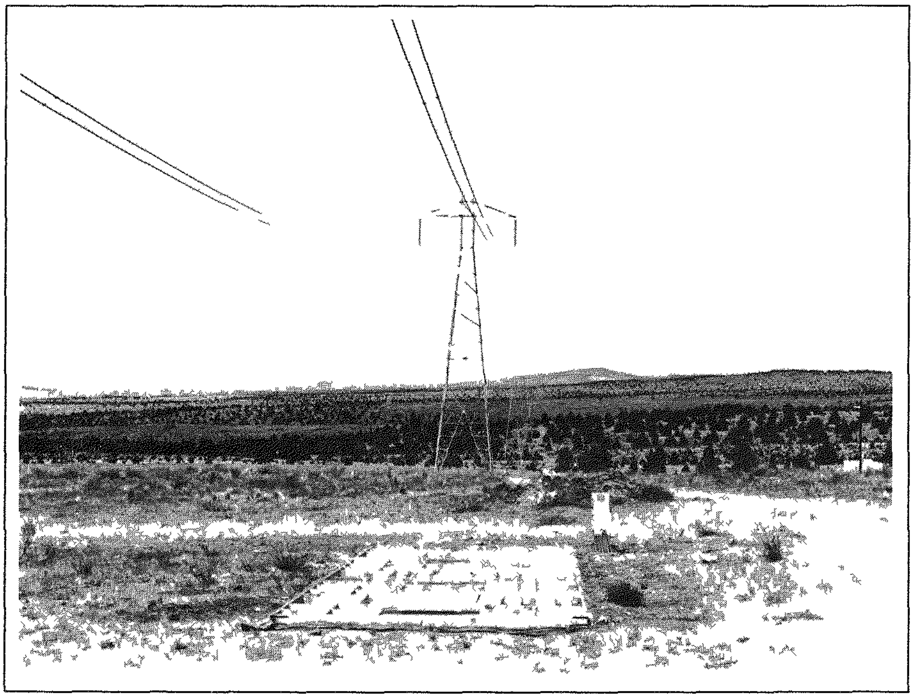

Figure 1 The Celilo-Sylmar (Pacific Intertie) dc Transmission Line in Central Oregon, Looking North Toward Tower 81/3 (See Figure 3). The towers average 36 m in height, with a pole separation of 12 2 m The line, energized in 1970, is scheduled to be upgraded from ± 400 kV to ± 500 kV in early 1985 One of the electric-field and air-ion monitoring stations is in the foreground, the test trailer can be seen on the right

Over the last 14 years, operating experience with the Intertie has been good and no harmful environmental effects have been documented A ± 400-kV dc line energized in Minnesota in 1978, however, was marked by significant controversy, and questions were raised about the possible biological effects of dc electric fields and air ions produced by such lines (Mains, 1983)

The electrical environment of a dc transmission line is quite different from that of an ac line Because the voltage polarity is constant on the dc conductors, air ions produced by corona are repelled by the charge on the conductors The electric fields cause the air ions to move toward conductors of opposite polarity or toward the ground Air ions are also carried away from a dc line by convective wind forces The ions form a space charge, which adds to the strength of the dc electric field from the voltage on the conductors, so field strength is highly variable compared to that of ac lines Electric field and air-ion levels on a dc line right-of-way may be two orders of magnitude greater than average ambient levels

The Pacific dc Intertie is scheduled to be upgraded to ± 500 kV by early 1985, thereby increasing the power capability to 2000 MW, electric-field and air-ion concentrations will also increase A proposal has also been made to further expand the capacity to 3100 MW by 1988, which would involve raising the current in the line to 3100 A Although these actions are not expected to result in any adverse environmental effects, electrical and environmental research directly applicable to a ± 500-kV dc line is limited. In addition, new dc transmission lines are under construction or planned elsewhere in the United States, and there is continued strong public interest in the possible effects of high-voltage transmission lines.

Bonneville Power Administration (BPA), an agency within the U.S. Department of Energy (DOE), has therefore initiated a study to monitor the electrical environment of the first commercial ± 500-kV dc line. Along with a group of other utility companies actively involved in dc transmission, BPA is also developing a study of possible effects on livestock and crops raised on the right-of-way of the ± 500-kV dc Intertie.

The objectives of this paper are to: 1) compare the calculated electrical parameters of the ± 500-kV dc Intertie with other existing and planned dc lines; 2) describe the electrical monitoring program; and 3) summarize the literature on the potential biological/environmental effects of HVdc lines and outline a proposed agricultural research program.

THE HVdc ELECTRICAL ENVIRONMENT

As mentioned above, a significant factor in the HVdc electrical environment is the presence of air ions generated by corona on conductors. As discussed by Bracken (1978), the presence of this space charge leads to three parameters which describe the dc environment (Figure 2). In contrast, the electric field alone is sufficient to describe the electrical environment for ac.

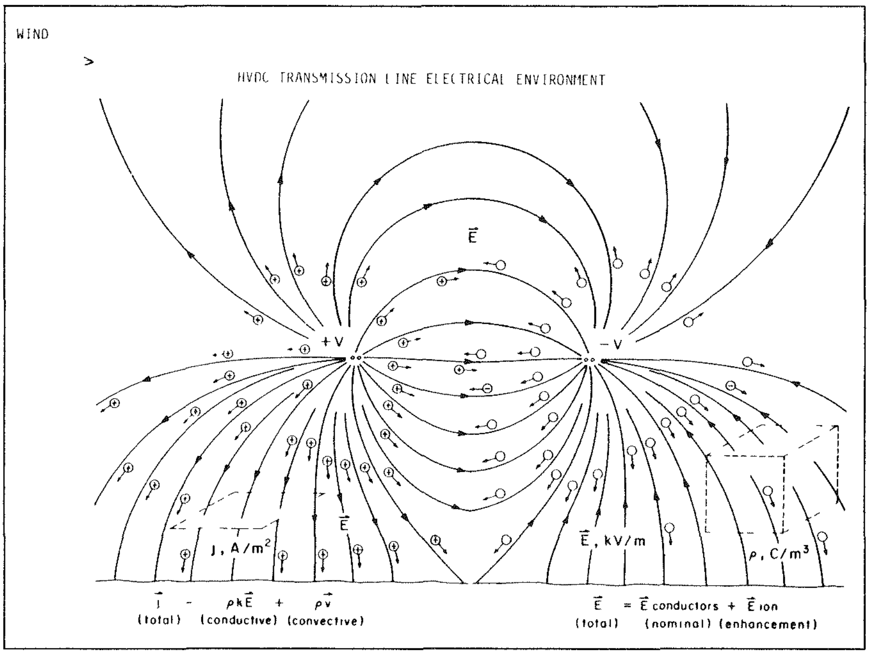

Figure 2. Diagram of the Electrical Environment of an HVdc Transmission Line. See text for a discussion of the electrical parameters (From Bracken, 1978).

The first dc parameter, the electric field, is actually the superposition of two fields: the nominal field, which results from the charge on the conductors, and the field resulting from the space charge. The ions which make up the space charge can provide a significant contribution (50%) to the field and are free to move along the field lines because of coulomb forces. In addition, the portion of the field resulting from space charge can vary greatly because the ions can be transported by air movement.

The ions constitute the second electrical parameter, which can be expressed either as ion concentration (ions/cm^3) or as space charge density (nc/m^3). If we assume singly *charged unipolar ions, the ion concentration is given directly* by the space charge density divided by the electronic charge (1.6×10^{-19} C).

The third electric parameter is the ion current density, A/m^2. The total current density is the sum of the conductive current from the electric field and the convective current resulting from the wind. The relative importance of the two components depends on proximity to the transmission line and wind speed. At 50 to 100 m or more from a line, where fields are small, the convective term will dominate; underneath a line, the conductive term will dominate provided the wind is not very strong. For comparison, a wind speed of 1 m/sec corresponds to the velocity of positive ions in a field of 7 kV/m.

Another corona effect, audible noise, which is addressed only briefly in this paper, will also increase when the Intertie is upgraded. Average audible noise during fair weather at the edge of the Intertie right-of-way is approximately 34 dB(A) at ± 400-kV operation. At ± 500 kV, this level is expected to increase to around 42 dB(A).

In addition to the electric-field and corona-related effects, current in the conductors produces a static magnetic field. The maximum magnetic field beneath the Pacific Intertie is about 0.22 G for a current of 2000 A, increasing to about 0.34 G if the current is raised to 3100 A/pole. These levels are lower than the naturally occurring dc magnetic field of the earth (0.5 G) along the Intertie. The maximum field from the line and the earth's field have a nearly vertical orientation; for power flow south, the two fields are oppositely oriented, so they counteract (subtract) each other; for power flow north, their orientations are similar, so they are additive.

COMPARISON BETWEEN CALCULATIONS AND MEASUREMENTS

As indicated above, the electrical environment of a dc line is more complex and variable than for an ac line. Likewise, techniques for measuring and calculating electric parameters are more complex because of air-ion effects.

The electrical environment created by a dc line is highly dependent on weather conditions. The magnitude and direction of the wind has a significant effect on ion-current and electric-field levels. During fair weather, corona sources are, mostly, the insect and vegetation material on the conductors, which give rise to the formation of discrete corona streamers. These sources increase the space charge density, which raises the ion-current and electric-field levels. The levels are highest in the summer months, when the numbers of insects and amount of plant materials on the conductors increase. Hence, the performance of a dc line is very season-dependent. In rainy conditions, a large number of corona sources are present in the form of water droplets. This more uniform distribution of corona sources increases the amount of space charge, which tends to prevent the formation of large, discrete corona streamers. Tests conducted at the High Voltage Transmission Research Facility in Massachusetts have shown that average levels of ion currents and electric fields in rainy weather are generally of the same magnitude as the maximum levels observed in fair weather (Comber, Nigbor, and Zaffanella, 1982). However, maximum levels during rain may exceed fair-weather maxima. The range of levels during rain is generally narrower than during fair weather because of the more stable corona generation.

The calculation technique used at BPA to predict electric-field current density and charge density is based on an analytical, idealized, no-wind model. This technique is described in detail by Bracken, Capon, and Montgomery (1978).

Because of simplifying assumptions made in the analytical technique, it is very important to compare the results with measured data. Fortunately, test data were acquired by Bracken (1980) under The Dalles, Oregon dc test line in the late 1970s. Based on the comparison between these measurements and the calculated levels, he concluded that the ideal, no-wind, theoretical calculations represent levels for fields which are exceeded approximately 10% of the time during fair weather (i.e., L_{10} levels). The nominal (zero space charge) field represents levels that are exceeded approximately 90% of the time (i.e., L_{90} levels). These generalizations must be used cautiously, however, since they are very dependent on site location and may not apply at a site where the wind (magnitude and direction) and/or precipitation are different from those at the site measured. Furthermore, these measurements were made only during October and November; measurements even at the same place during a different time period might give different results.

CALCULATED FIELD AND AIR ION LEVELS FOR VARIOUS DC LINES

Table 1 shows a comparison of the calculated electrical performance of the Pacific Intertie with other existing and proposed dc lines (± 400 kV and above) in North America. The qualifiers summarized previously should be kept in mind when considering the data in Table 1.

Field and ion levels decrease rapidly away from a dc line. For example, as shown in Table 1, for the Pacific Intertie in Oregon (1985) at ± 500 kV, the maximum electric field on the right-of-way is 31 kV/m, and the maximum ion concentration is 1.12×10^5 ions/cm^3. At 19 m from the line, calculated values for these parameters are 19 kV/m and 4.40×10^4 ions/cm^3.

Because it was the first commercial HVdc line built in the U.S., the design of the Intertie was conservative, and later studies indicated that the line had sufficient clearances and insulation to enable safe and reliable operation at ± 500 kV. As indicated, electric-field and air-ion concentrations will significantly increase when the Intertie is upgraded to ± 500 kV. Smaller increases due to greater conductor sag would be expected on parts of the right-of-way, at least in Oregon, if the current is increased by the proposed Terminal Expansion Project. Calculation of the levels is complicated by differing conductor clearances and line-voltage conditions along the Intertie. Field and ion levels for the Intertie in California (Table 1) would be expected to decrease slightly as a result of line modification that would likely be done in that state, as part of the Terminal Expansion Project, so as not to exceed minimum conductor clearance.

TABLE 1. Maximum Calculated Electric-Field Strength and Air-Ion Levels for Existing and Proposed HVdc Transmission Lines in North America Operating at ± 400 kV and Above. Calculations assume peak condition with no wind and fair weather.[a]

Line	Voltage (kV)	Year Energized	Conductor Clearance (m)	Total D-C Electric Field (kV/m)	Maximum Current Density (nA/m^2)	Maximum Air Ion Concentration ($ions/cm^3$ x 1000)
Pacific Intertie						
(OR)	± 400	1970	12.2	19	29	69
(CA)	± 400	1970	9.8	27	66	112
(OR)	± 500	1985	12.2	31	76	112
(CA)	± 465[b]	1985	9.8	36	130	160
(OR)	± 500[c]	1988	11.6	33	91	125
(CA)	± 450[b,c]	1988	9.8	34	114	150
CPA/UPA						
(MN)	± 400	1978	15.2	17	20	53
(ND)	± 400	1978	10.7	28	69	112
Nelson River, Canada	± 450	1977	12.2	28	63	103
Quebec, New England (Quebec)	± 450	1986	12.5	17	18	48
Walker County, Texas	± 400	1986	10.7	28	71	117
Intermountain Power Project	± 500	1986	12.2	24	41	80
Phoenix-Mead	± 500	?	11.6	23	37	76

[a] Peak calculated levels on the right-of-way are shown for comparison purposes. Actual field and air-ion levels near an HVdc line are constantly changing because of wind; most of the time they would be less than the peak values. Line design information available from the Authors (report ETKF-84-7).

[b] Predominant operating mode is to export power to California; during full load, voltage on the Intertie is lower in California than in Oregon.

[c] A Terminal Expansion project in under consideration which would involve increasing current on the Intertie. This would increase conductor sag (because of higher temperature), increasing the electric field and ion levels on a small portion of the right-of-way.

For new ± 500-kV dc lines, conductor bundles are generally selected based on the cost of power losses. With the increased cost of energy in recent years, this has often led to designs with conductor bundles, e.g., triple or quadruple, that are larger than the twin bundle used on the Intertie. As a result, the proposed ± 500-kV dc lines also have reduced corona activity and lower dc electric field and ion levels. Because existing conductor bundle size on the Intertie was a design constraint, corona performance was a controlling parameter. Therefore, to maximize the power transfer capability of the Intertie, the line may be operating near the upper limits for dc fields and air-ion levels for ± 500-kV dc lines in the U.S. For similar reasons, calculated audible noise levels for the Intertie are 3-4 dB(A) higher than the proposed ± 500-kV lines listed in Table 1.

BPA HVdc ELECTRICAL MONITORING PROGRAM

The voltage upgrade of the Pacific Intertie to ± 500 kV provides an opportunity to make measurements to further assess the accuracy of the model used for calculating HVdc electrical parameters. Such measurements are also needed to better define the off-right-of-way electrical environment near HVdc lines. Recent studies in Minnesota have indicated that space charge was measurable 0.4 to 0.8 km downwind of the ± 400-kV dc line (Hendrickson, 1984).

BPA has designed and initiated a program to characterize the electrical environment of the Pacific dc Intertie under actual operating conditions. Long-term continuous measurements of electric fields, air ions, and audible and radiofrequency noise will be made at ± 400 kV and will continue as the Intertie is upgraded to ± 500 kV. Field and ion measurements will be made on the right-of-way and out to distances of 365 m. Figure 3 shows a layout of the test site and identifies the parameters and instrumentation involved in the study. The data acquisition system for the dc study will involve approximately 30 channels of electrical data and 10 channels of meteorological data.

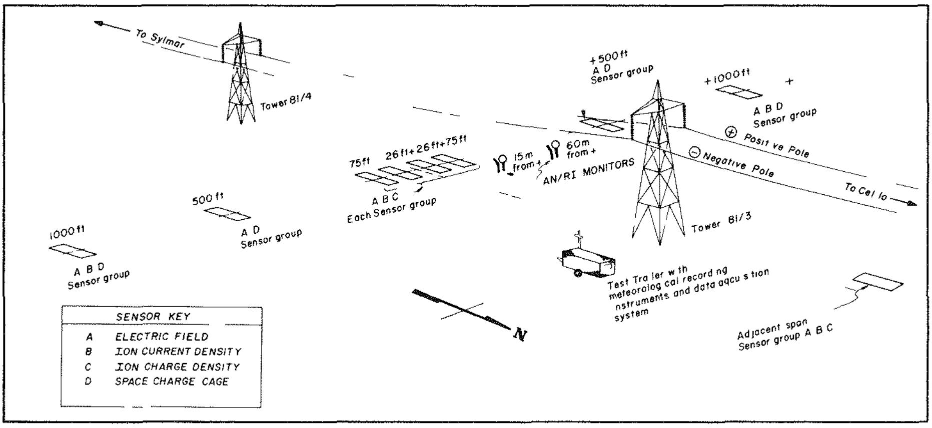

Figure 3. The BPA Grizzly Mountain HVdc Research Site in Central Oregon, Showing the Layout of the Electrical Monitoring Program. An agricultural study may also be conducted at the same site. (See text for discussion.)

The Grizzly Mountain HVdc Research Site is located in central Oregon, between the towns of Madras and Prineville, on the Crooked River National Grassland administered by the U.S. Forest Service. Electrical measurements are expected to begin in October 1984. An agricultural study, also proposed for the same site, is described below.

HVdc ENVIRONMENTAL CONSIDERATIONS

Three basic environmental considerations can be defined which are related to the electrical properties of an HVdc transmission line: 1) perception of dc electric fields; 2) shocks from metallic objects; and 3) possible biological effects of dc fields and/or air ions. Other effects, including audible and radiofrequency noise resulting from corona, are not addressed in this paper.

Under certain conditions, it is possible for people to perceive the electric field near a dc line. Tests near the BPA HVdc test line at The Dalles, Oregon indicated that perception generally occurred infrequently in fields above 30 kV/m (Bracken, 1978). Previous evaluations (Hill et al., 1977) by operating personnel at The Dalles ± 600-kV dc test line, working in maximum fields of 40 kV/m, indicated that personnel were seldom aware of the presence of the field. Other research at BPA, however, indicated that the perception of dc fields may be considerably enhanced by thick fog (Chartier et al., 1981).

Shocks from metal objects near a dc line are generally much less likely than for objects near an ac line, because the coupling mechanism which charges the objects is radically different for the two types of lines. For ac, coupling is a capacitive charging effect; for dc, the coupling mechanism is resistive, with the charge obtained from the surrounding ionic space charge. Since current densities near a dc line are very small, e.g., 100 nA/m^2, a very large object would be required to intercept sufficient charge so that a person would collect a perceivable current or receive a noticeable shock. Standard grounding procedures prevent such occurrences.

Most environmental interest has focused on the possible biological effects of dc lines. The controversial CPA/UPA ± 400-kV dc line energized in Minnesota in 1978 brought this issue to national attention. Although the primary issues concerned the need for the line and right-of-way acquisition procedures, health effects were a highly visible and emotional issue in the controversy (McConnon, 1984; Mains, 1983). Surveys after the line was energized indicated that some people reported a variety of adverse effects which they associated with the line (Genereux and Genereux, 1980). However, a majority of the Science Advisory Committee formed by the State of Minnesota concluded there was no indication that the ± 400-kV line presented a risk to human health from short-term exposure (Bailey et al., 1982).

Interest in health effects also developed over a proposed ± 450-kV dc line to be built between Canada and New England. This prompted the State of Vermont to sponsor a survey of residents living near the Celilo-Sylmar dc line in California (Nolfi and Haupt, 1982). The study found no relation between perceived short-term health effects and proximity to the dc line.

No controversy developed in 1979 when a ± 500-kV dc line was first proposed for the Intermountain Power Project in the Southwest. However, health effects were an issue in a recent legal challenge to the Environmental Impact Statement for the line. Recently, a proposed ± 400-kV-line project in Texas has also led to some renewed interest in the potential biological effects of HVdc lines.

Banks and Williams (1983) assessed the public-health implications of the ± 400-kV Celilo-Sylmar line and of the three other dc lines operating in North America at the time. Those authors found no evidence for any overt, acute health effects associated with exposure to the HVdc environment.

A dissenting view about the potential for adverse effects of HVdc lines was presented by Brambl (1982). In a minority report in the findings of the Minnesota Science Advisory Committee, Brambl argued that while there is no proof for adverse effects, available information indicated "a sharp probability for ill effects" from the CPA/UPA ± 400-kV dc line. He suggested that air ions were the most probable agent for such effects.

BIOLOGICAL EFFECTS OF DC FIELDS AND AIR IONS

Only limited research has been done on the effects of HVdc lines on plants, animals, and people. As a result, the extensive and controversial literature on air ions and dc fields is usually discussed by reviewers in an effort to evaluate the potential for effects from such lines. A summary of this research follows.

Plants

Griffith (1977) studied wheat growing at various distances from the ± 400-kV Intertie in Oregon. Calculated maximum total dc electric field strength was ± 18.6 kV/m. At harvest time, no significant differences that were related to the dc line were found in plant height, or in the quantity, number, or germination of seeds.

Endo et al. (1979) reported that wheat exposed to a ± 20-kV/m dc field (with corona) beneath a test line in Japan showed a darkened condition on leaf tips. However, the authors reported no effects on the growth or yield of wheat or rice. The Minnesota Science Advisory Committee (Bailey et al., 1982) reviewed the data in the paper by Endo et al. (1979) and found, contrary to the original authors, that the dc field did appear to affect plant growth and yield.

A number of laboratory studies involving the effects of dc electric fields on plants were done by L. E. Murr at Pennsylvania State University. With a field strength of 20 kV/m, Murr (1966a) reported an approximate 10% decrease in dry weight in the leaves of bean plants. In another study (1966b), Murr found that a dc field strength of about 100 kV/m for an extended time (over 10 hr) was necessary to induce physical leaf damage in bean and corn plants.

Bachman and Reichmanis (1973) exposed barley plants to high positive dc fields and reported that growth was retarded for field levels above 200 kV/m and enhanced at fields below that level.

Kotaka and Krueger (1968) reported that air ions can accelerate or retard plant growth. Oxygen ions at concentrations of 1.8×10^4 ions/cm^3 accelerated growth of oat, barley, lettuce, peas, and maize. Carbon dioxide ions impeded production of chlorophyll and devitalized seedlings. In a later paper, Krueger et al. (1978) reported that concentrations of 2.7×10^4 to 1.7×10^5 air ions/cm^3 alone or with a dc field of 0.46 to 9 kV/m stimulated growth of barley.

Pohl and Todd (1981) reviewed the literature and concluded that "electro-culture" can potentially increase crop growth and production. Those authors also presented results of their research which indicated that negative ions (average current density of 4 pA/cm^2) significantly increased bean growth and resulted in earlier blooming and slightly increased growth rates in violets and geraniums.

Possible mechanisms for reported effects of dc fields and air ions on plants were discussed in a report by Dow Associates (1980). Some evidence was presented to indicate that both positive and negative air ions stimulate oxygen consumption and uptake of iron, and affect the synthesis of cytochrome and other enzymes.

Wildlife

Wildlife inhabiting areas near the ±400-kV Intertie were studied by Griffith (1977). Some differences were noted in the abundance of small mammals and birds on the right-of-way compared to those in control areas. Some species were more frequently observed near the line, while others were more abundant in the control areas. Griffith believed these differences were most likely related to differences in habitat (vegetation) caused by construction activities on the right-of-way.

One of the questions in the survey of landowners near the ± 400-kV line in Minnesota dealt with wildlife (Genereux and Genereux, 1980). Thirty-one percent (119) of the 384 respondents believed that the dc line had affected wildlife. The most common responses were: 1) wildlife avoid the areas under the line; 2) the wildlife are gone; and 3) birds have been killed by the line. Apparently, no actual data have been reported on wildlife abundance or distribution near the Minnesota line.

As with insects, there is some evidence that birds and other wildlife can detect weak dc electric and/or magnetic fields (Kirschvink, 1982). Such fields, as produced by the earth, may provide some guidance to birds during migration, in addition to such factors as wind, sun, stars, barometric pressure differences, landmarks, etc. There is no evidence that fields from a dc line interfere with the orientation of migrating birds.

Livestock

Incidental observations during the study by Griffith (1977) indicated that beef cattle are frequently found on the Intertie right-of-way. The animals graze on grasses growing in construction-disturbed areas and use towers for rubbing posts and for shade. In some areas, ranchers use the transmission-line access road to feed and water cattle at sites on or near the right-of-way. There are apparently no reports from ranchers of any effects on their livestock that were attributed to the ± 400-kV dc Intertie.

Some landowners (29% of those surveyed) near the CPA/UPA ±400-kV dc line in Minnesota reported various adverse effects in their livestock which they believed were related to the line (Genereux and Genereux, 1980). This prompted the Minnesota Environmental Quality Board to sponsor a study of dairy cattle near the dc line (Martin et al., 1983). The study included 500 herds, located at various distances from the line. Production was evaluated by examining Dairy Herd Improvement Association records from before and after the line was energized. The study found no chronic or acute effects of the line on average milk production. Also, intercalf intervals, rate of culling for reproductive problems, and incidence of abortions were no higher in herds near the dc line than in herds 10 to 16 km away.

Other than by distance from the line, no estimate of actual field or air-ion exposures received by the cattle near the ± 400-kV line were made. The researchers observed: "If, in fact, substantial exposure to air ions and electric fields is present on a very few farms, then this study could not have observed power line effects (Martin et al., 1983)."

Laboratory Animals and Humans

Outside of possible work in the USSR, we are aware of only four or five research projects that have been initiated specifically to study effects of the HVdc environment on laboratory animals. Only preliminary results have been reported from most of these studies.

The Electric Power Research Institute (EPRI) has sponsored research on air ions at the University of California at Berkeley since 1980. The research was done in the laboratory, where Dr. A. Krueger conducted several well-known studies air ions. Preliminary work indicated no effects of air ions on growth of male mice, or on their resistance to influenza virus (Kellogg, 1982).

With an improved protocol, work was recently conducted at Berkeley on long-term exposure of female mice to 10^5 air ions/cm^3. Overall, no consistent effects were found on serum glucose, cholesterol, blood urea nitrogen, globulin, or whole-blood serotonin (Kellogg, 1983). However, the researchers believed that the differences between group means for some of these parameters indicated genuine effects. Preliminary work with male mice in a new exposure system indicated some changes in blood serum components following short-term exposure to air ions (Kellogg, 1983).

Studies of dc fields and air ions have been sponsored by EPRI at Rockefeller University since 1980. Male rats were exposed for 18 to 72 hr to 5×10^5 air ions/cm^3 and dc fields of 3 or 12 kV/m (Charry, Bailey and Weiss, 1983). Preliminary results indicated no effects of 18-hr exposure on turnover of certain neurotransmitters in the brain, on spontaneous motor activity, or on food or water consumption.

Biological studies are expected to begin in late 1984 in the newly developed exposure facilities at Battelle-Northwest (Anderson and Weigel, 1983). Rodents will be exposed for 30 days or more to dc fields of up to 60 kV/m and 10^5 to 10^6 air ions/cm^3.

Laboratory studies to simulate an HVdc line are also underway in Japan. Reports to date, however, have focused only on the exposure systems (Kobayashi et al., 1983; Shimizu, Yamashita and Matsumoto, 1984).

In addition, a study by Fam (1981) acknowledged dc lines as one reason for investigating dc fields. In the study, mice were continuously exposed to a very strong dc electric field (340 kV/m). The possible presence of air ions was mentioned but not quantified. Compared to that for control mice, mean water consumption for the exposed males was approximately 10% lower. The exposed males, however, grew at a faster rate, and their final body weights were nearly 12% greater than those for controls. Some differences were noted in blood components between exposed females and controls.

Most older research with dc fields and air ions was done for purposes other than to simulate a dc line. This includes research on weather-related ion effects on humans, and research aimed at assessing possibly therapeutic effects of air ions. Reviews of this body of research usually reach similar conclusions: Although numerous effects have been reported, they are generally inconsistent; many studies suffer from procedural/exposure difficulties, and their applicability to the HVdc environment is unclear (Bailey et al., 1982; Banks et al., 1982; and Sheppard, 1983).

For example, the review by the Minnesota Science Advisory Committee suggested that air ion concentrations above 2.0×10^4 ions/cm^3 may modify behavior of some sensitive human subjects in a laboratory setting (Bailey et al., 1982). The review further indicated that high ion concentrations (more than 3.5×10^5 ions/cm^3) may have affected the serotonin metabolism of a small percentage of the human population but the reports were not consistent or convincing (Bailey et al., 1982).

RESEARCH NEEDS

Based on the reviews of the literature summarized or referenced above, it appears that, at least under certain laboratory conditions, air ions and/or dc fields, at concentrations comparable to those produced by a ±500-kV dc line, may have affected various physiological parameters in plants, animals, and humans. Although such effects generally appear to be rather mild and transitory, some unreplicated studies have indicated effects that could impair health (e.g., see review by Brambl, 1982).

Relating the laboratory studies to the actual HVdc electrical environment poses several problems. As discussed previously, unlike ac transmission-line fields, which remain relatively constant, fields and ions from a dc line are of two polarities, and levels are continuously changing with line operating conditions and weather (primarily, wind). In addition, the species and relative mix of air ions near an HVdc line varies with temperature, humidity, altitude and wind and depends on the air pollution and particulates in the area. Charged aerosols may also be an important component of the dc line environment, particularly off the right-of-way. At least initially, the HVdc laboratory studies will expose organisms to high and relatively constant fields and/or ion concentrations. Studies of animals and plants living in natural conditions near a dc line are essential for assessing the relevance of the laboratory studies.

Proposed Agricultural Study

A study of plants and livestock may be done at the same site on the Intertie where the electrical monitoring study (described above) is located (Figure 3). The objective is to assess whether operation of a ± 500-kV dc transmission line results in any changes in plants or livestock which are detectable under controlled, simulated farming and ranching conditions. These two biological systems were selected because, typically, they are found on the right-of-way and experience long-term exposure to maximum field and ion levels. By locating the agricultural study at the electrical monitoring site, detailed, long-term data on electric fields, air ions, and weather will be available for characterizing exposure conditions in the study areas.

If approved, the agricultural study will begin in early 1985 and extend through two livestock/crop production cycles, concluding in 1988. Scientists from Oregon State University's Eastern Oregon Agricultural Research Center are assisting BPA in planning the study. The study may be jointly sponsored by a group of six to eight utility companies that are actively involved in HVdc transmission.

Beef cattle will be used in the study since there are no dairy farms along the Intertie, and few other kinds of livestock are typically found near the line. Three or four pens, each approximately 2.4 ha, will be located on and near the right-of-way in two spans of the line. Identically sized pens will be located in a control area at least 460 m upwind from the line. Approximately 100 treatment and 100 control cows will be used so that statistical tests will have an 80 to 90% probability of detecting absolute changes in biological parameters of at least 10 to 20%.

Parameters to be studied include gestation period, calving success, birth and weaning weights, birth defects, illness/disease, and behavior Breeding protocol may involve some combination of artificial insemination and natural breeding Treatment and control animals will be fed a uniform chopped-hay ration year-round

At least one crop and one forage plant species will be grown near the "minimum clearance" span where electrical monitoring will occur Plants will be located in plots beneath the positive and negative conductors and in control areas at least 460 m upwind from the line Options include planting directly in the soil at the site, or using lysimeters or pots containing uniform soil mixtures

Study parameters will include length of stems and leaves, biomass, seed weight and viability, growth rate, and physical damage/discoloration Plant sample sizes will be determined based on a criterion of having an 80 to 90% probability of detecting changes in biological parameters of at least 10% of normal values

SUMMARY AND CONCLUSIONS

Upgrading the Pacific Intertie in 1985 will make it the first commercial ± 500-kV dc transmission line in North America The dc electric field strength and air-ion concentrations expected from the line are calculated to be higher than for existing or other proposed HVdc lines in the U S The Intertie may, therefore, be near the upper limits for these parameters for commercial dc lines in the foreseeable future. Because of the large variability in HVdc electrical parameters from effects of weather, BPA has initiated a long-term study to monitor these parameters on and off the Intertie right-of-way in order to assess the accuracy of earlier calculations

A large body of older laboratory research includes reports of adverse and beneficial biological effects of dc fields and air ions at levels which could be produced by the ± 500-kV Intertie These reports are highly controversial, and the possible application to the HVdc environment is uncertain Laboratory studies to simulate ± 500-kV line parameters have begun only in recent years

Research is also needed on plants and animals exposed to realistic dc field and air ion concentrations near an operating ± 500-kV line Planning is underway for a joint study of livestock and plants that would be done near the Pacific dc Intertie in Oregon, beginning in 1985 The study could provide the information needed to supplement the recently initiated HVdc laboratory research Although no adverse environmental effects are expected from the ± 500-kV dc Intertie, continued research is necessary to evaluate this prediction and to obtain information needed for responding to public and environmental agency concerns that arise when new HVdc lines are proposed

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HIGH-VOLTAGE DIRECT-CURRENT TRANSMISSION LINES: A PUBLIC HEALTH HAZARD?

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ABSTRACT

High-voltage direct-current (HVdc) transmission technology offers certain engineering and economic advantages for long-distance transfer of bulk power, as well as for asynchronous interconnections Presently, there are four overland HVdc transmission lines operational in North America They were all placed in service during the 1970s, coincident with rising concern over possible adverse health effects from exposure to the 60-Hz electric and magnetic fields associated with alternating-current transmission lines Under these circumstances, it is hardly surprising that the controversy has extended into the HVdc domain At that time, the lack of reliable laboratory, clinical and epidemiological data on the biological and health effects of certain HVdc electrical environmental agents (i e , electrostatic fields and small air ions) gave apparent support to these concerns After it was placed in operation in 1978, the Minnesota segment of one of these lines resulted in numerous complaints of adverse health effects on humans and livestock These were formally documented by a health-perceptions survey conducted by a state official in 1980 Thirty-five percent of the respondents felt that their health had been adversely affected by the line's operation In response to this finding, several additional HVdc human health studies have been undertaken in the United States Four of these are also surveys, either of complaint data regarding other North American HVdc systems or of various health indices for community or occupational groups who are presumably exposed to the HVdc electrical environment These studies of human health data on HVdc transmission are primarily descriptive in nature, and only two have been published All have serious limitations, such as small numbers of subjects, lack of exposure data, and a wide variety of methodological problems In addition, an epidemiological study concerning dairy-cow performance in Minnesota has recently been completed This study represents the most detailed and scientifically sound examination thus far of potential health effects related to proximity to HVdc transmission lines Despite the lack of reliable laboratory and human health data on effects of the HVdc electrical environment, the six studies, taken collectively and viewed from an epidemiological perspective, do not provide any reliable indication of an association They are sufficient to conclude that there is no evident pattern of adverse health effects in proximity to any of the four North American HVdc transmission systems

Electric power transmission in the United States and Canada is almost exclusively in the form of 60-Hz alternating current (ac). However, because of certain engineering and economic advantages, overhead high-voltage direct-current (HVdc) transmission technology is an increasingly attractive candidate for long-distance transport of bulk power, as well as for asynchronous interconnections (Reeve, 1984) At present, there are four overland HVdc transmission systems operational in North America. They were all placed in service in the 1970's, coincident with rising concern over possible adverse health effects from exposure to the 60-Hz electric and magnetic fields associated with high-voltage overhead ac transmission lines. Under these circumstances, it is hardly surprising that the ac controversy has extended into the HVdc domain. However, because of fundamental differences in properties between the ac and HVdc electrical environments, ac bioeffects studies are not applicable to questions regarding HVdc.

Critics characterized HVdc transmission as large-scale advanced technology with little known about its electrical environment and potential public health and welfare impacts. At the time these four lines were built, the lack of reliable laboratory, clinical and epidemiological data on the biological and health effects of certain HVdc electrical environmental agents (i.e., electrostatic fields and small air ions) gave increased credence to these concerns.

The Minnesota segment of the ± 400-kV Cooperative Power Association (CPA), Eden Prairie, MN/United Power Association (UPA), Elk River, MN transmission line (CPA/UPA Line) has been the object of numerous complaints of adverse health effects. Apparent support for these allegations was provided by a health-perceptions survey conducted by a Minnesota state official in 1980. Thirty-five percent of the respondents felt that their health had been adversely affected by the line's operation (Genereux and Genereux, 1980).

Although generally recognized to be of such poor quality that its results are meaningless (Bailey et al., 1982; Sheppard, 1983), this survey nonetheless spurred five additional studies in the United States. Four are also surveys, either of complaint data regarding other North American HVdc systems or of various health indices for community and occupational groups who are presumably exposed to the HVdc electrical environment. The fifth study is a retrospective, cohort epidemiological study of dairy-cow performance in Minnesota.

The purpose of this paper is to put the claims regarding HVdc transmission lines into perspective by examining — individually and collectively — all six of these studies, which represent the totality of available human and veterinary public-health data on the operating experience of the four North American HVdc systems. By so doing, some cautious conclusions can be reached regarding the public-health implications of the HVdc electrical environment.

NORTH AMERICAN HVdc TRANSMISSION SYSTEMS

Three HVdc transmission lines currently operate in the United States (Figure 1). The longest is the 846-mi, ± 400-kV Pacific Intertie (upgraded to ± 500 kV early in 1985), which is now capable of interchanging up to 2000 MW between the Los Angeles and Columbia River basins. It is routed through Oregon, western Nevada and southern California, and was placed in commercial service in 1970. Both of the other two lines transmit power from mine-mouth generating plants in central North Dakota to converter stations in Minnesota. These are the ± 250-kV Square Butte Line, which is 465 mi long and has a transmission capacity of 500 MW, and the 436-mi, ± 400-kV CPA/UPA Line with a capacity of 1000 MW. They were placed in service in 1978 and 1979, respectively. The combined distance of the three lines is 1747 circuit-mi, representing only 0.6% of the 305,054 circuit-mi of high-voltage transmission line (rated at 71 kV and above) in operation in the United States at the end of 1982 (NEMA, 1984).

In Manitoba, Canada, the Nelson River Transmission Project involves two parallel HVdc lines on a common right-of-way (Figure 1). These lines transmit hydro power generated on the Nelson River in northeastern Manitoba to a converter station near Winnipeg. Nelson River Bipole 1 is 556 mi long and is presently operated at ± 450 kV (1620-MW capacity); the 582-mi Bipole 2 has an operating voltage of ± 250 kV (900-MW capacity). These two lines were placed in service in 1972 and 1978, respectively.

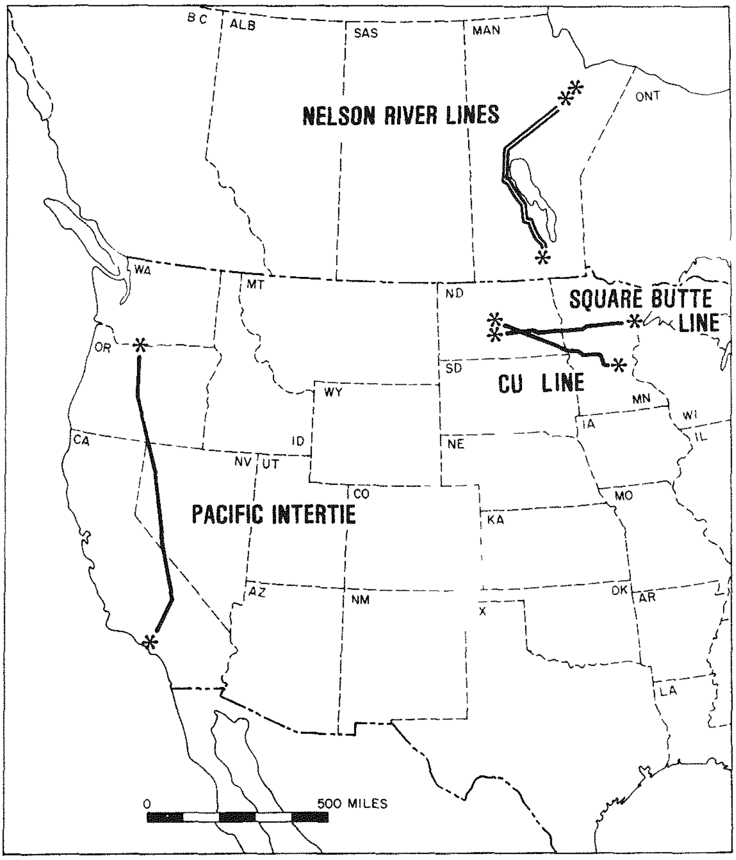

Figure 1. North American HVdc Transmission Systems.

These four North American facilities have a combined length of 2885 circuit-mi, which is almost half of the 5882 circuit-mi of overhead bipolar HVdc systems rated at ± 250 kV and above installed worldwide. (CIGRE, 1982).

THE CPA/UPA LINE CONTROVERSY

All six health studies had their origins, either directly or indirectly, in the controversy surrounding construction and operation of the CPA/UPA Line in Minnesota. The Minnesota segment is 176.3 mi long on a 160-ft right-of-way. It crosses 32 townships of predominantly agricultural land in eight counties in the west-central portion of the state, requiring easements in 476 parcels. The line was routed to maintain at least 300 ft of clearance from existing residences and barns, unless the landowner agreed otherwise in writing. It is designed for 1400-ft spans, so that there are approximately four lattice-steel towers per mile.

For ± 400-kV operation, the National Electrical Safety Code requires a minimum clearance of 35 ft above the ground. However, the Minnesota Environmental Quality Board (MEQB) required that the line maintain a minimum clearance of 50 ft "over croplands," ostensibly to avoid undue impact on agricultural operations. Therefore, as constructed, the CPA/UPA Line has a minimum clearance of 35 ft in North Dakota and 50 ft in Minnesota.

The project has been controversial since its inception in 1973. There were numerous legal challenges, and protest activities plagued all phases of construction and initial operation (McConnon, 1984).

The CPA/UPA Line was initially energized on October 17, 1978, followed by intermittent operation for testing of the converter facilities over a period of approximately 6 mo. Continuous operation began in May 1979, and the line was placed in commercial service on August 1, 1979, concurrent with Coal Creek Unit 1.

Protesters have raised numerous issues over the long history of the CPA/UPA Line controversy. However, with the line in operation, these have generally faded, with the exception of the human and animal health question. Anecdotal reports of adverse health effects from landowners and others along the CPA/UPA Line have sustained the controversy.

In response, the MEQB in partial collaboration with the Minnesota Department of Health, sponsored a number of studies, including a literature review (McSwain et al., 1980), formation of a group of seven Science Advisors (Bailey et al., 1982), electrical environment monitoring (MEQB, 1981, 1982, 1983, 1984), and an epidemiological study of dairy-cow performance (Martin et al., 1986). In addition, the line owners, CPA and UPA, undertook two health surveys (McConnon, 1982; Miller, 1981).

As a further result of the 1980 Minnesota survey, two other studies have been undertaken as part of the environmental impact assessment of a proposed HVdc interconnection between Quebec and New Hampshire. One, sponsored by the Vermont Department of Public Service, was a health perceptions interview survey of acute health effects indices in a residential community through which the Pacific Intertie passes (Haupt and Nolfi, 1984); the other, conducted for Vermont Electric Power Company and New England Electric Transmission Corporation, surveyed complaint data for all four North American HVdc transmission systems (Banks and Williams, 1983).

MINNESOTA HEALTH-PERCEPTIONS SURVEY

On February 20, 1980, a health perceptions questionnaire, signed by the Minnesota Environmental Quality Board chairman, was mailed to the 570 landowners-of-record from whom easements in Minnesota had been obtained for the ± 400-kV CPA/UPA Line. (As landowners, the recipients did not necessarily live near the line.) An additional 125 copies were distributed by a protest organization to Minnesota residents who, although not owning property on the right-of-way, lived in the vicinity and believed that they may have been affected by the line's electrical environment (Genereux and Genereux, 1980).

The survey was an attempt to gain more systematic data on symptoms and prevalence of health effects complaints. Seven questions were asked about human and livestock health and effects on wildlife. In addition, information was requested on physicians, nurses, veterinarians, etc., consulted by the respondents. The questionnaire was patterned after a somewhat earlier survey by a State legislator in January 1980, and it is believed that both questionnaires were sent to the same landowners-of-record.

Since the initial response was low (22%), a telephone follow-up survey was undertaken. To conserve resources and to avoid "unnecessarily" recontacting landowners, completed responses to the legislator's survey were used where possible. These landowners were telephoned only to complete unanswered questions, and respondents who had indicated no effect were not recontacted (Genereux and Genereux, 1980).

Out of the 695 distributed questionnaires, only 221 (32%) were returned by mail, including those used from the legislator's survey. A majority of the landowners had to be contacted by telephone in order to obtain an adequate sample for the survey's purposes. Even with this extraordinary effort, data were eventually analyzed from only 454 respondents, representing 65% of the distributed questionnaires, a marginally acceptable response rate for health surveys. There is no way of knowing the extent to which the questionnaires were distributed to actual residents near the line, whether or not they were landowners. Hence, the 65% response rate is, in fact, meaningless.

The survey's first question was: "Have you suffered any adverse health effects which you believe are a result of living close to the powerline?" Of the 394 respondents answering this question, 35% indicated, "Yes"; 47% said, "No"; and the remaining 18% replied, "Don't know." The survey went on to ask, "If so, what are these effects?", followed by a list of 17 symptoms. The results are tabulated in Table 1. The number of symptoms averaged 3.23 for each of the 188 respondents who answered this part of the question.

If these perceptions are an accurate representation of health effects attributable to the HVdc electrical environment, clearly a major public health problem would exist. However, the design and administration of this survey were highly contrary to professional survey practice. Many of its methodological flaws are discussed by Bailey et al. (1982), Banks and Williams (1983), and Sheppard (1983) in their respective reviews of HVdc human health effects studies.

An additional complication is that the survey was conducted in an atmosphere of extreme hostility, a situation that can cause problems for even the best of health surveys. For example, the CPA/UPA Line crosses eight counties in west-central Minnesota. Figure 2 provides a county-by-county profile of 391 of the responses to the first question. The figure illustrates the high rate of affirmative responses from Pope and Stearns Counties.

TABLE 1. Disease Symptoms Attributed to the CPA/UPA Line by Landowners and Others, Minnesota, 1980 (Genereux and Genereux, 1980)

Symptom	Percent Responding (N = 394)
Headaches	28.7
Respiratory problems	16.8
Fatigue	15.2
Tingling sensations	12.2
Stress	11.9
Dizziness	10.9
Nosebleeds	10.9
Rashes	10.4
Eye problems	7.4
Numbness	5.6
Nausea	5.3
Ear problems	4.1
High blood pressure	3.6
Feeling of being "high"	2.0
Shocks	1.8
Menstrual problems	1.5
Miscarriages	0.8
"Other"	5.3

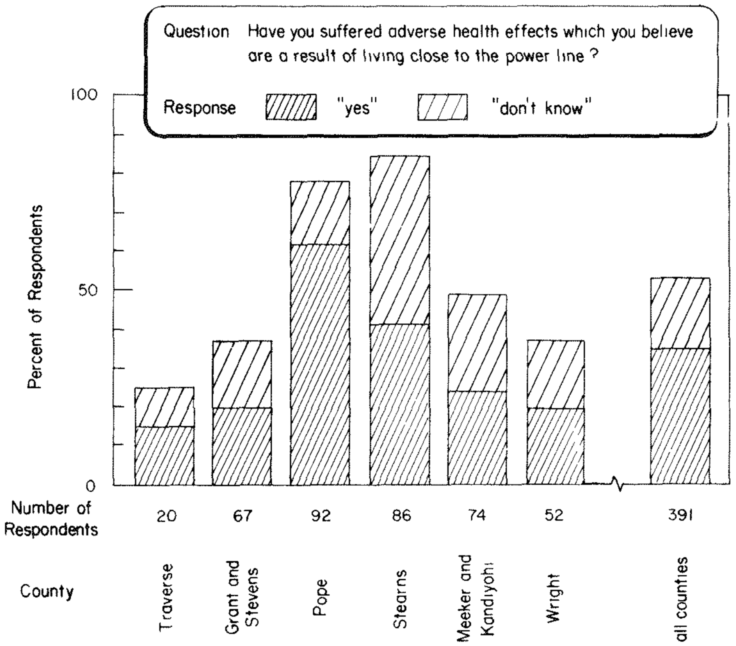

Figure 2. Perception of Adverse Health Effects Attributed to the CPA/UPA Line by Landowners and Others, Minnesota, by County, 1980 (Genereux and Genereux, 1980).

The CPA/UPA Line has the same conductors, configuration and clearance across Minnesota, and there are no known local environmental, demographic, or other factors that could explain such a dramatic increase in prevalence of symptoms in these two counties. The two adjacent counties were, however, the focal point of protest activity, and also the places where the condemnation rate was highest and the amount of vandalism to the line was greatest. These facts reflect the intensity of opposition and suggest possible respondent bias as responsible for the anomalous rates in the two counties. This possibility was not examined.

Because of the many flaws in design and administration, and the absence of systematic follow-up in the field by trained public-health professionals, very little credence can be given to the essentially anecdotal data reported by this survey (Banks and Williams, 1983). It offers little additional insight beyond the public complaints that precipitated it (Bailey et al., 1982).

SICK-LEAVE STUDY OF HVdc ELECTRICAL WORKERS

Although some limited occupational health data exist for ac electrical workers, there are no published studies on the experience of linemen and others exposed to the HVdc electrical environment. McConnon (1982), however, has taken a limited look at one group of HVdc electrical workers in an analysis of the sick-leave experience of UPA, Elk River, Minnesota, employees. UPA has operating and maintenance (O&M) responsibility for the ± 400-kV CPA/UPA Line and converter stations.

McConnon analyzed the sick-leave rates of all UPA employees over the 5-yr period 1977-1981, which includes roughly 2-1/2 yr before and 2-1/2 yr following the in-service date of the line.

Average annual sick-leave days were classified into one of four occupational categories. Of particular interest is the "dc electrical O&M" group, which was defined as those electrical O&M employees who spend more than half of their time working on the CPA/UPA Line or the converter stations. Sixteen of these HVdc electrical workers had been employed by UPA prior to the start of the study period. In this "original" group, eight employees were linemen with responsibilities that included insulator cleaning and changing, trip or relay testing, line inspections, and right-of-way maintenance and weed control. The other eight worked at the converter stations, where their activities brought them into proximity with energized conductors.

McConnon (1982) reached the following conclusions:

"1. The sick-leave rates of electrical O&M personnel who normally work near dc facilities are generally lower than those of other employee groups at UPA.

2. The sick-leave rates of dc personnel are comparable to those of UPA management, professional and administrative personnel.

3. The change in sick-leave experience of electrical O&M personnel normally working near dc facilities generally follows the annual trend changes of other UPA groups over the study period.

4. On the average, the sick-leave experience of the original 16 employees making up the electrical O&M group who normally work near dc facilities is the same or better than that of the electrical O&M group as a whole."

Figure 3 compares McConnon's findings for all UPA personnel with data for three groups of O&M employees. Overall, they suggest no acute health effects among these 16 workers.

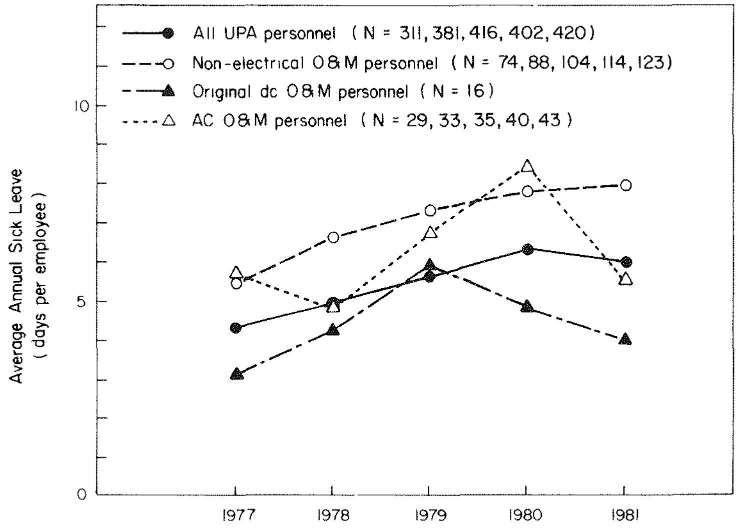

Figure 3. Sick Leave Rates for United Power Association Employees (Banks and Williams, 1983).

The examination of occupational groups who may experience increased exposure to the HVdc electrical environment is a valid approach to detecting potential health effects. The sick-leave experience of the 16 "original" HVdc electrical workers appears to be unremarkable with respect to that of other UPA employees both before and after the CPA/UPA Line in-service date. However, the limitations of sick leave as a health-related index prevent any broader interpretation of this finding (Banks and Williams, 1983).

NORTH DAKOTA LANDOWNER OPINION SURVEY

In December 1981, Miller Research Services (Miller, 1981), Minneapolis, MN, conducted a telephone opinion survey of landowners along the ±400-kV CPA/UPA Line in North Dakota. The purpose of this brief investigation was to determine the extent to which opinions and attitudes about the line in North Dakota, particularly in relation to health effects, differed from those in Minnesota. It was sponsored by the line's owners, UPA and CPA, Eden Prairie, Minnesota.

The telephone interviews were conducted more than 2 yr after the CPA/UPA Line in-service date. Only adults who resided on property crossed by the right-of-way were interviewed. Respondents were not aware of the true purpose of the survey because various questions were also asked about unrelated, but important, North Dakota environmental issues.

For the 75 respondents, results related to CPA/UPA Line health issues are as follows:

1. Seventy-nine percent of the respondents had not heard of any health problems associated with the Minnesota segment of the CPA/UPA Line.

2. Seventy-two percent of the respondents were not aware of any problems with the CPA/UPA Line since its completion.

3. Of those respondents who were aware, only 19% mentioned health-related problems. With the exception of one respondent who reported a "heart condition problem," these were concerns that the respondents had heard about rather than personally experienced.

4. When asked, "Do you personally feel that the [CPA/UPA] Line is dangerous?", 67% answered, "No"; 24% responded, "Yes"; and the remaining 9%, "do not know." When asked why, no respondent reported being ill because of the line.

The general absence of perceived health effects among the North Dakota respondents is in marked contrast to the results of the earlier survey in Minnesota. It should be noted that the minimum clearance of the CPA/UPA Line in North Dakota is 35 ft (versus 50 ft in Minnesota), resulting in higher average ambient levels of HVdc electrical environmental agents.

Despite its much smaller sample size, this survey undoubtedly provides a more unbiased indication of attitudes and perceptions of CPA/UPA Line health problems than does the Minnesota survey. Unlike the latter, Miller Research Services conducted its study on a "blind" basis, with randomly selected respondents who unquestionably resided on land crossed by the line, and in the absence of significant controversy and organized protest activity. The survey cannot demonstrate that no health effects are occurring; it does support the possibility, however, that the acute symptoms attributed to the CPA/UPA Line in Minnesota (Table 1) are the result of bias or other causes, not of exposure to the HVdc electrical environment.

SAUGUS, CALIFORNIA, HEALTH-PERCEPTIONS INTERVIEW SURVEY

Although the ± 400-kV Pacific Intertie traverses sparsely populated regions in Oregon, western Nevada and southern California for most of its 846-mi length, a short section passes through Saugus, California. This densely populated residential community was seen to offer two decided advantages for the examination of health perceptions related to HVdc electrical environment exposure: a high density of homes (including those on lots abutting the right-of-way) provided sufficient sample sizes, and there had been no public controversy over the Intertie during its 11 yr of operation.

This area was therefore selected for a door-to-door health perceptions interview survey, which was conducted in November 1981 by Associates in Rural Development, Inc. (ARD), Burlington, Vermont, under sponsorship of the Vermont Department of Public Service (Nolfi and Haupt, 1982). The survey's objective was to determine if respondents' general perceptions of health and specific health problems could be associated with proximity to the HVdc transmission line.

The study area included homes up to 0.85 mi away from the line. Two natural clusters were used: homes within 0.14 mi of the Intertie centerline formed the presumably exposed ("near") group, and those between 0.65 and 0.85 mi to the west comprised the control ("far") group. In the near group, except for lots abutting the right-of-way, only homes on the west side of the line were included, since the investigators believed that two multiple-circuit ac transmission lines paralleling the Intertie to the east on a common 305-ft right-of-way might confound any observed effects (Nolfi and Haupt, 1982).

The survey instrument format and a number of questions were adapted from the U.S. National Health Interview Survey questionnaire. Several questions were related to general health perceptions and indices. Others addressed those acute symptoms purported to be associated with the HVdc electrical environment in Minnesota (Table 1) or reported by the air-ion bioeffects literature. Respondents were asked about the occurrence of these acute symptoms during the 2-wk period just prior to their interview.

Households were the sampling unit, and all homes more than 5 yr old were included in the population. Questions were asked directly of each adult at least 17 yr old who was at home, and indirectly for adults not at home and for children at least 2 yr of age.

The home interviews were conducted door-to-door over a 13-day period, November 2-14, 1981, by three trained interviewers. Altogether, data were collected on 438 individuals from 128 households, a 61.5% response rate which, according to the investigators, is "lower than usually expected from door-to-door interviewing, probably because the community had recently been subject to sales people and pranksters posing as survey interviewers and so was unusually suspicious" (Haupt and Nolfi, 1984).

A comparison of reported symptom prevalence and other health indices for the near and far groups revealed no systematic differences. As summarized in Table 2, differences in symptom rates between the two groups are small, and those that do exist do not systematically favor either group.

TABLE 2. Proportions of Groups Near to and Far from the Pacific Intertie Reporting Various Health Problems, Saugus, California, November 1981 (Nolfi and Haupt, 1982)

Symptoms During Preceding 2 Weeks	Percent of Near Group (N = 245)	Percent of Far Group (N = 193)	Difference[a]
Headaches[b]	27.3	30.6	-3.3
Sore or dry throat[b]	26.1	25.9	0.2
Stuffy nose or respiratory congestion[b]	28.6	26.9	1.7
Drowsy for no apparent reason	4.5	2.6	1.9
Had rashes	4.9	5.7	-0.8
Felt tense for no apparent reason	1.6	3.6	-2.0
Felt dizzy	2.9	2.6	0.3
Felt depressed for no apparent reason	2.4	3.6	-1.2
Irritated eyes or dim vision	8.2	8.8	-0.6

[a] No positive difference is significant at the P = 0.05 level.
[b] At least once

A comparison was also made between the control group and those households of the near group located directly adjacent to the right-of-way. This "adjacent group" of 126 was assumed to have the highest exposure potential. Again, no significant differences were observed. Likewise, attempts to associate symptoms and derived symptom scales with distance from the line showed no significant correlation.

The data were also examined for correlation between several control variables and distance or symptom scales. The control variables tested included age, sex, form of interview (direct or indirect), occupation, education, hours at home, years of residence and number of floors in the house. Only the last two variables were statistically correlated with the symptoms scale. Thus the investigators concluded that these factors did not confound their findings.

After acknowledging that their study cannot address unperceived health effects, low-frequency effects or effects not included in their questionnaire, Nolfi and Haupt (1982) conclude, "We can state with confidence that no meaningful power-line health effects were indicated by this research."

This interview survey represents a sharp departure from its Minnesota counterpart. The serious methodological flaws in data collection were avoided, and the successful effort at conducting the Saugus interviews in a blind fashion — that is, without the participants linking the study to the presence of the transmission line — was an important feature in minimizing certain sources of bias. Sample sizes were sufficient to permit statistical comparisons of the data between those residing near to and far from the line. Professionalism is also evident in questionnaire design and administration, as well as in the use of trained interviewers.

However, the study also has a number of deficiencies that limit the conclusions that can be drawn. Many of these are discussed by Bailey et al. (1982), Banks and Williams (1983), and Sheppard (1983). Of particular importance are the invalid exposure assumptions which greatly narrow the conclusions that can be reached. A major concern is the use of distance from the Intertie as a surrogate for direct measurement of personal exposure to the various physical agents of the HVdc electrical environment. No electric-field or air-ion density measurements were taken during the study.

The exposure potential is further obscured by the abnormal operating schedule of the Intertie during the symptom reporting period. Due to low demand in the fall, power exchanges are small; as a result, annual scheduled inspection and repair (SIR) occurs during this period. The 1981 SIR program started on September 14 and was completed on December 18. The Saugus interviews were conducted between November 2 and 14. Respondents were asked about symptoms for the 2-wk period immediately preceding their interview; thus the actual symptom reporting period is a total 27 days, falling roughly midway in the SIR schedule.

As shown in Figure 4, the Intertie was operating in monopolar mode for most of this period; the other pole was out of service for inspection and repair. Haupt and Nolfi (1984) contend that this situation "ensures a variety of electromagnetic environments"; in fact, it further weakens their exposure assumptions. For example, it is estimated that the Intertie was producing positive air ions only about 44% of the time during the 27-day symptom-reporting period. Yet many of the symptoms inquired about in the Saugus survey questionnaire were apparently selected from those that have been reported in the scientific literature to be associated with positively charged small air ions. This is the agent, according to Haupt and Nolfi (1984), that produces the "serotonin response," which is purportedly responsible for "mucous membrane irritation, migraine headaches, nausea, and a variety of other symptoms." Thus, no defensible inferences can be drawn regarding air ion (or any other HVdc physical agent) exposure levels or duration, regardless of a respondent's distance from the line. Even if exposure levels were to differ in the long run, however, the use of a 2-wk period for symptom reporting and the use of inappropriate chronic indices are not adequate to detect all health differences that might occur (Bailey et al., 1982). Nonetheless, the results do not suggest any demonstrable pattern of adverse health effects associated with proximity to the Pacific Intertie, and they clearly indicate that those who lived near the line did not perceive their health status any differently that those living further away.

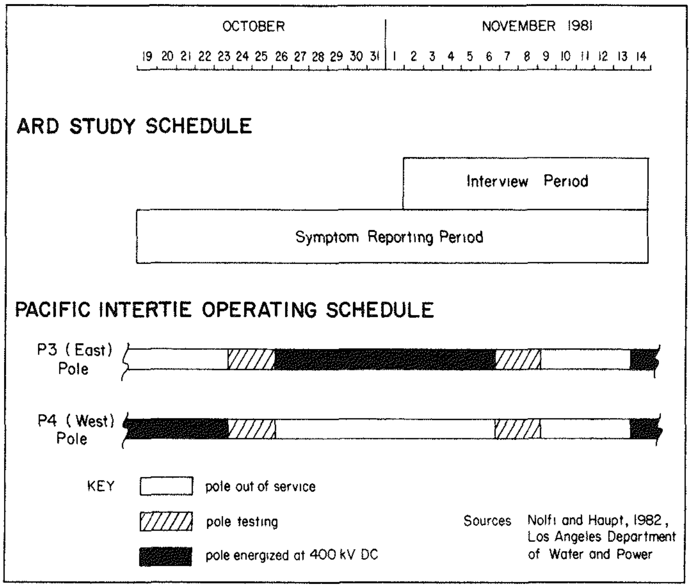

Figure 4. Pacific Intertie Pole Energization Status in Relation to Saugus, California, Resident Health Perceptions Survey Schedule (Banks and Williams, 1983). ARD = Associates in Rural Development, Burlington, VT.

UTILITY/HEALTH AGENCY PUBLIC COMPLAINT SURVEY

Respondents to the 1980 Minnesota survey attributed several perceivable acute health effects on nearby resident populations to the HVdc electrical environment (Table 1). Although these perceptions were not confirmed by the two other resident health surveys in North Dakota and in Saugus, California, the possibility remains that HVdc transmission systems could be responsible for increased prevalence of symptoms among those living or working near them. If so, the highly anomalous symptom patterns might have come to the attention of appropriate authorities. Although there are no reports in the literature or elsewhere suggesting that this is the case (other than in Minnesota), the possibility had not been systematically explored. Accordingly, in March 1982, Banks and Williams (1983) wrote to each of the six utilities with operating and maintenance responsibility for all or part of one of the four North American HVdc transmission systems (Figure 1), requesting information on any health-related complaints that it might have received, as well as engineering data, including detailed routing.

From March to July 1982, as routing information became available, letters were also directed to state/provincial environmental and health agencies and to county health officers. These letters summarized the health complaints attributed to the CPA/UPA Line in Minnesota and specifically requested any information on similar complaints directed toward the HVdc transmission line(s) routed through the agency's jurisdiction.

All six utilities reported that they had received no complaints, formal or otherwise, regarding human health effects. At least one response was received from each of the five states (Oregon, Nevada, California, North Dakota, and Minnesota for the ± 250-kV Square Butte Line only) and from Manitoba. Like the utilities, all state/provincial-level respondents were consistent in stating that no health complaints had been received.

At the county level, letters were sent to health officers in four states (North Dakota does not have county-level health agencies) and to regional medical officers of health in Manitoba, a total of 24 local health officers. All 19 (79%) respondents also uniformly indicated that no health-related complaints had been received by them or their agencies (Table 3). These local health-officer responses are particularly important. All four HVdc transmission systems generally traverse sparsely populated areas. While exposure to the HVdc electrical environment is therefore limited, it nonetheless appears reasonable that if the nature and severity of symptoms reported in Minnesota were at all representative, their occurrence elsewhere should have been evident to at least some local health officers. Although these officials were asked only for professional judgment and not for a systematic survey of local health status, this still appears to be a reasonable expectation. Many of the county-level respondents' letters suggested strong connections with local direct health-care providers, and it would seem that with such a network, any symptom patterns similar to those attributed to the CPA/UPA Line in Minnesota would have come to the attention of at least some of these local health officers.

The absence of public complaints to local health officers is consistent with the findings of the North Dakota and Saugus, California health surveys.

TABLE 3. Complaints of Adverse Health Effects Attributed to HVDC Transmission Lines Reported to Local Health Officers, United States and Canada, 1982 (Banks and Williams, 1983)

Health Officer's Area	Nature of Complaints Received[a]
Oregon (Pacific Intertie)	
Wasco County	None
Jefferson County	None
Crook County	None
Deschutes County	None
Lake County	None
Nevada (Pacific Intertie)	
Washoe County	None
Pershing County	N/R
Churchill County	N/R
Lyon County	N/R
Mineral County	N/R
California (Pacific Intertie)	
Mono County	None
Inyo County	None
Kern County	None
Los Angeles County	None
Manitoba (Nelson River Lines)	
Interlake Region, Selkirk[b]	None
Thompson Region, Thompson[b]	None
Minnesota (Square Butte Line)	
Wilkin County	None
Otter Tail County	None
Becker County	None
Wadena and Cass Counties	None
Hubbard County	None
Crow Wing County	N/R
Aitkin County	None
St. Louis County	None

[a] N/R = No response received

[b] Provincial Medical Officers of Health stationed in the specific community

MINNESOTA DAIRY HERD IMPROVEMENT ASSOCIATION RECORDS STUDY

In addition to inquiring about human health, the 1980 Minnesota survey included questions on perceived effects of exposure to the CPA/UPA Line electrical environment on livestock health. Of the 454 respondents, 216 indicated that they had "livestock on the property which is crossed by the powerline." Question 4 asked, "Has your livestock appeared to suffer adverse health effects which you believe may be a result of being near the powerline?" [emphasis in original]. Twenty-nine percent of the 217 respondents answering this question said, "Yes"; 45% replied, "No"; and the remaining 26% did not know. This question was followed by the query, "If so, what are these effects?" Respondents could select from five listed symptoms. Nineteen percent of the 218 respondents who checked at least one symptom indicated "Breeding problems"; 18%, "Aborted or deformed offspring"; 16%, "Stress or nervousness; and 12%, "Changes in milk production." Because of the previously described flaws and biases in this survey, it is not possible to assess the significance of these figures. There are also other anecdotal data indicating that at least some Minnesota dairymen perceived power-line-associated losses as high as 25% in milk production or reproductive efficiency (Genereux and Genereux, 1980; Bailey et al., 1982). Although local professional veterinary opinion generally did not hold that the line per se was causing biological effects, some individual veterinarians felt that sufficient data were not available to evaluate the question.

With these concerns in mind, the MEQB contracted with the University of Minnesota College of Veterinary Medicine to perform a retrospective epidemiological cohort study of dairy-cow performance using existing Minnesota Dairy Herd Improvement Association (DHIA) records. The study involved a statistical analysis of dairy herd records both before and after the CPA/UPA Line was energized. Herds near the line were compared to herds farther away from the line. In all, 6 yr of data — involving over a quarter of a million individual records — from the DHIA data base between mid-1976 and September 1982 were analyzed on 500 Holstein herds representing almost 24,000 milking cows per year. The animal data included: 305-day milk production per cow; 12-mo rolling herd average of milk production; herd size; intercalving interval; abortion rate; and daily rate of decline in milk production during later stages of a lactation cycle (Martin et al., 1986).

Distance from the line was used as a proxy for exposure levels to HVdc electrical environmental agents. The 500 herds were grouped into six zones or strata as follows:

Stratum	Distance from Farmstead to the CPA/UPA Line (miles)
1	0 - 1/4
2	1/4 - 1/2
3	1/2 - 1
4	1 - 3
5	3 - 6
6	6 - 10

Stratum 1 was assumed to represent the maximum exposure potential; Stratum 6 served as the control, where no exposure to the line's electrical environment was considered likely to occur. In addition to distance from the line, each herd was classified as to the side of the line (north or south) on which it was located.

The number of herds studied within each stratum was as follows:

	Number of Herds		
Stratum	North	South	Total
1	10	15	25
2	9	10	19
3	9	11	20
4	68	51	119
5	75	66	141
6	96	80	176
Total	267	233	500

The study found no statistically significant changes in dairy-herd performance associated with proximity to the CPA/UPA Line. No significant association was found between 305-day lactation milk production and distance from the line, either prior to energization or in either of two subsequent years (Figure 5). The 12-mo rolling herd average for milk production (Figure 6), considered an important herd-performance indicator, increased by 842 pounds of milk per cow between the period ending May 1979 and the period ending September 1982, with the increase approximately parallel in all six strata. The herds in Stratum 1 (nearest the line) experienced an above-average increase of 978 pounds per cow. Herd size over this period showed a modest increase (four cows per herd) across all strata, with no significant association between the size of the increase and proximity to the line.

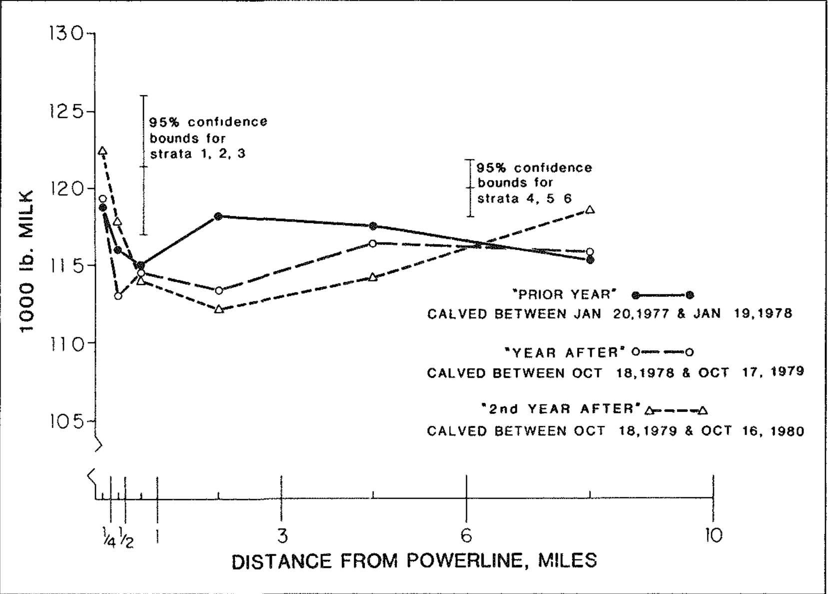

Figure 5. 305-Day Milk Production for First Lactation Cows, Average per Cow (Martin et al., 1983).

Quality and efficiency measures in the DHIA records, such as percent butter fat, ratio of pounds of milk to pounds of grain fed, and somatic cell counts, showed no significant association with distance to the line. Following energization of the line, the intercalving interval, rate of culling for reproductive problems and incidence of recorded abortions were no higher near the line (0 to 1/2 mi) than away from the line (6 to 10 mi).

After a cow has been milking for approximately 7 wk, her milk production reaches a peak and begins to decline in a predictable, straight-line fashion for 7 or 8 mo until she is eventually dried off prior to calving. The study found no significant deviation in the steady decline of milk production following any of three key dates in the CPA/UPA Line start-up schedule: initial energization; line operation increased from 6 to 71% of the time; and line operation exceeded 90% of the time.

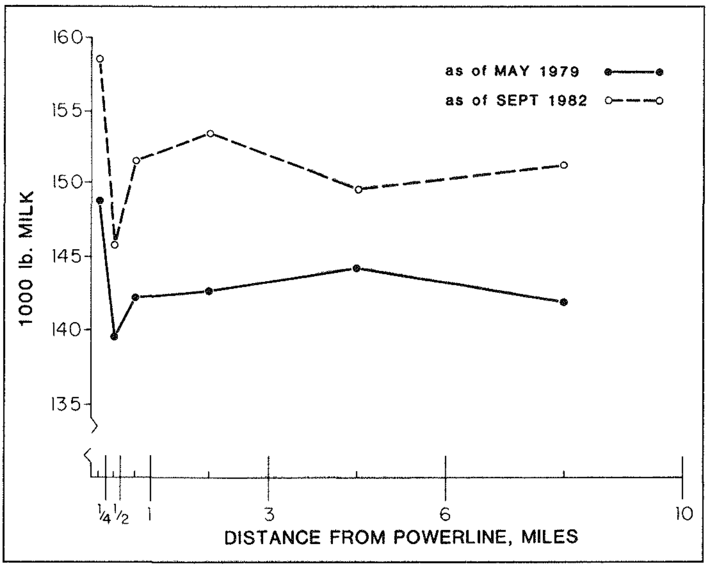

Figure 6. Comparison of 12-Month Rolling Herd Average, May 15, 1979 Versus September 1, 1982 (Martin et al., 1983).

The DHIA study is clearly characterized by a better design than any of the other health studies discussed herein. Some of its major strengths include:

1. The study did not rely on "recall" or on subjective judgments of which performance variables might be associated with operation of the line.

2. Objective measures of animal performance or health status were assessed, including milk production, milk quality and reproductive efficiency. The investigators considered these measures to be highly sensitive but nonspecific indicators of any adverse health effects occurring in a dairy herd.

3. The design permitted detection of changes in performance that might be associated with the start-up schedule of the line.

4. The large sample size and use of appropriate statistical procedures provided the capability of detecting differences as small as 5% between adjacent strata and over time.

5. Although distance was used as a surrogate measure of exposure, the exposure assumptions were strengthened by monitoring data on air-ion density and electric-field levels, wind speed and direction, and on the line's operating history.

6. In contrast to humans, dairy herds are confined to a relatively small area with little movement of animals to areas of significantly different exposure potential.

7. The study was designed, administered and reviewed by professionals with considerable expertise in epidemiology, veterinary science, dairy-herd performance, electrical engineering and statistics.

As acknowledged by the investigators, however, several aspects of the study limit the conclusions that can be reached. If substantial exposure to air ions or the electric field had been present on only a very few farms near the line, then the study could not have statistically detected effects that may have existed. Secondly, data collected by DHIA is most useful for production purposes; they are not optimal for a planned experiment. Since only about 40% of the dairy herds in Minnesota belong to the DHIA, the possibility exists, although it is remote, that DHIA herds are for some reason less (or more) susceptible to effects of the HVdc electrical environment. Finally, the percentage of farms that remained in the DHIA program during the study period was significantly lower in the innermost stratum (68%) compared to those in the other five strata (86 to 89%). While this differential drop-out rate did not affect their conclusions, the investigators were not able to determine the cause(s) without violating their anonymity agreement with participants.

At present, the DHIA study represents the most detailed and scientifically sound epidemiological study of the potential health effects associated with the HVdc electrical environment. The investigators observed no consistent changes of 5% or more in individual animal or herd milk production or reproductive efficiency associated with proximity to the CPA/UPA Line, despite perceived dairy production losses as high as 25% attributed to the line. The study therefore offers significant evidence that neither short-term nor long-term physiological or reproductive effects are likely to be occurring in dairy herds as a result of proximity to HVdc transmission lines.

DISCUSSION AND CONCLUSIONS

In judging the likelihood of a causal association between altered health status and exposure to the HVdc electrical environment on the basis of these six studies, four epidemiological guidelines are useful. Since these guidelines are intended for evaluating the likelihood of causation once an association has been observed, they represent quite stringent tests for determining the existence of an association:

Temporal Relationship

For a relationship to be considered causal, the events that are presumed to be causative must precede those thought to be effects. Three of the six studies examined temporal aspects. McConnon (1982) and Martin and colleagues (1986) both compared health-related indices before and after key dates in the CPA/UPA Line start-up schedule, finding no differences.

In the Saugus, California, survey, Haupt and Nolfi (1984) indicate that they conducted sensitivity tests "to ensure that the brief down-time periods did not alter the basic effectiveness of the research design and analytic techniques." This statement apparently indicates that the investigators observed no differences in response patterns during and/or shortly after three 2-hr switching periods and a 4.6-day outage on the ± 400-kV Pacific Intertie during the 27-day symptom-reporting period, although it is difficult to characterize 4.6 days as a "brief down-time period."

In the case of the 1980 survey in Minnesota, data are available that do not support the claims of adverse human health effects associated with the HVdc electrical environment. In-depth interviews of active protesters in Pope County were conducted in 1978 by a public health nurse to explore the relationship between protest activity and human health effects. Some of her reported findings are: "25% of the population experienced increased tension since the conflict began; 13% noted an increase in the frequency of headaches; and 22% experienced fitful sleep. Twenty-two percent felt depressed and listless since the conflict began. Nine percent reported that they and/or their children had nightmares during the height of protest activity (winter months of 1977-78)." (McCall, 1979). These anecdotal data suggest that some Pope County residents were experiencing health problems similar to some of those listed in Table 1 as a result of their protest activity and that these problems began well before the CPA/UPA Line was placed in service. (The line was first energized on October 17, 1978.) These findings and data do not suggest any pattern of potentially causative events preceding the occurrence of reported symptoms.

Dose-Response Relationship

The existence of a dose-response relationship (that is, an association in which the frequency of the effect increases as exposure increases) is usually considered to favor a causal hypothesis. In this regard, the following points can be made:

1. The CPA/UPA Line conductors in North Dakota are 15 ft lower than in Minnesota (otherwise, the geometry and conductor configurations are identical), resulting in higher total electric field and higher small-air-ion density levels in North Dakota. Yet in North Dakota — unlike in Minnesota — there was no indication of any health-related problems attributable to the CPA/UPA Line.

2. *Martin and colleagues (1983) found that dairy-herd milk production and reproduction* parameters were essentially identical across all strata. Even when the herds in the innermost stratum (0 to 1/4 mi) were compared to herds in the outermost stratum (6 to 10 mi), no differences were observed.

Furthermore, the CPA/UPA Line is continuously operated with the north pole at positive polarity and the south pole at negative polarity. If there were a differential susceptibility of dairy cows to positive and negative air ions, differences in production and reproduction parameters for herds on opposite sides of the line might reveal effects. However, a comparison of herds north of the line with those to the south in the two innermost strata (0 to 1/2 mi) revealed no such differences. For these reasons, the available data do not suggest the existence of a dose-response relationship.

Consistency

An association consistently observed by different investigators, in different populations and/or in different areas is more likely to be causal. Here, two observations can be made, one general and one involving a specific comparison between two studies:

1. The six studies encompassed five states and one province. Of the four HVdc transmission lines under study, adverse health effects have been attributed only to the ± 400-kV CPA/UPA Line in Minnesota, through which the ± 250-kV Square Butte Line is also routed.

2. The group adjacent to the Intertie in the Saugus, California, survey involved 126 individuals living in homes that were as close as 85 ft to the Pacific Intertie centerline, whereas for the CPA/UPA Line there were (at most) five residences within 300 ft for its entire length in Minnesota. This suggests that any pattern of adverse health effects associated with proximity to HVdc transmission lines would have been more often reported and more readily detected in Saugus.

The interviewers inquired about "any persistent or serious illnesses or health problems that keep returning." Thus, respondents had an opportunity to report any perceived chronic problems (i.e., those existing prior to the start of the 27-day symptom-reporting period) in addition to the acute symptoms and other health indices specifically inquired about in the questionnaire. Unfortunately, except for allergies and asthma, the nature and prevalence of such chronic symptoms are not reported. Differences among sample groups for allergies or asthma are not significant, although the numbers are low.

However, the investigators were very familiar with the 1980 Minnesota survey. If the acute perceived health problems attributed to the CPA/UPA Line (Table 1) in Minnesota were at all characteristic of HVdc electrical environment exposure in severity and extent, it would seem likely that this open-ended question would have picked up at least some some of these symptoms, whether or not any exposure had actually occurred during the 27-day symptom-reporting period. Neither the Nolfi and Haupt (1982) report nor the Haupt and Nolfi (1984) report indicates any pattern of such effects. On the basis of these data, no consistency has been observed.

Coherence

A causal hypothesis is supported by other known facts or observations. At present, there are no established biological mechanisms of action by which electrostatic fields and small air ions could exert biological effects. The lack of even an accepted theoretical basis for postulating such effects forces any discussion of a causal relationship into speculation.

Well-designed and replicated experiments are the best basis for establishing the existence of cause-effect relationships. Unfortunately, the vast bulk of the relevant bioeffects research is methodologically defective in one way or another, has produced contradictory results, or has not been independently replicated (Bailey, 1982). Thus, nothing definitive can be drawn from these tentative laboratory and clinical findings.

Applying these four epidemiological guidelines leads to the conclusion that the six health studies do not provide any reliable indication of an association between exposure to the HVdc electrical environment and reported symptoms or health-related indices. Furthermore, they are sufficient to conclude that there is no evident pattern of adverse health effects in proximity to any of the four North American HVdc transmission systems, suggesting a general absence of perceivable symptoms associated with the HVdc electrical environment.

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AN EXTREMELY LOW-FREQUENCY ELECTROMAGNETIC FIELD EXPOSURE SYSTEM

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ABSTRACT

An extremely low-frequency exposure system that simulates the electromagnetic field conditions under a high-voltage electric power transmission line was designed and built. It can accommodate up to 16 adult rats in individual cages, and creates fields of up to 100 kV/m and 10 G. The equations used in the design of the magnetic field coils were computerized. The program provides information on the magnetic-field distribution. Computer simulation was also used to study fringing of the electric field at the electrode edges and the field disturbance caused by the plastic cages. Measurements revealed that the magnetic field is uniform within ± 5% and that the electric field is uniform within ± 2%.

The electromagnetic field created under a high-voltage, three-phase, electric power transmission line consists of an electric field, resulting from the voltage of the line conductors with respect to ground, and a magnetic field resulting from the currents that flow through these conductors. While the voltage is usually steady, straying no more than 10% from the nominal, the current value depends on the power conveyed along the line to the load sites and, therefore, on the power consumption. The line current can thus vary substantially from hour to hour, and even from day to day. The electromagnetic field environment of a power transmission line thus exhibits a steady electric field and a time-varying magnetic field.

The electromagnetic fields to which humans standing under a line may be exposed are those existing close to ground level, up to 6 or 7 ft above ground. In this region, the electric field of an ac transmission line is pulsating sinusoidally with time,

$$E = E_m \sin(2\pi f) t \hat{y}, \tag{1}$$

where y is a unit vector perpendicular to ground and f is the line frequency in hertz. The magnetic field is of constant amplitude, rotating in space at a constant speed, f.

$$B = B_m \cos(2\pi ft + \Theta) \hat{x} + B_m \sin(2\pi ft + \Theta) \hat{y}, \tag{2}$$

where x is a unit vector parallel to ground and perpendicular to the line direction, which is taken to be the z-direction. Theta (Θ) is an angle which depends on the characteristics of the electrical load at the end of the line. This type of field is said to be circularly polarized.

Under contract with the New York State Department of Health, construction was undertaken at the University of Medicine and Dentistry of New Jersey, in Newark, of an exposure system capable of simulating the electromagnetic conditions described above. The ranges targeted were 100 kV/m, rms, for the electric field and 10 G, rms, for the magnetic field. From the outset, the authors decided to design a system flexible enough to use in studies requiring various experimental exposure conditions.

MAGNETIC FIELD SYSTEM

Equation (2) shows that the magnetic field has two spatial components, perpendicular to one another, which can be produced by two sets of coils with orthogonal axes. The 90° phase shift may be achieved by energizing the coils of one axis from the line voltage between phases b and c of a 3-phase utility system; the coils of the other axis are energized from the voltage of phase a to neutral, as depicted in Figure 1. The two 240-V variable autotransformers shown in the figure allow independent adjustment of the magnetic field intensity along each axis. Their settings are different even for equal field intensities because the line voltage, V_{bc}, is 73% larger than the phase voltage, V_a. For a 120/208-V supply,

$$V_a = 170 \sin 2\pi ft \text{ and} \tag{3}$$

$$V_{bc} = 294 \sin (2\pi ft - \pi/2). \tag{4}$$

Capacitors, C, are used to compensate for the low power factor of the coils, thus reducing considerably the currents drawn from the autotransformers.

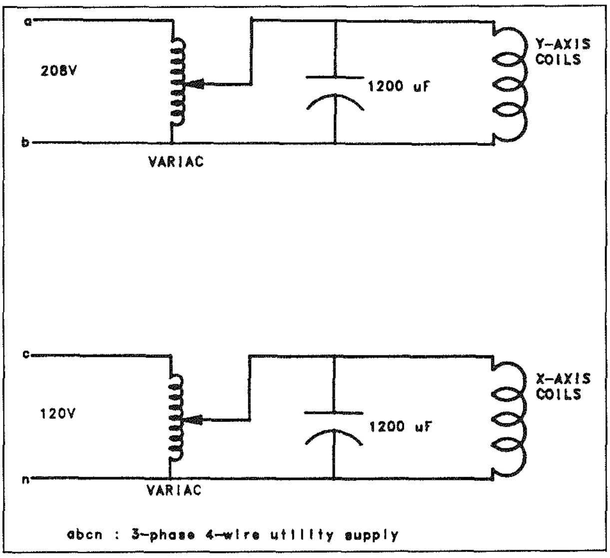

Figure 1. Basic Connections of Magnetic Field Exposure System. Three-phase supply provides orthogonal-phase voltages needed to create a circularly polarized field. Capacitor compensation reduces current demand on supply.

Elliptically polarized fields, which exist at some distance from a transmission line, may be produced by adjusting the autotransformers so as to have the ratio of the magnetic-field intensities along the two axes equal to the ratio of the major-to-minor axis of the ellipse.

Design

The design is based on the assumption that the coil resistance is small in relation to its reactance. The magnetic field is thus directly related to the voltage, V, applied to a coil by Faraday's Law:

$$V = 2\pi f N \emptyset, \tag{5}$$

where N is the number of turns of the coil, and $\emptyset$ is the total magnetic flux going through the coil. Thus, if the three coils shown in Figure 2 have the same number of turns and are supplied with the same voltage, they will be linked by the same flux.

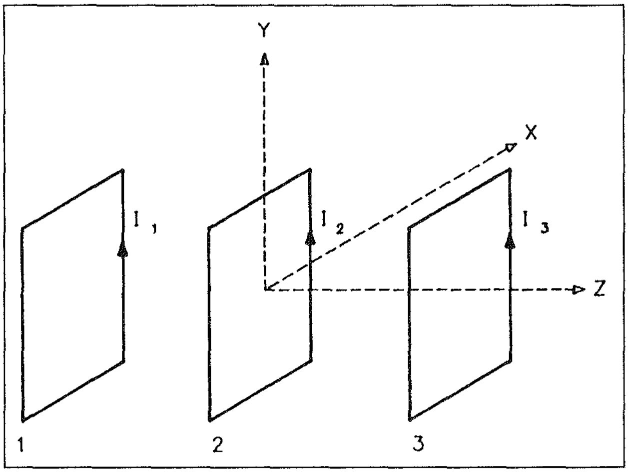

Figure 2. Coils Parallel to xy-Plane Create Main Magnetic Field Along z-Axis.

The flux linking a coil is not due solely to its own current, because part of the magnetic flux created by the current in the other coils also goes through that coil. The closer the coils, the larger the mutual flux linkage and, thus, the smaller the current through each coil. Thus, current I_2 in Figure 2 will be smaller than I_1 and I_3. Due to symmetry, I_1 is equal to I_3.

We then investigated the field created by a rectangular coil at any point in space. Consider a conductor running parallel to the y-axis at a height, h, above the xy-plane, as shown in Figure 3, with a current, I. The coordinates of the conductor extremities are (a,-b,h) and (a,b,h). At any point in space P(x,y,z), the resulting magnetic flux density is

$$B = \frac{0.001\, I}{d^2} \left[(x-a)\hat{z} - (z-h)\hat{x} \right] (\cos\beta - \cos\alpha), \tag{6}$$

where

$$d = \left[(x-a)^2 + (z-h)^2\right]^{1/2}, \tag{7}$$

which equals the distance from field point to conductor.

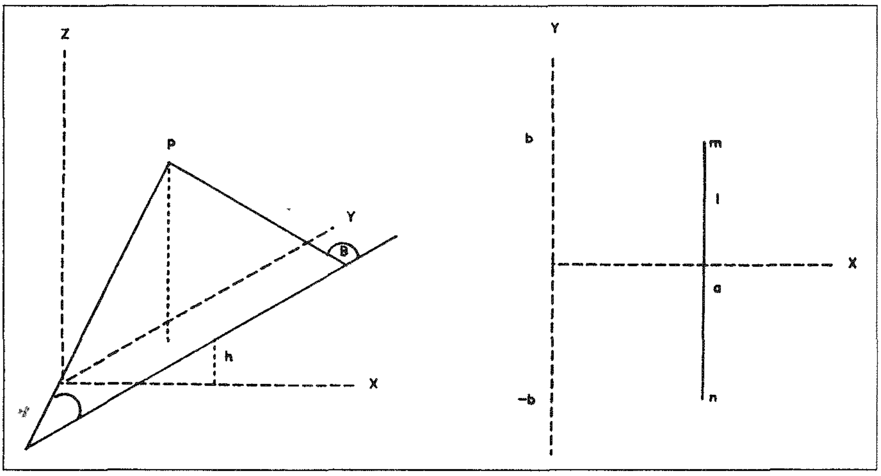

Figure 3. Current I in a Conductor Lying Parallel to the xy-Plane, at a Height h About It. The left figure is an isometric view of this conductor, showing its space relation to a field point, P.

α,β = angles formed by directional vectors from conductor extremities to P with respect to the y-direction.

B is in gauss if all dimensions are in meters. If the current direction is provided by the sign of I, β is always the angle at the extremity having the larger y-value.

Applying Equation (6) to the coil of Figure 4, we obtain

$$\begin{aligned} B = {} & \frac{0.001\,I}{d_1^2}\left[(z-h)\hat{y} - (y-b)\hat{z}\right](\cos\beta_1 - \cos\alpha_1) - \\ & \frac{0.001\,I}{d_2^2}\left[(x+a)\hat{z} - (z-h)\hat{x}\right](\cos\beta_2 - \cos\alpha_2) + \\ & \frac{0.001\,I}{d_3^2}\left[(z-h)\hat{y} - (y-b)\hat{z}\right](\cos\beta_3 - \cos\alpha_3) + \\ & \frac{0.001\,I}{d_4^2}\left[(x-a)\hat{z} - (z-h)\hat{x}\right](\cos\beta_4 - \cos\alpha_4) \end{aligned} \tag{8}$$

where

$$d_1^2 = (y-b)^2 + (z-h)^2 \tag{9}$$

$$d_2^2 = (x+a)^2 + (z-h)^2 \tag{10}$$

$$d_3^2 = (y+b)^2 + (z-h)^2 \tag{11}$$

$$d_4^2 = (x-a)^2 + (z-h)^2 \tag{12}$$

$$\cos\beta_1 = \frac{x-a}{\left[(x-a)^2 + d_1^2\right]^{1/2}} \tag{13}$$

$$\cos\beta_2 = \frac{y-b}{\left[(y-b)^2 + d_2^2\right]^{1/2}} \tag{14}$$

$$\cos\beta_3 = \frac{x-a}{\left[(x-a)^2 + d_3^2\right]^{1/2}} \tag{15}$$

$$\cos\beta_4 = \frac{y-b}{\left[(y-b)^2 + d_4^2\right]^{1/2}} \tag{16}$$

$$\cos\alpha_1 = \frac{x+a}{\left[(x+a)^2 + d_1^2\right]^{1/2}} \tag{17}$$

$$\cos\alpha_2 = \frac{y+b}{\left[(y+b)^2 + d_2^2\right]^{1/2}} \tag{18}$$

$$\cos\alpha_3 = \frac{x+a}{\left[(x+a)^2 + d_3^2\right]^{1/2}} \tag{19}$$

$$\cos\alpha_4 = \frac{y+b}{\left[(y+b)^2 + d_4^2\right]^{1/2}} \tag{20}$$

Consider now three identical coils, as in Figure 4, lying coaxially at $z = -h$, O, h and carrying currents I_1, I_2, I_3, respectively. Equation (8) may now be written for each of the coils and these equations summed up to obtain the net flux density in space. Integrating the z-component of this net B over the surface of each coil produces the flux linkages $\emptyset_1$, $\emptyset_2$, $\emptyset_3$ as linear functions of I_1, I_2, I_3. Since all fluxes are to be equal, say, to $\emptyset$, three linear equations may then be set up in four unknowns, $\emptyset$, I_1, I_2, I_3:

$$0 = -\O + a_1I_1 + a_2I_2 + a_3I_3, \tag{21}$$

$$0 = -\O + b_1I_1 + b_2I_2 + b_3I_3, \tag{22}$$

$$0 = -\O + c_1I_1 + c_2I_2 + c_3I_3. \tag{23}$$

The value of 0 is determined from Equation (5), after selecting adequate values of V and N. The necessary fourth equation is provided by the expected net value of the magnitude of B at the origin, B_O:

$$B_O = d_1I_1 + d_2I_2 + d_3I_3. \tag{24}$$

The solution of equations (21) to (24) provides the currents that flow in each coil.

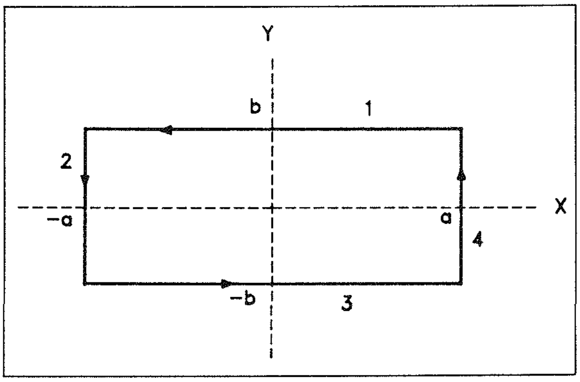

Figure 4. One of the Coils Shown in Figure 2, Lying Parallel to the xy-Plane and Carrying a Counterclockwise Current. Its axial magnetic field is in the z-axis direction.

A computer program was devised to investigate the field uniformity in a cage of dimensions 36 x 26 x 20 cm. For a coil size of 6 x 6 ft, I_3 equal to I_1, and I_2 = 75% of I_1, the resulting field values are shown in Table 1. These values are referred to a point at the center of the system (origin). The field within the cage is uniform to better than 5%, a fact which was verified experimentally. Eleven meters along the axis of the coils, the field drops to less than 0.2% of the value in the cage, also verified experimentally.

Construction

The coils were built on wooden frames of inner dimensions 6 x 6 ft and 6 x 6.8 ft for the vertical and horizontal fields, respectively. Each frame was actually made up of two contiguous frames, each carrying eight parallel 58-turn windings made of #20 AWG magnet wire. Each layer of wire was sprayed with insulating varnish in order to strengthen it electrically. To limit vibration and hum to an acceptable level, the windings were tied very tightly against the wooden frames, by means of lockable nylon straps, at distances of 6 in.; 12 or 13 ties to a side. Great care was taken in aligning the frames and assuring the orthogonality of the two magnetic axes.

TABLE 1 Magnetic Field Distribution

Location, m (x,y,z)	Field, % (x,y,z)	Location, m (x,y,z)	Field, % (x,y,z)
0 1,0 2,-0 1	-0 2,-0 4,99 4	0 1,0 2,0 1	0 2,0 4,99 4
0 27,0 1,-0 1	-0 8,-0 2,99 6	0 27,0 1,0 1	0 8,0 2,99 6
0 44,0 2,-0 1	-2 7,-0 4,102 1	0 44,0 2,0 1	2 7,0 4,102 1
0 27,0 3,-0 1	-0 8,-1 0,100 6	0 27,0 3,0 1	0 8,1 0,100 6
0 1,0 2,0 24	0 4,0 8,98 3	0 1,0 2,0 44	0 2,0 6,96 7
0 27,0 1,0 24	1 3,0 4,98 3	0 27,0 1,0 44	0 6,0 2,96 5
0 44,0 2,0 24	3 8,0 8,98 1	0 44,0 2,0 44	0 6,0 4,94 4
0 27,0 3,0 24	1 2,1 5,98 3	0 27,0 3,0 44	0 6,0 6,96 0
0 1,0 2,0 58	0 4,0 4,96 3	0 1,0 2,0 78	1 0,1 7,95 0
0 27,0 1,0 58	0 2,0 4,96 5	0 27,0 1,0 78	0 0,0 0,95 2
0 44,0 2,0 58	1 9,0 4,96 2	0 44,0 2,0 78	1 0,1 7,101 5
0 27,0 3,0 58	0 2,0 0,96 7	0 27,0 3,0 78	2 1,2 1,98 5
0 0,0 0,2 0	0 0,0 0,26 7	2 0,0 0,0 0	0 0,0 0,-6 5
0 0,0 0,4 0	0 0,0 0,3 3	4 0,0 0,0 0	0 0,0 0,-1 3
0 0,0 0,6 0	0 0,0 0,1 0	6 0,0 0,0 0	0 0,0 0,-0 4
0 0,0 0,8 0	0 0,0 0,0 4	8 0,0 0,0 0	0 0,0 0,-0 2
0 0,0 0,11 0	0 0,0 0,0 2	11 0,0 0,0 0	0 0,0 0,-0 1

The measured X/R ratio of a coil at 60 Hz was 7.3, corresponding to a power factor of 0.135. Power factor compensation was achieved by shunting the set of coils of each axis with a 1200-μf capacitor.

In spite of their difference in size, the coils that produce the horizontal and vertical fields have the same power factor. The phase shift between these two fields therefore depends on the phase shift between the applied voltages. The latter are at 90° with respect to one another (Figure 1). Oscilloscope observations of the fields, using coil probes, confirmed the desired phase shift of 90°

Because of their high X/R ratio, the coils tend to act as low-pass filters, attenuating the harmonics present in the utility supply. This fact was also verified experimentally by observing on an oscilloscope the voltage induced in a coil probe. The waveshape observed was nearly sinusoidal in spite of the harmonic enhancement effected by the probe. Spectrum analyzer measurements showed a distortion of -53 dB with respect to fundamental.

Experimentation with ordinary 1/8-in steel plates for shielding proved their total ineffectiveness. Shielding could be obtained, however, using high permeability materials, such as μ-metal, albeit at considerable expense (estimated at over $50,000). Shielding of the sham-exposure assembly from the energized one was therefore achieved by distance, the centers of the two assemblies lying 35 ft apart.

ELECTRIC FIELD SYSTEM

The electric field was basically obtained from the application of 30 kV to parallel plates, 0.3 m apart. The closest distance from plate to wall was 1.2 m. Computer mapping of the field between the plates, assuming the wall to be a conducting grounded surface, showed no appreciable difference in fringing, in the neighborhood of the edges, between the following two cases: (a) one plate grounded and the other at 30 kV; (b) one plate at -15 kV and the other at + 15 kV, (Potdar, 1984). Option (b) was adopted because it poses less of a corona and insulation problem. Two Hypotronics (Brewster, NY) high-voltage test sets, rated 0-15 kV, 40 mA continuous, were used with their low-voltage supply wired so as to produce high voltages 180° apart (in time opposition). In actual use in the system described below, the output current from these sets is 13 mA at 15 kV.

Figure 5 shows the parallel-plate configuration used to create the electric field. It comprised four double plates, and one single plate at the top; only the double plates served as shelves for animal cages. The upper part of the each double plate had four rectangular holes into which the cages were placed (Figure 6). Cages rested on the lower part of these double plates. Since all parts of a double plate were connected, the inner space was field-free. All intraplate wiring could therefore be accommodated in that space without any likelihood of corona; in fact, the wire used was of the inexpensive, low-voltage kind commonly available. This space also allowed anchoring of the high-voltage cables without any concern for corona. Nevertheless, all high-voltage cables were terminated with adequate stress cones and corona balls.

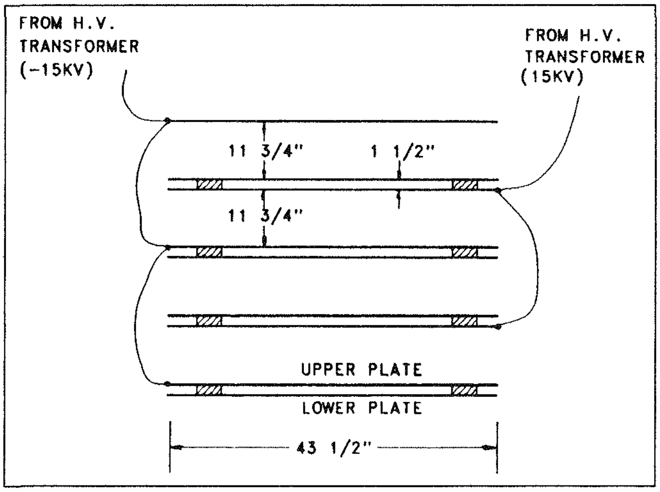

Figure 5. Electric-Field Exposure System, Consisting of Four Double-Plate Electrodes and a Top Single-Plate Electrode. The spacers between the plates of a double-plate electrode have conducting surfaces, thus providing electrical continuity to the plates. The space between the plates, away from edges, is basically field-free.

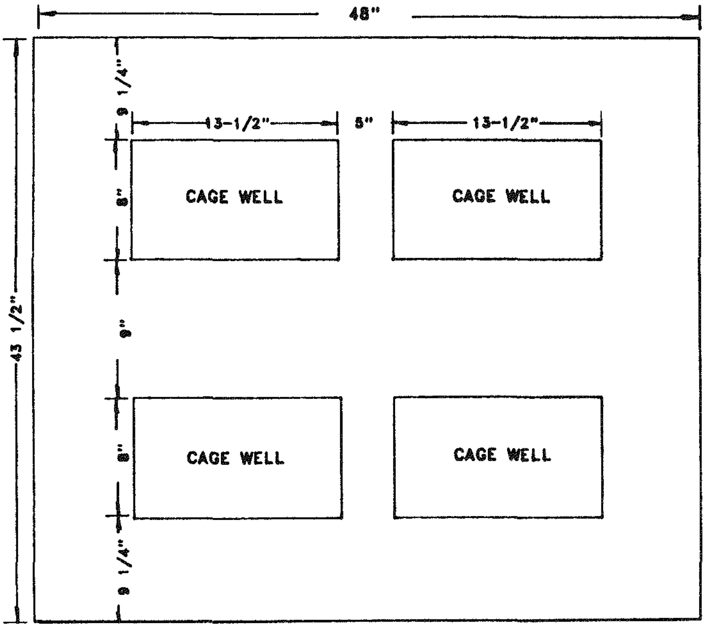

Figure 6. Upper Part of a Double-Plate Electrode, Showing Four Rectangular Holes. With no holes in the lower plate, four wells are formed, into which cages are dropped.

Based on the measurements made by Kaune (1981), cages were kept one cage-width apart in order to prevent a shielding effect of one animal on the other.

The various shelves were supported on 3-in. PVC pipes. A 1-in. PVC pipe, used to supply water from a common bottle, ran through the inner space of the double plates, and was tapped with steel Lixits® (Systems Engineering, Napa, CA) each extending through a hole in a cage. A separate bottle was used for each voltage, i.e., two bottles in all. Connection of the Lixits to the PVC pipes allowed isolation from the plate, as well as isolation of one animal from another. In order to limit the current flow as an animal used the Lixit, the latter was connected through a 10-kΩ resistor to its double plate.

Since the electric field assembly was exposed to the magnetic fields, it was essential to keep eddy currents as low as possible. Unrestrained eddy currents would not only cause heating effects, but would also affect the magnitude, uniformity, and phase of the magnetic field, which was perpendicular to the plates. Cage lids were therefore made of plexiglass, and the plates (electrodes) of 1-in. plywood, covered with two coats of conducting paint. Great care was taken in preparing the electrode surfaces, eliminating all sharp edges and painting them to a smooth finish.

To provide contact of the caged animal with the electrode, a metal grid, resting about 1 in. above the plastic cage bottom, was installed at the same level as the upper plate of the double-plate assembly (Figure 7). Electrical contact between the grid and the electrode was made by means of an alligator clip inserted through a hole drilled near the cage bottom and clipped to a leg of the grid. The alligator clip was connected to the electrode with a low-voltage wire running in the inner space of the double-plate assembly. Since the clip and its lead hardly emerged from that inner space (and, at any rate, were shielded by the grid), corona was avoided.

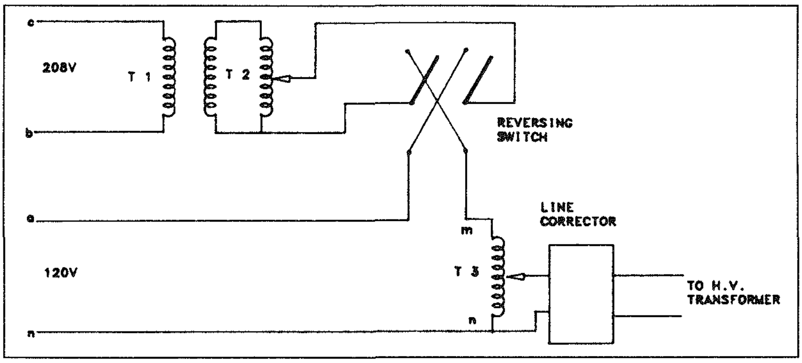

Figure 7. Cage Positioning in Electrode Well. The size of a well is large enough to allow a Lixit® to be inserted in hole drilled in cage wall. Through another hole in cage, a wire terminating in an alligator clip is inserted and connected to metal grid lying inside cage.

With the electrodes lying horizontally, the electric field was in the y-direction. Phase adjustment of the electric field relative to the y-axis magnetic field was carried out using the circuit shown in Figure 8; T1 is a 240/120-V isolation transformer; T2 and T3 are variable autotransformers. Since the voltage from c to b is in quadrature with the voltage from a to n, addition of a portion of V_{bc} to V_a affects much more markedly the phase of their sum, V_{mn}, rather than its magnitude. Thus, T2 was used to adjust the phase of V_{mn} and T3, its magnitude. The reversing switch enabled positive and negative adjustments to the phase angle. In this manner, phase corrections of up to ± 40° were possible.

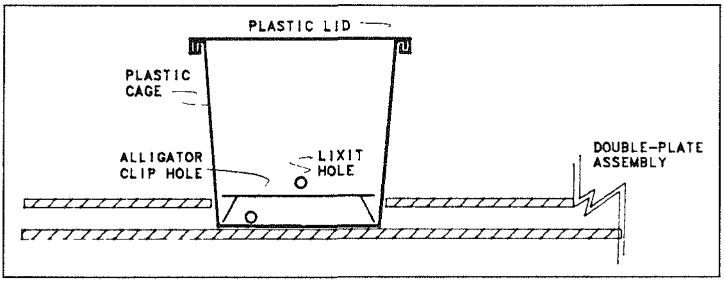

Figure 8. Electric Circuit Supplying High-Voltage Transformer. The upper part of the circuit enables phase corrections to be made to the main voltage (a-n), energizing the high-voltage transformer. The line corrector serves to filter and regulate the resulting voltage.

The exposed animal standing in its cage on a metal grid was thus contact-connected to the electrode just below it. The animal was coupled only to the electrode just above it through the medium of the electric field; in other words, it was capacitively coupled to the upper electrode. This coupling favors harmonics at the expense of the fundamental, as observed on an oscilloscope, using a flat probe. The harmonics originated in the utility voltage and varied considerably during the day. Furthermore, some of these harmonics were amplified by the resonance between the inductance of the high-voltage transformers and the interelectrode and high-voltage-cable (about 80 ft) capacitances. For these reasons, a line corrector was interposed between the high-voltage transformers and their supply. The corrector served the dual purpose of suppressing the harmonics and regulating the voltage input to the transformers against line-voltage variations.

Electric-field uniformity within a cage was experimentally found to be within 2% of the undisturbed parallel-plate value, degrading to 5% near Lixits and cage walls. The most serious perturbation of the field occurred when the animal was placed in the cage (Kaune, 1981). Based on the analytical-difference approach to the solution of Laplace's equation (Potdar, 1984), a computer calculation was made of the equipotential surfaces within the cage with animals present (Figure 9). As can be seen from the figure, for a uniform field, the lines are evenly spaced; for field enhancement, the lines are more dense.

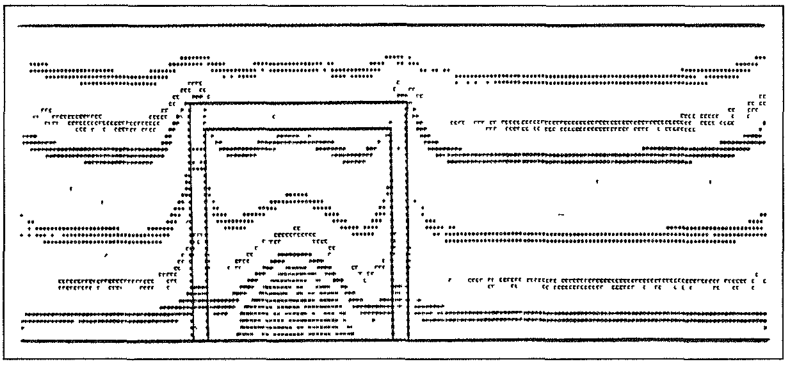

Figure 9 Potential Distribution Between Electrodes in Cage Region Equipotential surfaces plotted reveal enhancement of electric field around rat.

No visible or audible corona was observed, at 100 kV/m of undisturbed field, either in the presence or absence of animals.

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HIGH-INTENSITY, 60-Hz ELECTRIC FIELD EXPOSURE FACILITY FOR NONHUMAN PRIMATES

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ABSTRACT

The Department of Energy (DOE) has constructed at Southwest Research Institute an exposure facility designed to assess the effects of electric fields on nonhuman primates. A series of four experiments has been planned. Using operant methods for perceptual studies, the thresholds for detection and avoidance of electric fields will be measured. In addition, the effects of electric fields on operant and social behaviors will be determined. The facility consists of a prefabricated metal building 15 m wide by 43 m long. Contiguous to the building are two smaller structures, providing rooms for transformer controls, computers, and observation areas. The interior of the main structure is divided into two equivalent, but electrically isolated, areas by a grounded wire-mesh screen so that field-exposed and sham-exposed groups may be studied simultaneously. Each half of the facility is equipped with its own transformer, capable of producing a homogeneous, vertical electric field with an unperturbed field strength of at least 60 kV/m. Within each exposure area is a grounded steel grate measuring 5 by 8 m. Located 2.5 m above each grate is an electrical bus to which screen has been attached to form a plate. The plates are suspended from overhead structural members, using conventional high-voltage insulators. Each grate is large enough to support six individual fiberglass cages to house subjects in operant experiments and one larger fiberglass cage capable of housing eight animals as a social group. Mounted on each operant cage is a response panel constructed of materials which do not appreciably perturb the electric field. Prior to initiation of each experiment, the facility will be thoroughly characterized in terms of electric field homogeneity and related variables.

RATIONALE

As part of its extensive research program on 60-Hz bioeffects, the Department of Energy (DOE) is using the baboon (superspecies *Papio cynocephalus*) as a surrogate for the human in studies of 60-Hz electric fields. To increase confidence in the extrapolation from experiments with animal models to conclusions about the probable effects of field exposure on humans, it is prudent to conduct some experiments with the nonhuman primate. This model provides the greatest possible similarity to the human in physiologic function, behavioral complexity, and body conformation and posture. Availability of data from three sources (numerous experiments with nonprimate species, a few experiments with nonhuman primates, and limited studies with human subjects) will maximize the value of the risk-assessment process to be performed ultimately for DOE.

A series of four behavioral experiments using baboons as subjects is to be conducted at Southwest Research Institute (SwRI). Using operant methods for perceptual studies with primates, the thresholds for detecting electric-field presence and for avoiding electric-field exposure will be measured. In addition, the effects of chronic exposure to high-intensity, 60-Hz electric fields on the performance of two operant tasks and on social behavior will be determined.

OBJECTIVE

Following performance of a preliminary behavioral study in a prototype facility (Feldstone et al., 1981; Rogers et al., 1984), DOE and SwRI personnel designed and had constructed, in San Antonio, an exposure facility. It is capable of producing vertical, homogeneous, 60-kV/m (unperturbed field strength) electric fields to be used to complete the nonhuman primate research program.

EXPOSURE FACILITY

Building

The prefabricated metal building (Figure 1) encloses an area 15 m wide by 43 m long; the eaves and roof peak are 6 and 9 m high, respectively. Adjacent to the exposure building are two smaller structures, providing rooms for transformer controls, computers, and observation areas (Figure 2). The interior of the main structure is divided into two equivalent, but electrically isolated, areas by a grounded wire-mesh screen so that experiments can be conducted simultaneously with field- and sham-exposed groups.

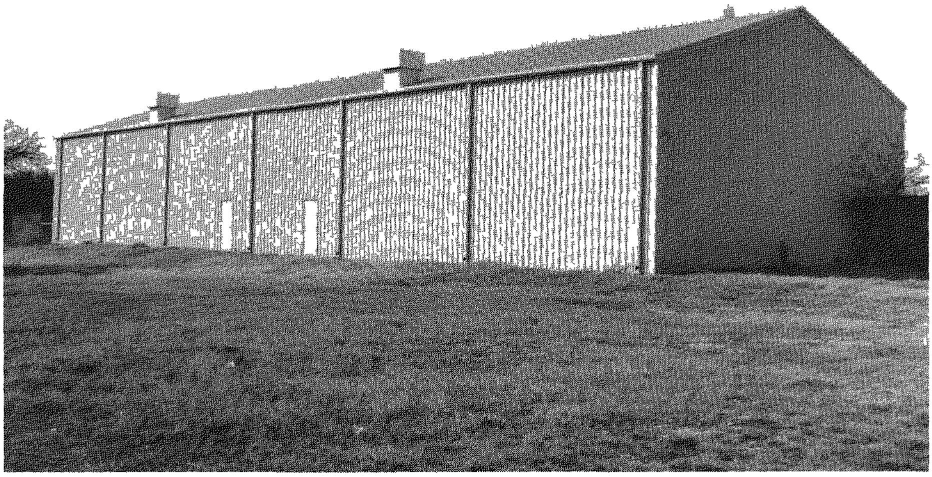

Figure 1. Exterior View of High-Voltage Primate Exposure Facility Constructed by the Department of Energy at Southwest Research Institute

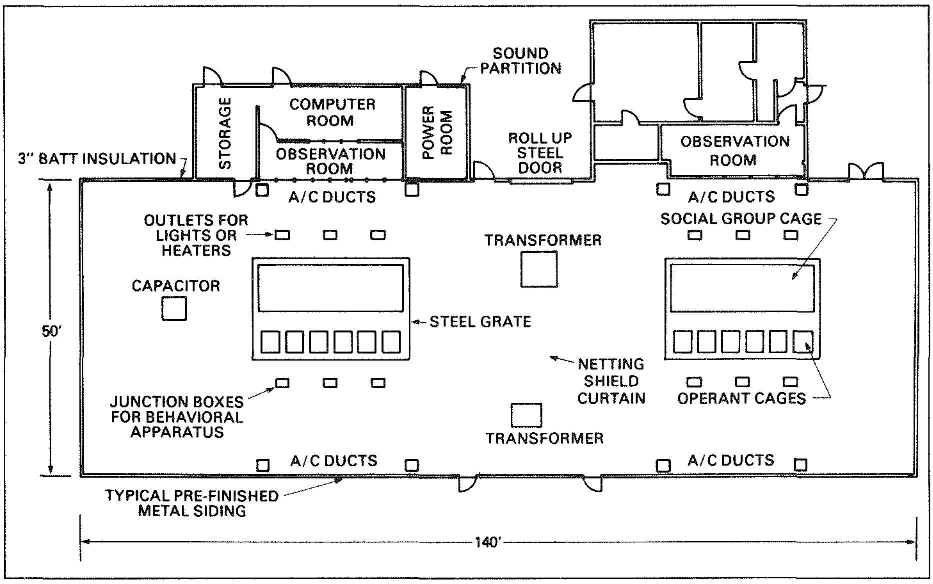

Figure 2. Floor Plan of the High-Voltage Primate Exposure Facility.

Ground for the system was established using 19-mm-diameter copper rods, each 5 m long, driven into the earth; a concrete floor, containing all of the conduits, equipment grounding points, and plumbing, was then poured. The floor also anchors the steel girts and beams comprising the structural skeleton of the prefabricated metal building. The interior surfaces of the prefinished steel roof and wall panels are covered with an 8-cm layer of vinyl-faced thermal insulation. A light-gauge wire mesh is used to hold the insulation in place and to electrically shield the interior of the building. The same wire material forms the curtain dividing the facility into two independent halves.

Ventilation is provided by intake fans, which produce a positive pressure within the facility; exhaust is through the continuous vent at the peak of the roof. The air handlers can produce 11 air exchanges per hour; no air is recycled. The air-conditioning system has sufficient capacity to reduce the temperature of ambient air by 10°C. Winter heating for the animals is provided by radiant heaters.

Separate, sound-insulated rooms house the transformer control panels, and a single control room contains the microcomputers used to control field operation and behavioral apparatus. Each portion of the facility includes an isolated observation room to allow systematic, quantitative behavioral study of social behavior.

Electric Field Generation Transformers

Each half of the facility is equipped with its own transformer: at one end, a high-voltage transformer, rated at 200,000 V, 200 mA, single-phase, and at the other end, a new, high-voltage transformer rated at 300,000 V, 2,000 mA, single-phase. The latter is a modular, resonant, tuned system designed to reduce harmonic content. Both transformers are located at the center of the longitudinal axis of the test facility. Either transformer can be energized at any time, or both may be energized at once. Both portions of the facility will be used as active exposure areas during some portions of the research program.

Bus and Grate. Located at the center of each exposure area is a steel grate measuring 5 by 8 m (Figure 3). The grates are mounted 38 cm above a section of the floor which is isolated from the main floor of the facility and slopes to sewer drains to allow removal of animal wastes. Both grates are grounded. Located 2.5 m above each grate is an electrical plate composed of a 6.4-cm-diameter aluminum conduit to which a fine-mesh aluminum screen has been attached to form a plate. The bus is suspended from the ceiling, using steel cables and conventional high-voltage insulators. We have found that placing 1.2-m lengths of the 6.4-cm conduit above the insulators to cover the ends of the cables and increase the radius of the suspension system effectively prevents formation of corona above the insulators and guard rings at a tested field strength of 72 kV/m. The side edges of the bus, which are 30 cm lower than its central plane, extend 30 cm beyond the grate. Electric fields are generated between bus plate and ground grate.

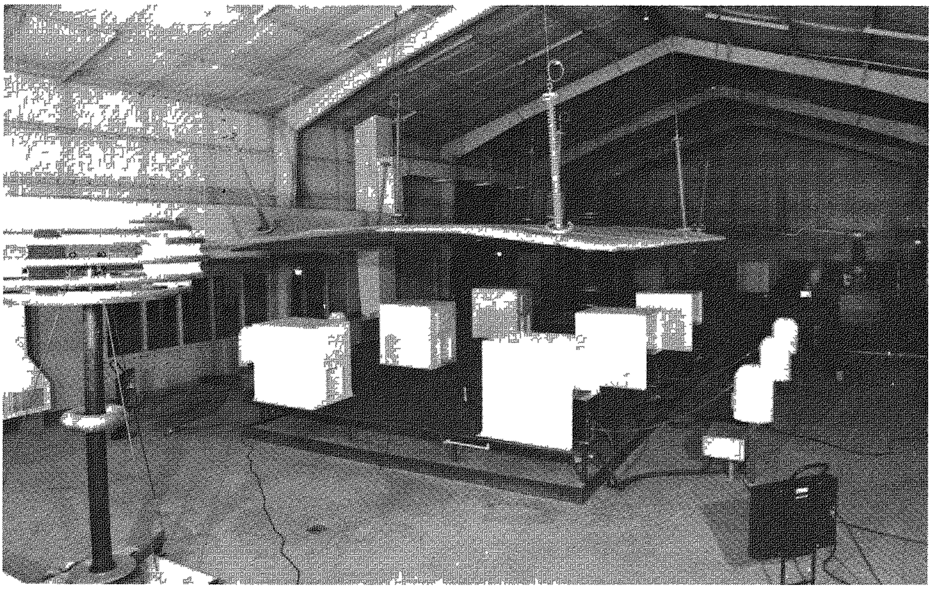

Figure 3. Interior View of the High-Voltage Primate Exposure Facility. The capacitative load for the 300-kVA transformer is in the immediate foreground. Behind it are visible the bus, grate, operant cages, corona guards for pellet dispensers, the observation room, and some of the nonmetallic ventilation ducts and radiant heaters for the west half of the facility. In the background, the screen dividing the facility in half and the east exposure area are also visible.

Field Probes. Optically coupled electric-field probes are used to map electric field characteristics (Spiegel et al., 1979). Two models (4 or 8 cm in diameter) of the spherical dipole probe are being used. A current-injection method is used to calibrate and to determine the frequency response of the 8-cm dipole, measured to the 16th harmonic. The band width of the probe is about 700 Hz. Because current-injection calibration is not possible with the 4-cm probe, its frequency response has not been determined. The 4-cm probe is calibrated using 1.2-m^2 parallel plates with a spacing of 25 cm. The transformer used to drive the plates has a 120-V primary and a 15-kV center-tapped secondary. With this system the probes can be calibrated with an accuracy of 3%; measurement error in field-mapping is 2%, therefore total measurement error is 5%.

Field Control. During behavioral experiments, a flat plate probe (Misakian, 1984), placed at the center of each grate to avoid variations in perturbed field strength produced by animal movements, will be used to continuously measure the electric field strength. In addition, a signal proportional to exciter voltage will be used to provide feedback control over field-strength. Microcomputers record field-strength data and control transformer operation. A separate relay system prevents exciter voltage from exceeding a preselected value in the event of malfunction of probe, interface electronics, or microcomputer.

Field Characteristics. Initial data indicated good field homogeneity across the grate from front to back, but homogeneity at the ends of the grate was poor, making total variability approach 15%. With no cages present, electric-field measurements were made along a line 0.6 m above the grate and 0.9 m in from the edge of the grate. Over a distance of 3 m, readings did not vary by more than 1%. Over the center of the operant cage at the edge of the grate, the field strength was 96.8% of the reference value, but at the edge of the cage nearest the end of the grate, the value had dropped to 85.1%. To correct this, the ends of the bus were extended 0.6 m and lowered in the same manner as used for the sides of the bus. Preliminary data suggest that the field produced by the modified bus is satisfactory. However, the entire field will be carefully mapped once again. Using the 8-cm probe to make the measurements, the only measurable harmonic distortion of the electric field in the exposure area was at 120 Hz, where the signal was down 59.7 dB from the fundamental. Thus the total harmonic distortion of the field produced by the series resonant transformer was 0.1%.

Safety Procedures. Facility operation is under the supervision of an electrical engineer; the behavioral study observers will not have access to the transformer control panels and will not be informed concerning the details of field exposure position and schedule. Principal safety features include provision of warning lights and signs, installation of interlocks on doors, and institution of a restricted access system based on hierarchical possession of controlled keys.

Cages

Fiberglass cages of proven design house the baboons; the cages, which have no floor, are bolted to the grate, causing the animals to live on the grate itself. Each grate is large enough to support a social cage measuring 7.3 m long, 1.8 m deep, and 1.2 m high and capable of housing six animals in a group. The social cages will face the observation areas. Water is provided in all cages by Lixit® (Hazelton Systems, Aberdeen, MD) valves projecting 4 cm above the grate. The electric current received by a baboon as it drinks will be measured and minimized by addition, if necessary, of resistors between the metal nozzle and ground. To avoid electric shocks when returning to the grate from an ungrounded position, the cages do not contain perches for the animals.

Each grate will also support six individual cages for operant subjects (Figure 4) The operant cages measure 1 2 m high by 1 0 m wide by 1 0 m deep and thus provide the space recommended by the National Institutes of Health Guide to Animal Care (NIH, 1978) for medium-sized baboons The operant cages will face away from the observation areas, but a television camera mounted along the far wall in each half of the facility allows visual monitoring of the animals The cameras can be moved along the row of cages and can be tilted and turned by remotely controlled motors During the initial part of the research program the social cages will not be used, and three operant cages will be placed along each edge of the grate

Figure 4 Close-up View of Individual Cage with Response Panel A plexiglass box protects the three levers in cylinders Fiberoptic links detect lever pulls, and the three light pipes, illuminated by incandescent lamps located beneath the grate, provide visual cues

Cage Shielding Effects

Electric-field measurements in the center of an operant cage indicated an attenuation of about 4.3%. (A remotely located probe served as the reference; normalized to reference values, the reading within the cage was 95.7% of the "no cage" value.) Movement of the probe toward and away from the side of a cage showed that the cage walls produced an effect on field strength extending for about 15 cm. With a metallic Faraday shield over a cage, the effect on electric field strength at the center of the adjacent cage was negligible. The field strength at the center of the cage covered by the Faraday shield was less than 100 V/m, the approximate minimum sensitivity of the probe. These data suggest that the cage spacing proposed for Projects 1 and 2 (see below) is adequate to avoid intercage interference.

Behavioral Study Equipment

Each operant subject will have a response panel, constructed of materials which do not perturb an electric field, mounted on its cage front. The panel includes three manipulanda with fiberoptic circuits to detect lever pulls, three cue lights illuminated by light pipes, and a hopper to receive food pellets. Pellet dispensers mounted 1.2 m above the floor and 1.8 m away from the grate will provide banana-flavored food pellets as rewards. All electrically conducting components of the behavioral system are mounted well beyond, and below, the grate. A microcomputer controls the behavioral apparatus and records animal responses.

Environmental Monitoring

Artificial lights around the inside periphery of the building are controlled by a timer. Temperature at the level of the grates is recorded continuously on remote pen recorders; temperature and relative humidity at various locations within the facility will be sampled using portable detectors. On a periodic sampling schedule, ammonia and ozone levels will be measured, using conventional air-quality monitors. A corona detection system is built into the transformer controls for routine monitoring of system performance. Experience indicates that this system allows detection of corona at field strengths approximately 5 kV/m lower than can be detected by visual or auditory inspection.

An extensive facility survey, including measurements with transformers on and off, as well as with and without the presence of animals, will occur at the beginning and conclusion of each experiment, and other measurements will be made at regularly scheduled intervals to document system operation during experiments. Variables to be measured include electric field strength and uniformity, field perturbations produced by cages, harmonics, corona, sound, grate vibration, drinking-water currents, temperature, humidity, and ambient ozone and ammonia concentrations.

PLANNED RESEARCH PROGRAM

Threshold Experiments

Aversion. The first project will evaluate the potential aversive character of exposure to 60-Hz electric fields by determining the threshold intensity which produces avoidance responses. A titration (or staircase) procedure based on the methods of Weiss and Laties (1970) will be used. Under computer control, field intensity will be increased at fixed temporal intervals. Animal responses will lower field intensity by a predetermined increment and time period. Statistical analysis of the record of field intensity maintained by an animal allows estimation of the threshold for field avoidance.

Detection. In the second experiment, the threshold intensity for detecting the presence of 60-Hz electric fields will be determined, using methods based on those employed by Stebbins (1970) for auditory research with monkeys. The animals will be trained to pull a lever to initiate test trials during which electric-field stimuli of various intensities will be presented for a few seconds. The animal will signal detection of the field by pulling another lever. If a field is present, a banana-flavored food pellet will be dispensed. If no field is present, a time-out period will occur to discourage guessing. (Blank trials will be presented to estimate the rate of guessing.)

Following training and preliminary assessment of thresholds, the Method of Constant Stimuli will be used to determine the field intensity detected 50% of the time. Five different stimuli, covering the range from essentially 0 to 100% detection, will be presented many times to provide data for statistical analysis.

The intrasubject stability and interanimal consistency of the thresholds will be determined. These experiments, which are within subject in nature, will each have six subjects. The two experiments will be performed together, each in one-half of the facility. It will take about a year to complete the experiments once the facility is complete and characterized.

In both experiments, special test sessions will be used to verify that the behavior is controlled by the electric field and not by some unrecognized artifact associated with electric-field generation. For example, thresholds will be determined using both functional Faraday shields constructed of wire mesh and "dummy" Faraday shields constructed of fiberglass screen similar in appearance to the wire mesh. Knowledge of the detection and aversion thresholds will be used to help plan and evaluate the other two projects and to assist in relating results from these experiments to other results with rodents, swine, monkeys, and humans.

Behavioral Toxicology Experiments

Design. Two other projects will assess the effects of chronic exposure to high-intensity electric fields on operant and social behavior. The design for these projects, which will be performed concurrently with different sets of subjects, includes baseline, exposure, and postexposure periods, each 8 wk in duration. Each experiment will include a sham-exposed group of monkeys, which will be tested simultaneously with the exposed group; thus, both within-subject and between-subject comparisons will be made. Two experiments will be done: in the first, experimental animals will be exposed to 60 kV/m for 12 hr per day, 7 days per wk. The field intensity for the second experiment will depend upon results of the first.

Operant Behaviors. In each of the operant experiments, 12 animals will be trained on both fixed ratio (FR) and differential reinforcement of low-rate responding (DRL) schedules until stable performance is demonstrated. Half the animals then will be assigned randomly to the exposed- or sham-exposed groups.

Although preliminary experiments at 30 kV/m (Rogers et al , 1984) detected few electric-field effects on operant behavior, some changes in behavior might be interpreted as indicating a field effect on timing of responses (Alternatively, the subtle alterations in some aspects of operant performance could have been mediated by sensory consequences of exposure to strong electric fields) The observation by Gavalas-Medici and Day-Magdelano (1976) that 7- and 75-Hz electric fields could affect (reduce interresponse times) the schedule-controlled behavior (DRL 5 with 2 5 sec limited hold) of monkeys and the operant effects detected in the preliminary studies provide part of the rationale for the proposed operant studies

Depending on field intensity, changes in operant behaviors related to field exposure might indicate a toxic effect Alternatively, interference with performance could result from other causes, such as distraction by cutaneous stimuli Interpretation of results will depend on the results of the entire program For example, if the detection threshold is 10 kV/m and the avoidance threshold is 20 kV/m, detection of operant effects at 60 kV/m, but not at 15 kV/m, would suggest an effect mediated by aversive sensory consequences However, if (hypothetically) similar disruption of operant behavior occurred at both 60 and 15 kV/m, a direct effect on the central nervous system might be suspected

Social Behavior Using the observational methods of primate ethology, the behavior of social groups of eight baboons will be measured Analysis will focus on "social stress" behaviors (tension, threat, attack, subordinate, affinitive, and approach), because alterations in these behaviors are important indicators of behavioral pathology Rogers et al (1984) discuss the methods used to collect and the processes used to interpret observational data on social behavior Preliminary experiments at 30 kV/m suggest that although some social behaviors were altered, usually only temporarily, by electric-field exposure, there was no indication of an adverse effect on the animals' normal social structure

ACKNOWLEDGMENTS

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A 60-Hz HUMAN EXPOSURE SYSTEM: DESIGN AND DOSIMETRY

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ABSTRACT

A facility has been constructed to permit double-blind experiments on the effects of 60-Hz electric and magnetic fields on human subjects. The square test room (2.45 m on a side) has the appearance of a typical office. Within the test area, a vertical, uniform, corona-free, 60-Hz electric field can be generated up to 16 kV/m. The uniform, two-axis, vertically rotating, magnetic field (H) has a maximum strength of 32 A/m (0.4 G flux density). Safety of participants and experimenters is assured by double-wall construction and by a series of safety interlocks. Mannequin tests used to determine the effect of clothing and experimental devices on total and segmental short-circuit current (I_{SC}) revealed shielding of 5.9%. A system for the continuous measurement of human I_{SC} that we developed was used for dosimetry, and as part of the control system, which allowed double-blind presentation of real and sham 60-Hz fields.

The use of high-voltage transmission lines in the vicinity of populated areas has stimulated a need to determine whether their associated electric and magnetic fields present any risk to human health and function. In order to do so, it is necessary to conduct a broad range of studies, from in vitro cellular experiments to epidemiological evaluations of risk. One important component of any comprehensive research program of this type is to examine, in double-blind studies, under highly controlled exposure conditions, the effects of electric and magnetic fields on human physiology, biochemistry, immunology, performance and daily function. As part of the New York State Department of Health Overhead Power Lines Project, a facility has been constructed which allows the double-blind presentation of electric and magnetic fields of known characteristics. Dosimetry, performance, physiology, and subjective data are collected. This paper describes the design and characteristics of the facility, and the results of experiments designed to evaluate some of its performance characteristics.

DESCRIPTION OF THE FACILITY

Physical Properties

The exposure room in the facility resembled a panelled office. A chair and footstool constructed of polyvinyl chloride (PVC) pipe and vinyl-covered cushions were positioned in the center of the room. The visual appearance of experimental environments can have profound effects on the participants, and every effort was made to reduce any fear or anxiety produced by the appearance of the room itself. The floor was carpeted, the walls had posters on them, and the room was softly illuminated.

The exposure room was 2.45 m on each side and 2.45 m high and was completely enclosed within another area which contained the field-generating apparatus. Access to the exposure room was through a 1-m-wide entryway, set 1 m back from the outer access area. The framework of the room was made of 5-cm PVC plumbing pipe set on a raised plywood platform. The inside walls were constructed of masonite coated with a simulated wood-grain finish and held with plastic fasteners to the supporting PVC structure. The ceiling was constructed of translucent acrylic panels supported on fiberglass "I" beams; incandescent lamps above the panels and the field generating structures provided illumination. Room air was conditioned by a dedicated, bi-directional temperature/humidity controller through a PVC duct system within the room walls. Figures 1 and 2 show the side and top views of the facility, respectively.

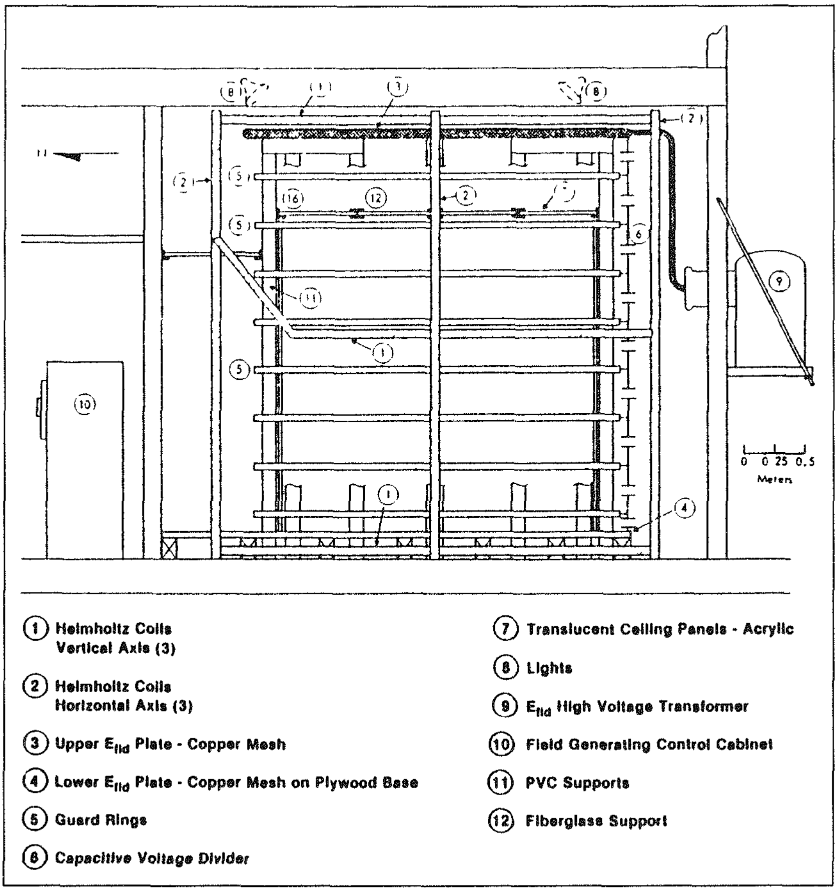

Figure 1. Side View of 60-Hz Human Exposure Chamber.

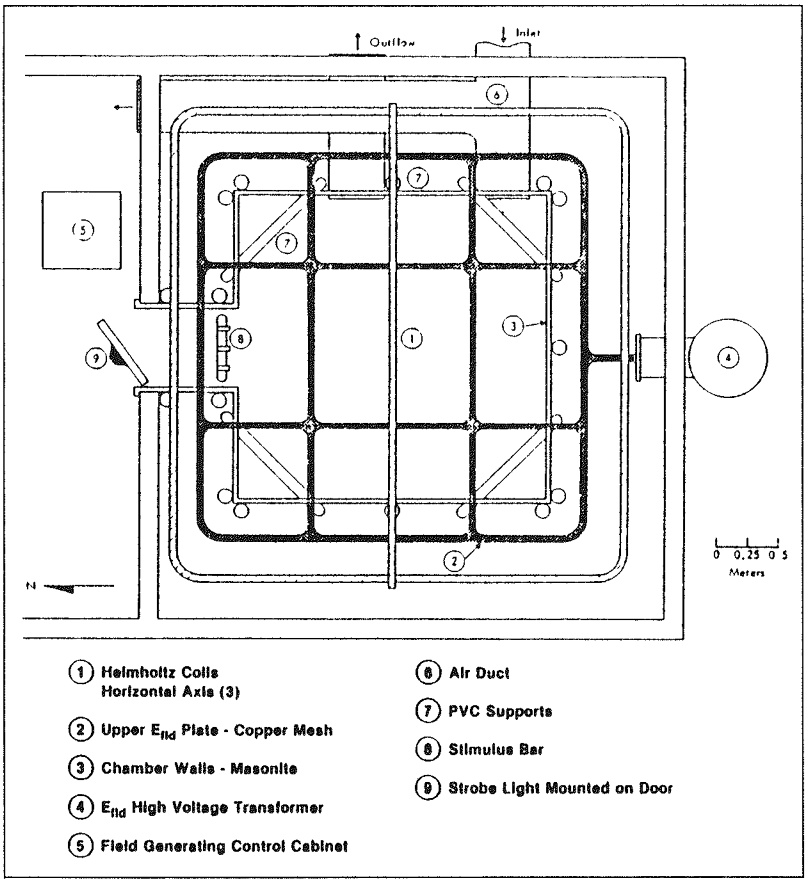

Figure 2. Top View of 60-Hz Human Exposure Chamber.

Electric Field Design and Characteristics

The upper plate of the electric-field generator was supported above the acrylic ceiling panels on the PVC framework, 2.75 m above the floor. This structure is 3 m square and was constructed of 2-cm copper pipe covered with copper screening. The floor was covered with another copper screen, which served as the ground plate of the system. Encircling the room, except for the doorway area, was an array of gradient bands constructed of 2-cm copper pipe. These bands were spaced at approximately 30-cm intervals between the top and bottom plates and were suspended from the PVC structure by adjustable nylon rope hangers.

The electric field was generated in a modified parallel-plate system. One phase of a three-phase 208-V line drove a power-line corrector. This device supplied up to 6 A of 60-Hz voltage with less than 0.2% total harmonic distortion. It provided the low-distortion input to a modified dielectric test generator, which delivered the adjustable high-voltage 60-Hz sine wave to generate the field. A capacitive voltage divider was used to set the voltage on each of the eight guard rings that encircled the exposure facility. Each gradient voltage was proportional to the distance of the ring above the ground plane. This system was necessary to generate a uniform, unperturbed field, since the dimensional limits of the space in which the facility was constructed placed constraints on using a more desirable ratio of plate spacing to size. It was also necessary to compensate for nonuniformities introduced by the proximity of the grounded building walls, as analyzed by Misakian (1984). The total capacitive load on the generator was calculated at 1,000 pf.

Because we anticipated that subjects would be seated within a cube measuring 0.5 m in all directions from a reference point 1.0 m above the ground plane in the center of the room, the uniformity of the fields was measured within this space. Electric-field-strength measurements were made with a Model 111 Power Frequency field meter (Electric Field Measurements Co., West Stockbridge, MA) suspended from the ceiling supports, leveled with a fiberglass rod, and read from outside the exposure chamber by means of a closed-circuit television system. Calibration for this instrument was verified with a similar National Bureau of Standards instrument. Uniformity of the unperturbed field in the 1.0-m cube is shown in Table 1. The values tabulated are valid for field strength up to 16 kV/m. No corona was detectable at this intensity, using either radiofrequency or chemical detection (ozone) methods. Blind observation methods also confirmed that no vibration or audible noise was detectable.

A major consideration in the design of this facility was safety for both the experimental subjects and the laboratory personnel. The maximum voltage on the upper plate was about 50 kV; lower, but still dangerous, voltages were present on the gradient bands. The system was made intrinsically safe by keeping all high-voltage elements enclosed in a space between the building walls and the inner walls of the exposure room. The distance between any high-voltage element and a point of contact by a person was at least 10 times the calculated flashover distance for the worst-case voltage.

In addition to this safety factor, which was built into the physical configuration of the room itself, a number of other measures were taken to minimize danger. The subject could, at any time, step on a floor pad that switched off the high-voltage generator. This system gave the subject immediate control of his own safety and contributed to his comfort and feeling of confidence in the system. The high-voltage generator also had a built-in, conventional over-current shutdown. This system monitors the output transformer load, and turns it off if the current exceeds a preset value. In a study reported in companion papers in this volume by Graham et al. and Fotopoulos et al., each of 12 subjects was studied for 4 full days in this facility without any of the active safety systems being actuated.

TABLE 1. Electric- and Magnetic-Field Uniformity in Exposure Chamber

	Uniformity (%) over an Area of 1 m^2 (16 kV/m maximum; 32 A/m maximum)		
Height of Measurement (m)	Electric Field	H_y Field	H_x Field
1.5	± 3.8	± 4.0	± 4.8
1.0	± 5.0	± 3.8	± 2.1
0.5	± 5.6	± 0.8	± 4.6

Magnetic Field Design and Characteristics

The circularly polarized magnetic field was generated by two sets of Helmholtz coils perpendicular to one another. One axis was oriented from the doorway to the rear of the room (X axis); the other axis was from floor to ceiling (Y axis). Each axis was independently generated by an array of three square coils, each of which was 3.2 m on a side. The coils were placed at either end and in the middle of each axis. The Helmholtz coils were wound with 24-gauge nylon/polyurethane insulated copper wire inside a slit ABS pipe frame. Each axis of the magnetic field was independently energized from an adjustable autotransformer. In compliance with the standard established for the New York State Power Line Project, this facility was designed so that the electric-field voltage and vertical magnetic-field currents were in phase, and the horizontal magnetic-field current was shifted from both by 90°. Components of the three-phase 208-V line were used to produce the required phase relationship between the electric field and each of the magnetic fields. Some design problems were encountered in producing the desired circular polarization of the magnetic field because of interactions with the structures making up the electric-field generation system. In particular, it was necessary to partially slit the copper-screen ground plane to reduce eddy current losses in the region close to the floor area. The maximum circularly polarized magnetic field that could be generated was 32 A/m. Nonuniformity measurements of the magnetic fields within the 1-m^2 area, also shown in Table 1, did not exceed ± 5.6%.

MONITORING SYSTEMS

When a subject was seated inside the exposure facility, his or her activity was monitored with a high-sensitivity, closed-circuit television camera and a two-way audio intercommunication system. These devices made it possible for the experimenter to be in continuous visual and verbal communication with the subject. During exposure periods, the electric-field intensity was continuously monitored with a flat current probe located at the ground plane of the exposure area; both axes of the magnetic field were monitored with a pair of shielded coils located inside the entryway ceiling. Signals from these sensors were conditioned to produce an RMS voltage, which was then sampled by a PDP11/03 computer and stored in a disk file. These monitoring systems provided a continuous record of the strength of both electric and magnetic fields throughout exposure.

During exposure to the fields, the subject was connected to a virtual ground in order to standardize exposure conditions. The grounding system also provided the means to unobtrusively obtain a continuous measure of the current induced in the subject's body by the electric field and allowed quantification of field dosimetry.

The virtual ground system consisted of a foil strip, which encircled each ankle, and was held in position by an outer Velcro® band. A 100-kΩ resistor was placed in each current path to minimize any current induced in the loop formed by the legs in the presence of the surrounding magnetic field. Since the I_{SC} for an average-size male in the seated position is about 100 μA in a 10-kV/m field, these input resistors raised the subject about 10 V above ground potential, which was low enough not to present a safety hazard to the subject. The I_{SC} monitoring circuit, shown in Figure 3, was similar to those used for monitoring both the electric and magnetic fields. An operational amplifier current-to-voltage circuit, followed by a true RMS converter and level shifting circuit, conditioned the signal for conversion to digital values in the PDP11/03 computer. Samples were taken once per second, and the mean and standard deviation over 60-sec epochs were calculated and stored in a disk file for further analysis.

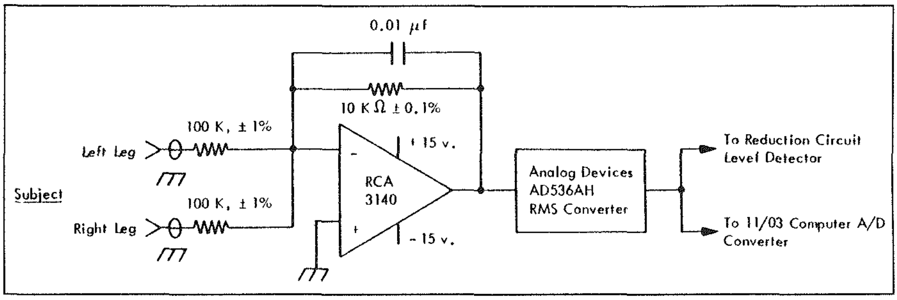

Figure 3. Short-Circuit Current Monitoring Circuit of Chamber Shown in Figures 1 and 2.

Contact between the skin and the foil was enhanced with an isotonic contact medium formulated with unibase cream and 0.1M KCl. This cream kept the contact area between the foil and the skin uniform and was well-tolerated for long periods of time.

Initial pilot studies were conducted to evaluate factors that might influence I_{SC} measurement. Although grounding one leg versus grounding both legs had no effect on I_{SC} values, connection was made to both legs in order to avoid a high-current-density path through the groin region, as reported by Kaune and Forsythe (1983) in model studies. Wearing street clothes produced higher readings than wearing a standardized, 50% cotton/50% acrylic sweat suit and cotton socks, but the shielding effect was minimal (approximately 3% difference in I_{SC}).

The relationship between field strength and I_{SC} was found to be linear over the range 2 to 16 kV/m. The effects of changing body position in a field of 16 kV/m were examined. Standing with arms fully extended above the head resulted in an I_{SC} 5.7 times that obtained when the subject was seated on the floor with the body curled. Replicability was also assessed over several sessions on the same person seated in a standardized position at a constant field strength (8 kV/m). The I_{SC} values obtained did not vary more than 1%.

We also conducted a pilot study to determine if body-size differences were reflected in I_{SC}. Seven men and five women of various sizes and shapes sat in the standardized position in a constant 8-kV/m field. Correlations were calculated between the I_{SC} measures obtained and the reported height and weight of the subjects. Correlation between I_{SC} and weight was 0.89, between I_{SC} and height 0.95, and between I_{SC} and height times weight was 0.94.

DOSIMETRY

The system described above for monitoring I_{SC} formed the basis for measuring individual exposure to the electric fields The pilot studies we had conducted indicated that I_{SC} was affected primarily by field strength, body position, and body size. The measure appeared to be reliable over sessions Before we could use this system in a double-blind study, it was necessary to conduct various formal tests of the validity, reliability and sensitivity It was also necessary to determine if the standard clothing and performance devices to be used in the double-blind study significantly shielded subjects from the field or distorted the current distribution within the body

Mannequin Tests

A 1 83-m polyester and wood, male mannequin was prepared for testing by spraying its entire surface with electrically conductive paint, segmenting it into nine non-electrically connected parts, and installing wires within the hollow shell to allow measurement of current in each separate body segment Various tests of the impact of clothing and performance devices were performed, the results are summarized in Table 2 on this and the next page Experimental clothing and devices, consisting of an optically isolated, hand-held response panel, lightweight headphones and two polyurethane pillows placed in the lap, produced minimal shielding (5 9%) and no marked distortion in segmental I_{SC} distribution Another test was made on the difference in total I_{SC} between the standing and the seated mannequin As expected, the standing value was higher by about 30%, since the grounded mannequin in this position severely compressed the field, producing enhanced I_{SC} Nevertheless, a calculated value of 20 7 μA/kV is reasonably close to the nominal value of 18 μA/kV, which can be derived from the field observation data of Deno and Zaffanella (1982)

TABLE 2 Results of Mannequin Testing in 60-Hz Electric Field

Effects of Clothing on a 1 84-m-High Mannequin (grounded)

Seated in the facility, electric field, 9 kV/m

Value of I_{SC} (μA)

Naked = 129 2
Clothed = 127 4

Shielding effect 1 4%

Effects of Experimental Devices on Mannequin

Seated in the facility, electric field, 9 kV/m Earphones on head pillows and response device in lap, dressed in standard clothing

Value of I_{SC} (μA)

Naked = 129 2
Clothed and with devices = 121 6

Shielding effect 5 9%

Difference (μA) in I_{SC} Between a Standing and a Sitting Mannequin

Standing clothed, in 9-kV/m field	186 6
Sitting, clothed, in 9-kV/m field	127 4

TABLE 2. Continued

Distribution of Currents in Various Body Segments under Differing Conditions

Segment	Sitting Naked (% of Total I_{SC})	Sitting, Clothed, With Devices (% of Total I_{SC})
Head	29.6	29.4
Chest and left arm	29.6	29.8
Midsection	5.1	4.7
Pelvis, left leg, and upper right leg	18.1	17.7
Lower right leg	4.2	3.8
Right foot	3.2	3.2
Right arm	7.4	7.7
Right hand	2.8	3.8
	100.0	100.0

Human Tests

The I_{SC} measures were incorporated into a controlled laboratory investigation of human perception of uniform, 60-Hz electric and magnetic fields. Ten male and ten female volunteers, selected according to specified criteria, participated. We measured I_{SC} at different field strengths, at different body positions, at different times of day, and under conditions of continuous, constant field exposure.

General Procedures. Each subject participated in four sessions. Prior to the start of each session, subjects changed into the standardized clothing, and removed all jewelry or other metal objects. Height and weight were measured, and the transducers for I_{SC} were attached. When the exposure room door was closed, monitoring and communication was via closed-circuit TV and audio intercom. Except when otherwise instructed, subjects sat in a standardized position. Temperature was 75°F ± 2°F, and relative humidity was 50% ± 2.5%; I_{SC} during this study was integrated over 3-sec epochs and over entire exposure periods.

Relationship between I_{SC} and Field Strength. Initially, the field was presented for 9 sec at each of five field levels (3, 6, 9, 12 and 15 kV/m), and three I_{SC} readings were obtained; analysis was based on the last of these readings. Figure 4 presents a plot of the means and standard deviations of I_{SC} at each of the five field-strength levels. Two-variable linear regressions were calculated for each subject separately and for groups of male and female subjects. The linearity of the relationship was clearly demonstrated for all subjects; F values ranged from 5,179 to 24,848. The correlation between field strength and I_{SC} exceeded 0.99. The slope of the regression lines was greater for male than for female subjects ($t = 4.42$, df 18, $P < 0.001$), as was the intercept ($t = 3.24$, df 18, $P < 0.01$).

Relationship with Body Size. Pearson's r was calculated between five measures of body size and: I_{SC} at 9 kV/m; I_{SC} at 15 kV/m; slope of individual regressions of I_{SC} on field strength; and intercept of individual regressions of I_{SC} on field strength. The results are summarized in Table 3. Although all but one of the correlations were significant, height and body surface were the best predictors of I_{SC} at both 9 and 15 kV/m and of the slope of the regression of I_{SC} on field strength. The intercept was only weakly predicted (9 to 27% of the variance explained).

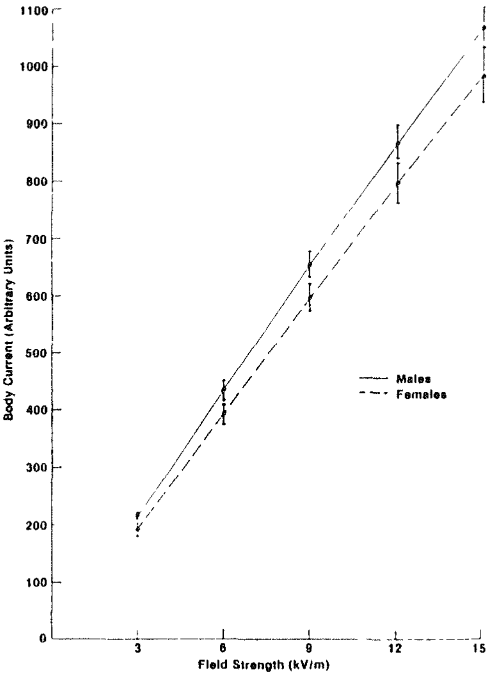

Figure 4. Relationship between Field Strength and Short-Circuit Current for Male and Female Human Subjects Exposed to 60-Hz Electric Field. Vertical bars indicate ± 1.0 standard deviation.

TABLE 3. Relationship Between Five Measures of Body Size and Short-Circuit Current in 60-Hz Electric-Field Human Exposure Chamber

	Pearson's r			
Measure	9 kV/m	15 kV/m	Slope	Intercept
Height	$+ 0.87^a$	$+ 0.90^a$	$+ 0.87^a$	$+ 0.52^b$
Weight	$+ 0.77^a$	$+ 0.78^a$	$+ 0.76^a$	$+ 0.42^c$
$\frac{\text{Height x Weight}}{100}$	$+ 0.85^a$	$+ 0.86^a$	$+ 0.84^a$	$+ 0.47^c$
Surface Area	$+ 0.88^a$	$+ 0.90^a$	$+ 0.88^a$	$+ 0.50^c$
Surface Mass	$- 0.60^b$	$- 0.60^b$	$- 0.59^b$	$- 0.31$

a = $P < 0.001$
b = $P < 0.01$
c = $P < 0.05$

Effects of Body Position. The I_{SC} at the five selected levels of field strength were then evaluated while the subject assumed each of seven body positions: (1) sitting with arms held horizontal; (2) sitting with arms held out in front of the body; (3) sitting with arms held up over the head; (4) standing with arms down at the sides; (5) standing with arms held horizontal; (6) standing with arms held out in front of the body; and (7) standing with arms held up over the head. When the subject assumed a particular position, the field was activated for 9 sec, and the integrated I_{SC} value for the last 3-sec period was recorded.

Analysis of variance revealed a highly significant body-position effect ($F = 616.69$, df 6,108, $P < 0.001$), which was further investigated using the Tukey B procedure. Sitting with arms stretched out in front produced a lower I_{SC} than any of the other positions. Sitting with arms out to the side, with arms raised, or standing with arms down at the side did not differ from one another. Standing with arms stretched to the side or with arms above the head produced the highest I_{SC} levels, but these two positions did not differ from one another. Again, I_{SC} was higher for males than for females ($F = 31.17$, df 1,18, $P < 0.01$), and increased as field strength increased ($F = 10{,}952.24$, df 4,72, $P < 0.001$). This increase was greater for male than for female subjects (interaction $F = 25.37$, df 4,72, $P < 0.01$).

Reliability of I_{SC}. To evaluate the reproducibility of I_{SC} over repeated measurements, two readings, taken approximately 5 min apart, were compared with each other and with readings taken approximately 12 days before. Within-session correlations were 0.99 for males, and 0.99 for females. Between sessions approximately 12 days apart, reliability was 0.92 for males and 0.97 for females.

Cumulative Body Current. Cumulative, 1-hr measures of I_{SC} were made during the fourth session of the perception study, which included three 1-hr exposures to a 12-kV/m, 16-A/m field; I_{SC} declined over successive exposures ($F = 7.03$, df 1,18, $P < 0.05$). Observations by the experimenters suggested that the significant time effect was due to slight changes in body position (slumping) during the relatively long exposure periods. The results again support the value of I_{SC} as an index of field exposure, particularly during long experiments.

CONTROL SYSTEMS

A major requirement for the facility design was that it allow performance of studies of human subjects under double-blind experimental conditions. Double-blind methodology requires the removal of all cues which could be used by either subjects or experimenters to determine whether real or sham fields are being presented. Although such methods are difficult to implement, they are essential in experiments where expectations can have a powerful influence on the outcome. It was therefore necessary to devise a system for this facility which would make it possible to present either real or sham electric and magnetic fields without either the subjects or the experimenters being able to distinguish between the conditions.

Subject Controls

In designing the subject-oriented portion of the double-blind system, the first question to be addressed was the extent to which subjects could perceive the fields. A study on the perception of electric and magnetic fields was therefore conducted in the facility; 10 men and 10 women served as subjects. Magnetic-field intensities up to 32 A/m (flux density of 0 4 G) were generated but were never perceived An electric field of 9 kV/m was presented but was not perceived by 90% of the subjects when seated in the center of the exposure area with the hands held in the lap Raising the arms above the head while seated, however, resulted in markedly increased perception The results suggested that, when a subject raises his arms or stretches, the ability of the subject to perceive the field is increased

This problem was successfully solved by taking advantage of the significant increase in I_{SC} which occurs in association with such body-position changes Testing with a small group of individuals established that I_{SC} increases about 30% when the arms are extended upward or outward in the field. Since I_{SC} was already available in averaged form, the detection of an increase could be used to rapidly reduce the strength of the field, thereby reducing the likelihood that an individual would sense its presence

After trial and error observations, it was determined that a reduction of the field to about 25% of its initial value triggered by a 20% increase in I_{SC} reduced detection of the field. A block diagram of this system is shown in Figure 5.

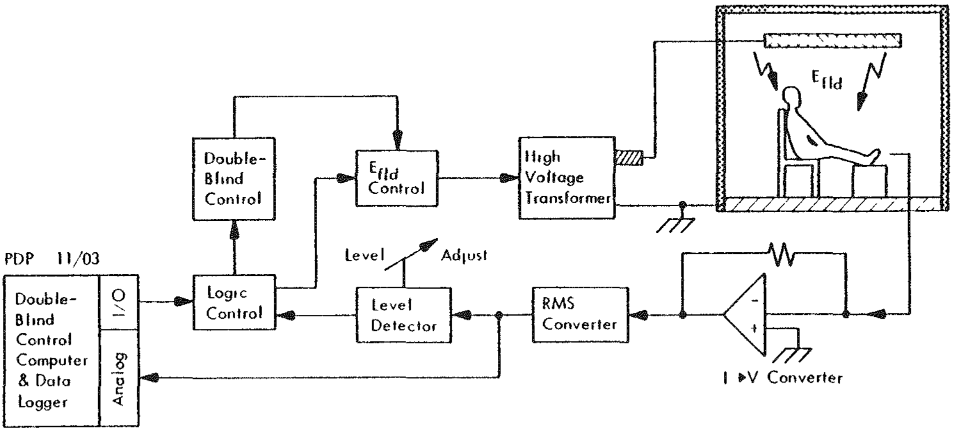

Figure 5 Block Diagram of System for Dynamic Electric-Field-Strength Reduction to Minimize Perception by Human Subjects

Originally, the system simply decreased the field 75%, then returned it to full strength after 30 sec. However, in pilot work we found that subjects could sense the electric field transient current produced by the abrupt return to full field strength. For this reason, we altered the procedure to return the field to full strength in four steps. We first installed a series of solid-state relays, because such relays have the advantage of operating in complete silence. However, we discovered that at each zero-crossing the relays produced a switching transient that resulted in significant harmonic distortion of the electric field. We then substituted an array of mechanical relays which produce transient-free switching. A timer sequence began the switching of a series of four voltage-dropping resistors into the primary of the electric-field generator transformer. The step-in/step-out rate was determined by a clock generator at a 100-msec rate to minimize switching transitions.

The sound made by the relays in switching the field was audible to both the subject and experimenter and provided a clue to the active field condition. We therefore installed an additional dummy relay that continuously switched at the same rate as the active relays. The switching sounds of the dummy and the active relays were synchronized, so that the dummy relay provided an effective auditory mask for the activity of the real relays. As a further precaution, the real relays were enclosed in sound-absorbing material.

EXPERIMENTER CONTROL

The real- or sham-field condition was encoded in a Master Subject File in the control computer. This file determined the condition for each day by setting a group of relay controls in the field generators to match the conditions designated for the particular day and particular subject. The experimenter initiated this process but remained unaware of which condition was set. All obvious cues, such as readout meters and relay sounds, were easily eliminated or masked. The more difficult and subtle indications of the field-on status, such as a slight skewing in a closed-circuit TV monitor when the magnetic field was switched, were eliminated by keeping the screen blank while the field status was established and delaying re-establishment of the video image.

After eliminating all visible and audible cues that might communicate the field status to either the subject or the experimenter, we realized that, if a malfunction occurred in the system, we would not be aware of it until the end of the 4-mo study. Therefore, we set up a data-logging procedure in the control computer that checked the field status, as reported by the monitoring transducers inside the chamber, against the predetermined Master Subject File. If a discrepancy was detected, a malfunction report was generated which delayed the experimental session until the problem was corrected.

During a 48-session double-blind study using this system, both experimenters and subjects recorded their opinion of the field status twice during each study day. Statistical analysis indicated that neither group could distinguish, at better than chance levels, between the real- and sham-field conditions.

DISCUSSION

Much of our existing knowledge about the effects of power-line-frequency fields on humans comes from anecdotal observations on people who have occupational contact with these fields. Valuable as these observations may be in providing us with real-world guidance concerning the problems that may need attention, they cannot answer the questions that require the rigor of controlled laboratory studies. This study was a first attempt to build a facility that utilizes the combined knowledge of various disciplines to overcome the impediments to making power-line effects on humans a subject for laboratory study.

A few of the shortcomings of this effort should be pointed out. The region of high electric- and magnetic-field uniformity was relatively restricted, and the electric field was considerably perturbed by a standing individual. These problems could be solved by using a larger physical space, which would allow greater spacing between the electric-field parallel plates and also permit the subject area to be moved toward the geometric center of the magnetic-field axis. During our study, it was possible to keep subjects in a relatively static seated posture. However, this space might be too restricted if activity or a different position in the simulated fields were an experimental requirement.

In investigating phenomena in a research area as controversial as this, where expectations might influence observations, the use of double-blind controls and counterbalanced experimental designs is necessary to obtain unbiased results. The methodology presented here provides an initial indication of how such controls can be employed in human research in this area.

ACKNOWLEDGMENTS

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OCCUPATIONAL EXPOSURE OF HIGH-VOLTAGE WORKERS TO 60-Hz ELECTRIC FIELDS, PART 1: EXPOSURE INSTRUMENTATION

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ABSTRACT

An investigation was started at Bonneville Power Administration (BPA) in 1980 to determine occupational exposure of personnel to electric fields. A miniature electric field exposure monitor (EFEM) was developed and constructed to continuously monitor the electric-field environment of many workers on a daily basis. The instrument stored electric-field exposure data digitally in a time histogram and was read out by the workers at the end of each workday. The EFEM measured the local electric field at the surface of the body, which can be related to other parameters such as induced current, if necessary. For convenience in interpretation and because of tradition, the local field measured by the EFEM is expressed in terms of the unperturbed electric field through the concept of the enhancement factor (EF).

Power-line electric and magnetic fields are well-known phenomena with short-term effects, such as nuisance shocks and induced currents. The long-term biological effects of such fields have been a source of concern for the past several years, especially since 1972, when the Soviet Union presented a paper at the CIGRE Conference in Paris. This paper described negative health symptoms which they claimed were experienced by electrical workers exposed to the electric fields in 400-kV switchyards (Korobkova, et al., 1972). A great deal of research has been conducted since that time, especially on laboratory animals exposed to fairly high-strength fields; to date, results have been inconclusive and, sometimes, contradictory.

One of the problems with studies involving humans has been the lack of electric-field exposure data because of a lack of instrumentation for obtaining such data. This has been partly due to the fact that no one really understands how the electric field interacts with the body; therefore, no one knows exactly what parameter should be measured. Nevertheless, several electric-field exposure-monitoring systems have recently been developed. This paper describes the 60-Hz electric field exposure monitor (EFEM) developed by the Instrumentation and Standards Branch of the Bonneville Power Administration (BPA) Division of Laboratories. We describe its calibration and special tests to determine the applicability of a uniform field calibration for subsequent use in nonuniform field conditions. A companion paper (Bracken and Chartier, this volume) describes the results of occupational electric-field-exposure measurements for 1981 exposure days for 135 BPA employees.

DESCRIPTION OF EFEM

The EFEM is based on the same principle as a much larger meter developed for EPRI (Deno, 1979). The electric field induces a current between a sensor plate and a small stainless steel box which contains the measurement and storage electronics. The current between electrodes is proportional to the incident field and, with proper calibration, indicates the field level.

The EFEM was designed for a large occupational-exposure study where workers would volunteer to wear the meter and would not be observed during the workday. Thus, human compatibility played a major role in the design decisions; the size of the EFEM and the time required to extract data were the most important factors.

The device has been miniaturized to the extent practical (size, 5.6 x 7.0 x 1.3 cm; weight, 118 g), so that it could be worn comfortably by employees over the course of a workday. The device automatically shuts off after 9.1 hr to conserve the batteries. Workers initially were given a choice of three locations on the body for wearing the meter (shirt pocket, lanyard or front of hard hat). The shirt pocket has been the preferred location because, although the EFEM is light, it upset the balance of the hard hat, which was considered a nuisance by some workers.

A block diagram of the signal processing circuitry is shown in Figure 1. The induced current is amplified and converted to a voltage proportional to the incident field. This 60-Hz voltage is then rectified to a dc voltage which is used to drive a voltage-to-frequency converter. The resulting output is a series of electrical pulses, the frequency of which is proportional to the incident field strength at the sensor plate.

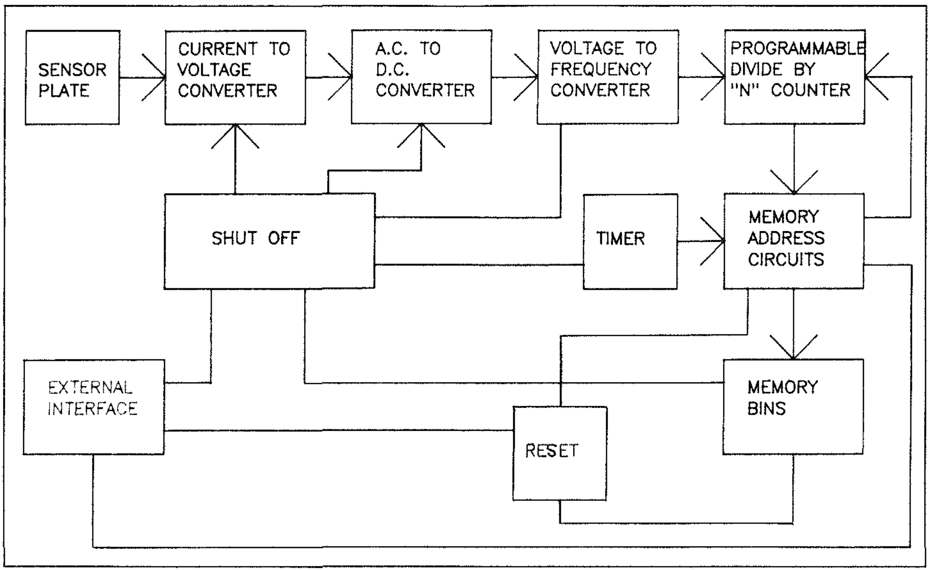

Figure 1. Electric Field Exposure Meter Block Diagram.

The pulse signal from the voltage-to-frequency converter is directed to a binary coded decimal (BCD) counter which controls an addressable selector switch. The selector switch addresses a particular storage location, depending on the number of counts (i.e., the average frequency) during a preset interval. A signal pulse is then stored at the selected location. Thus, for each 4-sec interval, a pulse is routed to one of eight storage counters; the particular location is determined by the average frequency, and thus the average incident field, over the 4-sec interval. The time histogram for the fields incident on the sensor is stored in eight digital counters. The total time the instrument is on is also accumulated in a counter as the total number of 4-sec intervals. The accumulated counts are read out sequentially with a special readout device (shown in Figure 2) that also serves as a battery charger. The time spent in fields above those recorded in the other eight bins can be computed.

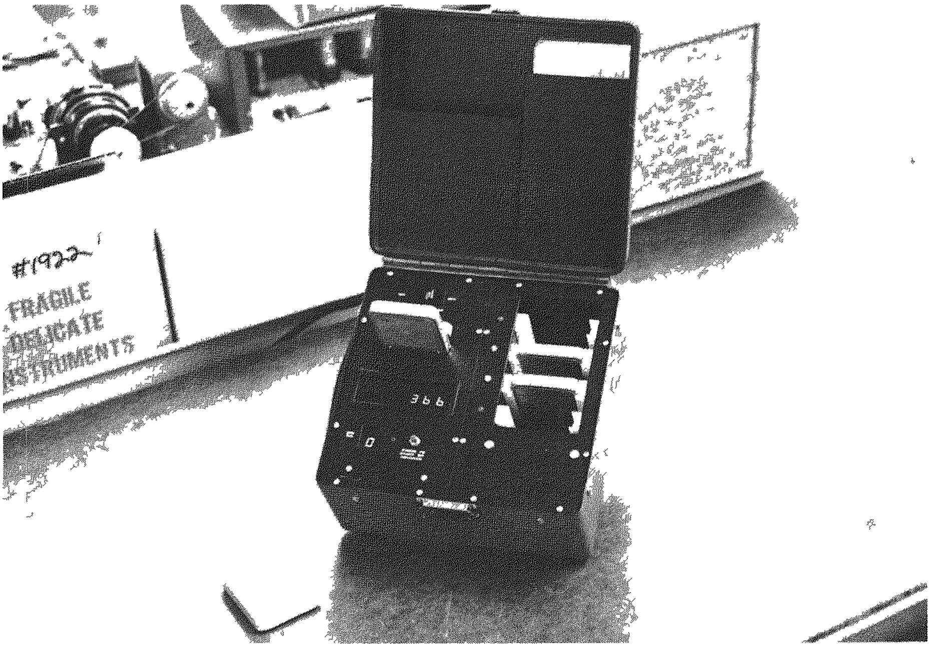

Figure 2. Electric Field Exposure Meter and its Reader.

Some flexibility is possible in the electric-field range of the storage locations or bins. Initially, the bins were of equal width. However, to increase the overall range of the device and provide more resolution at lower fields, a nonlinear bin scheme was implemented. The ranges for the EFEM with the greatest sensitivity are shown in Table 1. Essentially, the edge of bin 1 represents the threshold for detection of exposure above background levels. The fields in column 2 of Table 1 refer to unperturbed field at the surface of a flush-mounted EFEM in a parallel-plate exposure system. During the initial data collection, when workers were allowed to wear the EFEM on the hard hat, the EFEM sensitivity was one-half that shown in Table 1.

TABLE 1. Electric-Field Exposure Meter Bin Ranges

Bin Number	Unperturbed Field (kV/m)	Hard Hat Enchancement = 5.4 (kV/m)	Chest Locations Enchancement = 2.5 (kV/m)
0	0- 1	0.00-0.18	0.0 - 0.4
1	1- 3	0.18-0.56	0.4 - 1.2
2	3- 6	0.56-1.11	1.2 - 2.4
3	6-10	1.11-1.85	2.4 - 4.0
4	10-15	1.85-2.78	4.0 - 6.00
5	15-21	2.78-3.89	6.00- 8.40
6	21-28	3.89-5.20	8.40-11.2
7	28-36	5.20-6.66	11.2 -14.4
8	Total Time	Total Time	Total Time
X	36	6.66	14.4

A direct readout capability for the EFEM was also developed. The output pulses from the voltage-to-frequency converter are optically coupled to a receiver on the ground. The optical pulses are converted back to voltage pulses at a frequency proportional to the field incident on the meter. Using a frequency counter at ground level, a direct readout of the EFEM is provided without perturbing the field in its vicinity. This capability has been very useful in laboratory studies and for calibration of the device.

UNIFORM FIELD CALIBRATION

The primary full-scale calibration of the EFEM was performed in a parallel-plate facility, where a uniform field could be produced. The EFEM was flush-mounted at the center of a parallel-plate exposure facility with a plate spacing, d. Sufficient voltage, V, was applied to the plates to achieve the desired full-scale unperturbed field at the surface of the plate (V/d). With the EFEM mounted in the parallel-plate system, the output of the voltage-to-frequency converter was adjusted to 9.22 ± 0.02 kHz. This set the full-scale reading (upper edge of bin 7) to correspond to the unperturbed field between the plates. Even though the full range of the EFEM was set within ± 0.2%, the error in the lower bin edge was as great as ± 200 V/m (10 to 20%, depending on EFEM gain) because of internal noise and 60-Hz pickup during the calibration procedure.

To calibrate the EFEM in a uniform field, we located the edge of each bin. This type of calibration has been performed at BPA (Short, 1981) and at the National Bureau of Standards (NBS; Fulcomer, 1984). Table 2 gives the test results conducted at NBS for two EFEM (R-11, R-15), showing that the largest error between actual field and the bin-edge field occurred, as expected, in the lower bin. In all other bins, the error was generally less than 4%.

TABLE 2. National Bureau of Standards Electric-Field Values at the Boundaries Between Bins in the Electric-Field Exposure Meter (EFEM). The EFEM sensor was flush with surface, the case was connected to the surface. Values given are mean ± percent error.

Bin Edge	Design Field (kV/m)	EFEM #R-11 Actual Field (kV/m ± %)	% Between Actual and Design	EFEM #R-15 Actual Field (kV/m ± %)	% Between Actual and Design
0/1	1.0	0.883 ± 0.3	-11.7	0.942 ± 0.3	-5.8
1/2	3.0	2.962 ± 0.4	-1.3	3.047 ± 0.2	1.6
2/3	6.0	6.037 ± 0.2	0.6	6.20 ± 0.3	3.3
3/4	10.0	10.187 ± 0.1	1.9	10.374 ± 0.15	3.7
4/5	15.0	15.337 ± 0.1	2.3	15.615 ± 0.15	4.1
5/6	21.0	21.575 ± 0.1	2.7	21.805 ± 0.1	3.8
6/7	28.0	28.925 ± 0.1	3.3	29.29 ± 0.2	4.6
7/8	36.0	37.28 ± 0.1	3.6	37.60 ± 0.1	4.4

Responses of the EFEM were also checked with current injection. A current corresponding to the induced current in a full-scale field of 36 or 72 kV/m was coupled into the sensor plate through a capacitor (120 pF). The full-scale output of the voltage-frequency converter was adjusted to 9.22 kHz, which corresponded to the upper edge of the highest storage location (bin 7). This test was not a direct calibration. Because of tolerances in components, the response of each EFEM was not identical for identical currents (± 2%). However, this method of calibration was sufficiently accurate for calibration after maintenance.

DETERMINATION OF ENHANCEMENT FACTOR

Because the EFEM measures the local electric field on the body, the measurement can be influenced by body location, size, orientation of the wearer in the field, and his clothing. The field range of the EFEM, in terms of the unperturbed field in which a person is standing, depends on the particular location where the device is worn. The field EF is defined as the local field measured at the surface of the body, divided by the unperturbed uniform vertical field. Tests described below were performed to establish appropriate EF for various positions of the EFEM.

Static Tests

The EF for a particular body position and grounding status is the ratio of the field measured by the EFEM, under the selected conditions, to the unperturbed field. An overall EF was obtained by averaging measurements over several body positions and conditions, which were applied to all EFEM users. Exposure is given in terms of time spent with the field at the EFEM equal to an average local field at the surface of the body when assuming various postures and grounding conditions in a uniform field. The choice of positions and grounding conditions is somewhat arbitrary, because it is not possible to duplicate the wide variety of possible postures and grounding conditions that are experienced in an occupational environment.

Static tests were performed in the BPA Ultrahigh Voltage (UHV) Laboratory in unperturbed fields up to 20 kV/m with both the standard EFEM and the optic-link EFEM (OLEFEM), mostly with the latter.

Several types of static tests were conducted; the details and results can be found in Chartier, Bracken, and Capon (1984). Enhancement factors were obtained for five postures of one subject (grounded or insulated) wearing an OLEFEM in the shirt pocket, on a lanyard, and on a hard hat. The average EF for the shirt-pocket, lanyard (chest), and hard-hat locations were 3.1 ± 1.3, 3.2 ± 1.1, and 5.2 ± 1.7 respectively. The ratios of the measured EF for the insulated to grounded conditions were 0.73, 0.78, and 0.86 for the shirt-pocket, chest, and hard-hat locations, respectively.

Tests were also conducted to determine variability between 30 male and 1 female subject standing in a uniform 4.3-kV/m field, either grounded or insulated. The means and standard deviations for these tests are shown in Table 3.

TABLE 3. Measured Enhancement Factors (EF) for 30 Subjects Wearing Electric-Field Exposure Meters and Standing Erect, Arms at Sides. Values for insulated condition given in parentheses. Values given are the means ± SD

Clothing Worn	Number of Subjects	EF Shirt Pocket	EF Hard Hat
Shirt only	30	4.6 ± 0.7 (3.5 ± 0.7)	7.4 ± 0.6 (6.4 ± 0.6)
Outer coat over EFEM	26	4.7 ± 1.0 (3.6 ± 0.9)	7.3 ± 0.6 (6.2 ± 0.6)

A number of special tests were conducted to determine the variability associated with the location of the EFEM on the chest and on a hard hat. The results showed that considerable variation (± 20%) existed over the area where a lanyard or a shirt-pocket EFEM might be located.

Another important factor is the movement of the EFEM away from the body because of bulky clothing, or during bending or other movements. The reduction in field relative to the position flush against the body was less than 10% for distances up to 5 mm. At distances of 30 mm from the body, the reduction in measured field was less than 20%. When the EFEM was raised above a ground plane in a uniform vertical field, the reduction reached 8% at 15 mm and remained constant at that value out to 30 mm. Similar tests conducted at NBS (Fulcomer, 1984) in a uniform field and in a nonuniform field (EFEM on the side and the top of a small tower in a parallel-plate calibration facility) were in good agreement with these results (Fulcomer, 1984).

Other factors also affect EFEM performance. If the EFEM was worn with the sensor plate facing the body, the measured field was reduced by a factor of 0.67. The plastic pouch used for the lanyard and, in some cases, the shirt-pocket location reduced the measured field by about 5%. If the EFEM was placed in front of a pocket calculator, an increase in measured field of from 0 to 10% was observed. A 20% increase in measured field was observed when the EFEM was placed in front of a pack of cigarettes. A plastic-barrel ballpoint pen with metal ink cartridge, located in the pocket next to the EFEM, caused a reduction of measured field of from 3 to 10%. If located in front of the EFEM, the pen increased the EFEM reading by about 20%. All workers were, however, instructed to keep the shirt pocket free of other objects.

Wet clothing was observed to have a large but uncertain effect on EFEM performance. In some cases, much higher field readings were observed and, in others, much lower readings.

Dynamic Tests

Ten-minute dynamic tests were conducted during an initial set of laboratory tests. The subjects moved along 5- and 10-kV/m electric-field contours in the BPA UHV Laboratory while wearing EFEM in various locations. Walking, bending, standing, raising arms and other body motions were done in a random manner. The test route passed near walls and near grounded equipment, therefore the field was not vertical and uniform. Recorded data were distributed in more than one bin because of changes in posture, orientation, and shielding. The distribution over bins observed in these tests is indicative of EFEM response in the less than uniform fields that are expected in the workplace.

The EF measured in the dynamic tests along a 10-kV/m contour were EF = 1.9 and EF = 2.4 for the shirt-pocket and lanyard positions, respectively. Uncertainty in these values was associated with distribution over different bins. It was approximately ±30%, which is comparable to the uncertainty due to body positions in the static tests.

Enhancement Factor Summary

The results of the laboratory tests are summarized in Table 4, which shows estimated uncertainties in EF. Some of the effects that contributed to variations in exposure measurement result from the small size and location of the meter, but others are inherent in the quantity being measured: the electric field at the surface of the body under actual working conditions. It must be emphasized that the percentages in Table 4 are estimates for the purpose of providing a rough approximation of the variance in EF and, hence, in the threshold field. For example, statistically meaningful deviations are available for only two major sources of variance: different subjects and insulated versus grounded. In addition, estimated uncertainties are not necessarily independent. For example, some of the intersubject variability is from the difference in location on the chest. The uncertainty observed during random motion in the dynamic tests includes the effects of body position and body orientation with respect to the field (body shielding), which are the largest contributors to uncertainty in the EF. These effects alone yielded a root mean square uncertainty in EF of ± 50%.

TABLE 4. Sources and Estimated Magnitudes of Variation in Enhancement Factor (EF) of Electric-Field Exposure Meter Response under Various Conditions

Condition	Estimated Magnitude of Change in EF (%)	Comment
Internal noise and 60-Hz pickup during calibration	± 10 - 20 in threshold	± 200 V/m
Component tolerances	± 2	
Increase of field with height in final tests	− 5 − 10	shirt pocket hard hat
Body rotation for initial laboratory tests	± 30	body shielding
Breathing and slight body movements	± 3	
Intersubject variability of EF	± 15 ± 20	grounded insulated
Insulated versus grounded (all body positions)	− 27 − 14	shirt pocket hard hat
Coat worn over shirt	+ 2 − 2	shirt pocket hard hat
Location on chest and	± 20 ± 18	shirt pocket hard hat
Body position (5 positions)	± 40 ± 35 ± 30	shirt pocket lanyard hard hat
EFEM oriented with lid down	+ 10	shirt pocket/lanyard
Displacement 5 mm from body	− 10	shirt pocket
Sensor plate facing body	− 33	shirt pocket
In plastic pouch	− 5	
Other objects in pocket:	± 20	pen, cigarettes, calculators

With such large relative variations, the choice of an absolute value for the EF was not crucial. Static and dynamic tests indicated an effective value for the EF of between 1.9 and 3.1 for the shirt-pocket location. Although we have more confidence in the uniform field tests that yielded the higher value, body shielding, increased field with height, and other factors in Table 4 tend to reduce the EF. Therefore, the value selected for the average EF for the shirt-pocket location is EF = 2.5. A value of 5.4, as shown in Table 1, has been used as representative of the hard-hat location.

An EF of 2.5 implies that in an unperturbed field of 0.4 kV/m, the average field measured by the EFEM will be 1.0 kV/m. This corresponds to the threshold for detection in bin 1. Of course, the EF will vary with body position and orientation. Not all time spent in a 0.4-kV/m field will be at the threshold of detection; some time will be recorded above threshold and some will not be detected. The EF is thus a somewhat artificial concept to translate the local electric field that the EFEM measures into more familiar terms of unperturbed electric field. A different choice of EF, say, 2 or 3, would only change the average threshold to 500 or 333 V/m, respectively. This is not a significant change, considering the large uncertainties displayed in Table 4.

Admittedly, the large uncertainties in Table 4 and the lack of precision in choosing the effective EF can lead to doubt about the validity of a small device for measuring electric-field exposures. Even though the nature of such exposure in a complex occupational setting leads to large variations in measured values, the EFEM provides valuable exposure data.

DISCUSSION AND CONCLUSIONS

A miniaturized EFEM that accumulates exposure time in eight ranges has been developed at BPA. The meter has been acceptable to workers, with a preference expressed for carrying it in the shirt pocket.

The EFEM measures local electric field at the surface of the body. The EF is used to express the EFEM measurement in terms of the more conventional uniform unperturbed electric field. The EF is defined as the ratio of the measured local surface field on the body to the unperturbed electric field. There are large variations in EF at any point on a human body, and the average variation was determined in the laboratory for the EFEM located in a shirt pocket, on a lanyard, and on a hard hat. For the purposes of the BPA occupational exposure study, average EF of 2.5 and 5.4 have been used for converting data obtained with the EFEM located on chest and hard hat, respectively, to uniform field levels.

Laboratory evaluation of the EFEM performance indicates that the EF variations are fairly large. The largest variations are due to body position and body shielding. Other prominent sources of uncertainty are the specific location on the chest, the degree of insulation from the ground of the wearer, and anatomical differences between subjects.

ACKNOWLEDGMENTS

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EVALUATION OF 60-Hz ELECTRIC-FIELD EXPOSURE-MONITORING INSTRUMENTATION

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ABSTRACT

Results are presented from a 3-day measurement field day, which was held to compare and evaluate 60-Hz electric-field exposure-monitoring instrumentation. A conducting vest exposure meter and a small electric-field exposure meter (EFEM), located in a shirt pocket, armband or hard hat were compared in a series of static and dynamic tests. In some tests, the devices were worn simultaneously, without mutual interference to provide separate measures of identical exposure. Tests with stationary subjects wearing the instruments were used to measure the effects of grounding, and to establish the meter response in a standard posture for each subject. Dynamic occupational exposure simulations were used to compare accumulated measurements of exposure and to compare measurements with predicted exposures. The simulations were based on analysis of the work-related behavior of substation electricians and operators. Electricians' tasks at ground level and in a bucket truck were simulated near an energized test line. A simulated substation inspection was performed in a 230-kV substation. The exposure measurements, including simultaneous exposures, demonstrated an overall consistency between the meters. The vest demonstrated even less intersubject variability and less detailed exposure characterization. Values measured with the EFEM in a shirt pocket were below those made with the vest and with the EFEM in other locations. Insulation provided by shoe soles appeared to be the largest factor, during the substation inspection, in producing values below those predicted from the unperturbed field.

The evaluation of 60-Hz electric-field exposure-monitoring instrumentation described in this paper is part of an electric-field exposure assessment effort sponsored by the Electric Power Research Institute (EPRI). Several types of exposure-measuring instruments are currently being used to monitor 60-Hz electric-field exposures. EPRI recognized the diversity of these exposure meters and the need for evaluating their consistencies and limitations. This project was designed to perform this evaluation by:

1) developing methods for evaluating exposure instrumentation,
2) comparing and evaluating the response of electric-field exposure-measuring instrumentation, and
3) identifying areas where additional research on exposure measurements is needed.

The primary means for accomplishing these objectives was a 3-day measurement field day held at the Bonneville Power Administration (BPA) UHV Test Laboratory and at J. D. Ross 230-kV Substation in Vancouver, Washington from October 4 to 6, 1983. Participation in the field day was invited from research groups who are working directly or indirectly with exposure measurements. This approach to instrument comparison has proved successful in the past, especially when researchers are developing new measurement techniques and instrumentation. Not only are comparisons made between instruments, but perhaps more importantly, an opportunity is provided for open discussion and exchange of ideas among investigators.

There are, of course, recognized limitations to a measurement field day; particularly that the data are limited to a small, almost anecdotal, sample of possible exposure scenarios for using the instruments. Limited time is available to pursue interesting questions that arise during the course of measurements and to resolve ambiguities in results. Also, the instruments and facilities are limited to those on hand. With these caveats in mind, it is clear that a measurement field day cannot provide the same level of results as a research project that performs measurements over several months. This project was undertaken recognizing the shortcomings of the field-day format but, at the same time, with confidence that the data gathered could provide the basis for a meaningful assessment of the uses of the various instruments.

The performance of various meters has been reported by individual researchers (Deno and Silva, 1984; Chartier, Bracken and Capon, 1984; Looms, 1983). However, no direct comparisons of meter response in practical exposure situations were available. Therefore, it was our intent on the field day to include simultaneous measurements with exposure meters currently in use and to make these measurements under conditions that simulated real electric-field exposure situations.

Ultimately, two exposure meters were tested during the field day: a conducting vest and a small, shirt-pocket exposure meter. Both instruments are being used in 60-Hz electric-field exposure-monitoring projects. The conducting vest has been developed under EPRI sponsorship and is currently being used in research to evaluate human exposure to 60-Hz fields through measurements and modeling techniques (Deno and Silva, 1984; Silva, Zaffanella, and Hammon, 1984). The second meter available for testing was a small electric-field exposure meter (EFEM) developed by the BPA. It is currently being used to collect data on occupational electric-field exposure among BPA workers (Chartier, Bracken, and Capon, 1984). Persons involved in developing and using these meters participated in the field day. Also included among the 11 participants were engineers and physicists previously involved with field measurements and dosimetry, and representatives of research sponsors.

EXPOSURE PARAMETERS AND CONCEPTS

When describing environmental factors, in most cases a parameter exists which can be used to measure exposure. However, in the case of 60-Hz electric-field exposures, a mechanism for biological effects has not been established, and a relevant exposure parameter has not been identified. Possible candidates for the exposure parameter include unperturbed electric field, local surface field, local induced current density and total induced current. These quantities are not independent and may be related by measurements and/or modeling.

Similar uncertainty exists as to the appropriate way of characterizing the dose of exposure to 60-Hz fields. Is there a threshold for effects? Should exposures be accumulated over time? Without an identified mechanism for effects, it is impossible to answer such questions. However, meaningful exposure measurements can be made to determine relative exposures among groups and to identify important variables.

In the absence of a clear choice of exposure parameter or measure of dose, the general practice has been to relate measured exposures to an unperturbed, uniform electric field. Several concepts are in use to accomplish this. Measured exposures can be stated in terms of an "equivalent electric field." The equivalent electric field is the unperturbed, uniform electric field that would produce the same measured exposure as the one observed in a more complex situation. Since exposure meters are affected by the wearer's posture, the meter response in the equivalent field refers to a standard reference position: standing erect, arms at the side, and grounded.

The "activity factor" also relates measured exposures to an unperturbed electric field. The activity factor is the ratio of measured exposure in a known field to the theoretical exposure in the same field in the standard reference position. For uniform fields, the activity factor is the ratio of the equivalent electric field to the measured electric field.

The "enhancement factor" for a particular meter location on the body is the ratio of the surface field at that location to the uniform, unperturbed field. The enhancement factor at a given location does not have a single value. For example, in the shirt pocket the enhancement factor will depend on posture, arm position, and grounding status. Thus, to characterize exposure, an average enhancement factor is necessary. The field-enhancement factor can then be used to convert measured exposures to equivalent unperturbed field exposures.

In the results reported here, comparisons of exposure measurements are made in terms of the unperturbed electric field.

EXPOSURE METERS

Two exposure meters were tested during the field day.

Conducting Vest

As an extension of small, battery-powered dosimeters, Deno and Silva (1984) developed a conducting vest for use as an exposure measuring device. The latest version of the vest, which is being used in ac exposure measurement studies, was tested during the field day. The increased surface area and more symmetrical shape of the vest make its response less susceptible to body orientation and shielding than smaller meters that measure local field. A detailed description of the vest is given in Deno and Silva (1984).

Exposure data were accumulated in five electrolytic cell memories which correspond to the five equivalent field ranges in Table 1. The current in each field range is integrated over time. Exposures are thus recorded as the time integral of the electric field: $\int Edt$, where E is the average electric field over the surface of the vest. Because of the large surface area, the vest is sensitive to relatively low fields; the maximum for the lowest range is about 50 V/m. The highest equivalent field for which the time integral of the field was recorded is about 6.7 kV/m. Direct readout of vest current with a hand-held microammeter did not affect the response.

TABLE 1. Electric Field Range (in kV/m) for Conducting-Vest Electric Field Exposure Meter

Range	Equivalent Field
1	0.054
2	0.054 - 0.27
3	0.27 - 1.34
4	1.34 - 6.7
5	6.7

BPA Electric-Field Exposure Meter (EFEM)

A small (5.6 x 7.0 x 1.3 cm) EFEM was developed by BPA for deployment in a large occupational exposure study (Chartier, Bracken and Capon, 1984). The EFEM device has been miniaturized to the extent that it can be worn comfortably by employees over the course of a workday. The BPA device has been worn in a shirt pocket, on a lanyard and on a hard hat. Among workers, the shirt pocket is the preferred location.

Small exposure meters have also been worn in an armband on the upper arm during exposure studies (Deno, 1979; Looms, 1983). Therefore, the EFEM locations used during testing were the shirt pocket, armband and hard hat.

Essentially, a time histogram of exposure at various field levels was stored in eight digital counters or bins. A ninth counter recorded the total time the instrument was turned on and could be used to determine the time spent in fields above those recorded in the other eight bins.

The electric-field ranges tested are shown in Table 2. The unperturbed field in the second column refers to the field at the surface of an EFEM which was flush-mounted in a parallel-plate exposure system. The field range, in terms of the unperturbed field a person enters, depends on where the device is worn. Bin ranges for standing erect and grounded in a uniform field are shown in Table 2 for the shirt-pocket and hard-hat locations. Enhancement factors of 4.6 and 7.4 have been assumed, respectively, for these locations (Chartier, Bracken and Capon, 1984).

A direct readout capability of the EFEM, using an optical fiber link, was used to measure enhancement factors at each location for each subject during the field day.

Meter Comparison

Comparison of the measured exposures for the two meters cannot be done directly because they record different parameters. The vest records accumulated exposures in various field ranges in (kV/m) h. In this format the amount of time at a particular field level is not recorded. The EFEM records a time histogram of exposure in seconds; however, within the range of fields for each bin there is no record of field strength. To convert the time histogram to accumulated exposure it is necessary to assign a field for each bin and calculate the product of time and field. Choice of the minimum or maximum field for a particular bin yields a minimum or maximum accumulated exposure in that bin. This range of accumulated exposures can then be compared with predicted exposures or with exposures measured by the vest.

TABLE 2. Electric-Field Ranges (in kV/m) for BPA Electric-Field Exposure Meters Tested During the Field Day. (EF is Enhancement Factor.)

Bin Number	Unperturbed Field	Shirt Pocket EF = 4.6	Hard hat EF = 7.4
0	0 - 1	0.00 - 0.22	0.00 - 0.14
1	1 - 3	0.22 - 0.65	0.14 - 0.41
2	3 - 6	0.65 - 1.3	0.41 - 0.81
3	6 - 10	1.3 - 2.2	0.81 - 1.4
4	10 - 15	2.2 - 3 3	1.4 - 2.0
5	15 - 21	3.3 - 4.6	2.0 - 2.8
6	21 - 28	4.6 - 6.1	2.8 - 3.8
7	28 - 36	6.1 - 7.8	3.8 - 4.9
x[a]	>36	>7.8	>4.9
8[b]	Total Time	0 - 9.2 h	0 - 9.2 h

[a] x = Total Time (Bin 8) - Σ Times in other bins

[b] 9.2 h is maximum time countable by EFEM.

The field ranges are also different for each instrument, which further complicates comparisons. The range of the vest allows measurement of very low field levels but does not offer much resolution at the higher fields (above 1 kV/m) which are associated with occupational exposures. The EFEM, a small device, is not very sensitive to the low fields but with eight bins has resolution at the levels associated with occupational exposures. Because the higher field range is common to both instruments it was necessary to test the meters at these levels to yield useful comparisons.

TEST DESCRIPTIONS

Bench Tests

Three types of tests can be performed to compare the responses of exposure meters: bench tests, static tests and dynamic tests. During bench tests, the meter is not worn by an individual, and only the electronic components of the meters are calibrated and tested. The response of the signal-processing, data-processing and data-storage functions can also be evaluated in terms of a known input. Bench tests include current injection, exposures in parallel-plate exposure systems, frequency response, susceptibility to electromagnetic interference and spark discharges, and the effects of temperature and humidity. Because of the short duration of the field day, bench tests were not possible. However, bench tests made by the developers of the devices do not indicate any serious deficiencies with respect to these variables.

Static Tests

Static tests refer to exposures, usually in a uniform vertical field, during which the wearer of the meter remains stationary. The response of the meter is investigated as a function of various parameters, such as field strength, clothing, subject height, etc. The meter response is also compared with values of short-circuit body current and other exposure variables. Direct real-time readout of the meters is preferred for evaluating this type of test.

Static tests during the field day were performed in a uniform vertical field under the BPA 17.9-m-high, single-phase, ultrahigh-voltage (UHV) test line. The measured field at 1 m above ground level was 1.84 kV/m for 100 kV on the test line. The results of several static tests performed during the field day are discussed in the Results section.

Dynamic Tests

Dynamic tests involve moving test subjects in actual or simulated conditions of field exposure. These tests provide information about the actual performance of the meter as an exposure-monitoring device. Because of the importance of dynamic tests in comparing meter performance, considerable effort was expended to accurately simulate occupational exposure situations.

In order to produce realistic simulated tests that could be performed in a reasonable length of time during the field day, the activities of several BPA employees were analyzed by task, posture, and orientation relative to the field and grounded equipment. The employees selected for activity analysis were a crew of substation maintenance electricians and a 500-kV substation operator. The electricians worked in both 230- and 500-kV facilities. These two job categories had previously been identified as having relatively high exposures (Bracken, 1983). The subjects were videotaped during performance of routine work tasks.

Electricians' Tasks Simulations

From observations of electricians working in 230- and 500-kV substations, two tasks were chosen for simulation. The first entailed working from the bucket of a man-lift vehicle at 4 to 6 m above the ground. A ground strap was bolted to structural members on two sides of the tower supporting the single-phase test line, and the electrician performing the task worked with both his back and sides to the line while facing the tower structure. The second simulation involved placing and removing a ground lead, using a hot-line maintenance tool about 4 m in length. This task was also performed near the test-line tower.

Fields were measured near the test line tower where the electrician's tasks were simulated. Measurements were made at 1 m from the tower surface at several heights. The electric fields as a function of height are shown in Figure 1A; these values have been normalized to 300 kV on the test line. Field measurements were made from a bucket truck with a free-body electric-field meter located at least 2 m away from the grounded bucket. Simulations of the electrician's task in the bucket were performed at a height of about 5 m. At this location, with 300 kV on the test line, the vertical field 1 m from the tower was approximately 1 to 2 kV/m, and the maximum field was 4 to 5 kV/m. At the base of the tower where the ground-level task was performed, the vertical field was 1.1 to 1.8 kV/m, and the maximum field was 1.4 to 2.9 kV/m (Figure 1B).

Substation Inspection Simulation

Based on observation and analysis of a walking inspection of a 500-kV substation, a simulated inspection of the J. D. Ross 230 kV Substation was incorporated in the field day. An inspection route was laid out in the 230-kV substation for subjects to follow. The total elapsed time of the simulated inspection was approximately 1070 sec. Electric-field measurements were made at 10-sec intervals along the route, and the measurement locations were categorized as being "in the open" or "near equipment." For the 107 measurement locations, 59% of the time was spent in the open and 41% was spent near equipment. These proportions are comparable to the division of time observed during the 500-kV substation inspection.

The distribution of the magnitude of the fields measured at 10-sec intervals is shown in Figure 2. The maximum field of 7.3 kV/m fell, in almost all cases, within the recording ranges of both field meters. During the field day, confirming measurements at several random locations were made by participants as they learned the route. In all cases, the fields measured by participants agreed with the previous measurements.

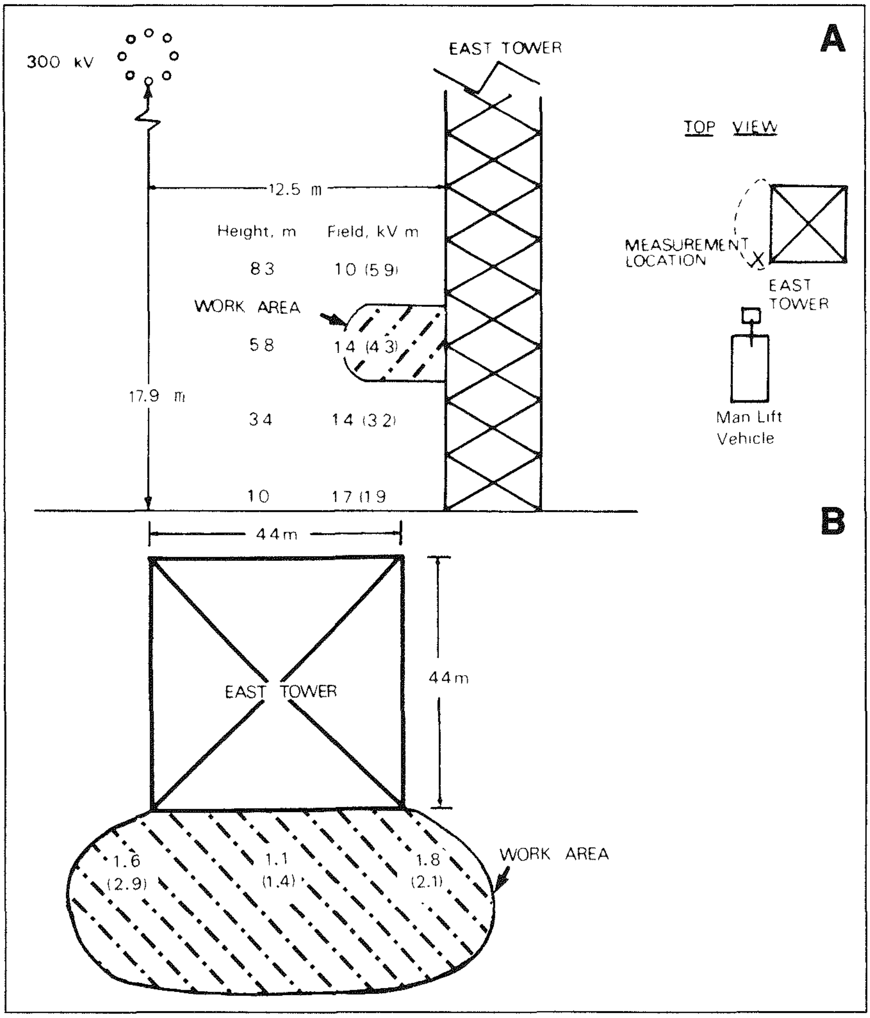

Figure 1. Field Measurements 1 Meter from Test-Line Structure: A, Fields as a Function of Height; B, Fields Measured 1 m from Base of Tower. Measurements adjusted to 300 kV. Maximum fields in parentheses.

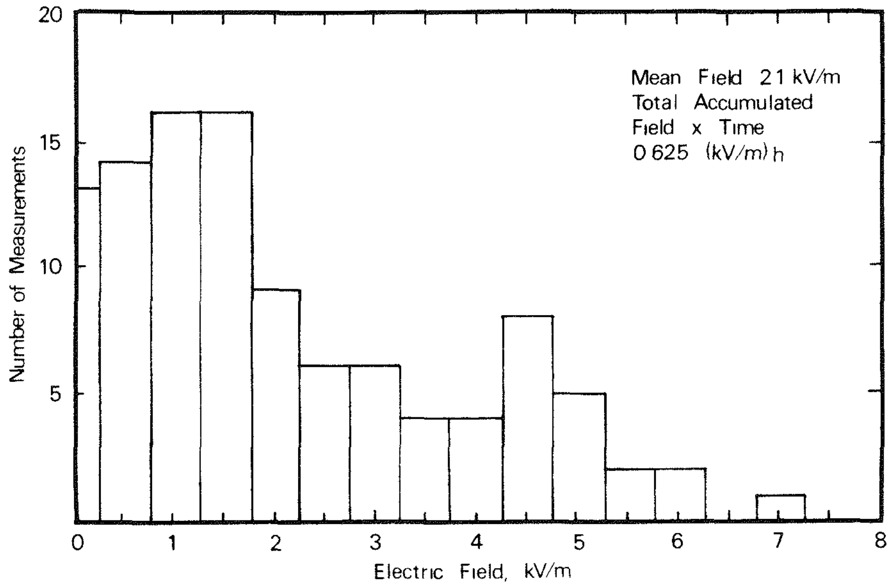

Figure 2. Distribution of Electric-Field Measurements made at 10-Sec Intervals along 230-kV Substation Inspection Route.

The route was marked with white stones to ensure that all participants followed a similar path during their simulated inspection. Before measurements were made, all participants were led along the route. Locations of meters or gauges on equipment were flagged, and participants were instructed to stop at each flag for approximately 10 sec to simulate a reading of the meter or gauge. During the simulated inspection, when exposure measurements were being made, the participant was accompanied by a substation operator to comply with safety requirements. The operator and participant were instructed to space themselves several meters apart to avoid shielding the participant.

RESULTS

Subjects

The responses of the vests and EFEM were measured on each subject while they stood in the reference position in a known uniform field under the BPA UHV test line. These measurements provided an individual calibration of the field ranges of each meter for each subject. The results for the five subjects (identified by letter) involved in the dynamic tests are shown in Table 3. The threshold field refers to the edge of the first storage location (bin) for the standard posture. For the vest, this corresponds to the field that induces 0.3 mA in the standard posture. For the EFEM, the threshold field corresponds to the field that results in a 256-Hz output from the voltage-to-frequency converter of the meter. The threshold field values and the multiples corresponding to higher bins were used to estimate accumulated exposures for the EFEM.

TABLE 3 Meter Responses with Subject in Standard Reference Position The EFEM locations, shirt pocket, armband, and hard hat, are denoted SP, AB, and HH, respectively The sensitivity of the shirt pocket EFEM was twice that of the EFEM used in other locations

		I_{SC}, μA		Threshold Field, kV/m			
Subject	Height, m	Total Body	Vest	Vest	SP	AB	HH
B	1 83	19 1	5 96	0 05	0 29	0 26	0 26
C	1 83	20 5	6 14	0 05	0 24	0 29	0 24
E	1 85	20 8	6 52	0 05	0 32	0 34	0 35
F	1 70	17 1	5 96	0 05	0 30	0 31	0 29
G	1 83	21 1	6 14	0 05	0 28	0 27	0 33

Variations in meter response among subjects were greatest for the hard-hat location and least for the vest location. Surprisingly, the subject with the highest normalized vest current had the lowest EFEM readings. Generalization to the variations in a larger population is not possible from this small homogeneous sample The comparison of the direct readout meters with the data storage meters indicated that responses were equivalent, within the range of experimental uncertainty, for these two modes of operation

Effect of Grounding the Subject

The resistance to ground of the subjects was varied from 0 Ω to >> 10 MΩ. The latter value refers to standing on a 0.63-cm-thick, insulating rubber mat. While wearing the vest, subjects grounded themselves by grasping the case of a microammeter tightly in their hands. The microammeter read the current going from the vest to ground through the subject and a variable resistor.

While measuring EFEM response to changes in grounding status, the subjects gripped a wire connected to earth through a variable resistor. The direct-readout EFEM was used to observe changes in the field at the three EFEM locations.

The effects of grounding on the responses of the two types of exposure meters are summarized in Table 4 The parameter used is the ratio of insulated-condition to grounded-condition meter response for the standard exposure posture. This ratio is essentially the activity factor for the meters in the insulated condition. It is well-defined for the direct readout mode of both the vest and the EFEM and for the storage mode of the vests. However, the ratio is not well-defined for the EFEM in the storage mode because of the finite bin width. In addition, changes in fields at the surface of the EFEM can occur even during a static test. These variations can result in counts in more than one bin during the same test conditions. The difference in the response of the vest in the direct readout mode and in the storage mode is attributed to some shielding of the vest by the hand-held microammeter

TABLE 4. Summary of Observed Ratios of Insulated-to-Ground Response for Standard Exposure Position, Measured at 5.5 kV/m. The EFEM locations, shirt pocket, armband, and hard hat, are denoted SP, AB, and HH, respectively. The sensitivity of the shirt pocket EFEM was twice that of the EFEM used in other locations.

Subject	Type of Meter	Direct Readout	Accumulated
B	Vest	0.82	0.88
D	EFEM (SP)	0.68	0.30 - 1
D	EFEM (AB)	0.71	0.48 - 1
D	EFEM (HH)	0.79	1

These results indicate that the reduction in measured exposure because of changes in grounding status is, at most, about 30%. In the case of the EFEM, this change cannot be readily distinguished in the accumulated exposure data.

The EFEM locations were all on the upper half of the body; consequently, the field at these locations, in the insulated condition, is lower than in the grounded condition. As expected, the least change is seen at the hard-hat location. An observation made with subject C demonstrated the reverse situation for fields on the lower portion of the body. The EFEM response on the outside of the ankle was 540 Hz when the subject was grounded and 1567 Hz when the subject was insulated.

Activity factors for shoes, also measured for various subjects, ranged from 0.69 to 0.90. These measurements, made with the vest, compared grounding through a gripped wire with grounding through the shoe soles. The lowest value represented synthetic soles standing on asphalt. The highest activity factor was for leather soles on a grounded aluminum plate. These values are consistent with the results for the grounded and insulated conditions given in Table 4.

Meter Interaction

The responses of the vest and EFEM when worn separately or simultaneously were measured. The EFEM was placed in the left-hand pocket of a polyester shirt worn over the vest. The same shirt was used by all subjects in the exposure tests. Subject B stood erect and grounded in a 5.5-kV/m field and was grounded by gripping the microammeter case in his right hand. His left arm was held at the side to avoid shielding the left-hand shirt pocket, where the EFEM was located.

The presence of the EFEM in the shirt pocket over the vest did not affect the measured short-circuit current of the vest. The EFEM response increased 3% when worn over the vest. This could be due to a slight difference of position or location of the EFEM when worn over the vest; however, this small difference is not significant and is well within the range of variations for EFEM measurements made at the same location at different times. For comparison purposes then, the meters can be worn simultaneously without degrading or affecting the performance of either type.

Bucket-Truck Simulation

The simulation of operations routinely performed by an electrician in a bucket truck was carried out by an electrician (Subject G). This subject was familiar with the use of the tools employed, the operation of the man-lift vehicles, and the applicable safety rules. He wore the vest and, simultaneously, three integrating EFEM, located in the shirt pocket, on an armband and on his hard hat. After the task was completed (810 sec), the EFEM were removed and read out sequentially. Therefore, the accumulated times for the three EFEM were different; the last two read had progressively longer recorded times. This additional time was subtracted from the lowest bins to reflect the low field at the location where the readouts were performed.

As shown in Figure 1A, the unperturbed fields measured at the work location were approximately 1.4 kV/m vertical and 4.3 kV/m maximum. Because the work platform and railings around it are metal and grounded, the field in the vicinity of the subject was perturbed from these values.

The measured exposures for the bucket-truck simulation are given in Table 5 in terms of several exposure variables. For the vest, the integrated exposure in (kV/m)h is given by field-strength range and in the aggregate. The largest accumulated exposure was measured in the 1.17- to 5.86-kV/m equivalent field range. The average equivalent field estimated from the integrated exposure and the elapsed time was 1.3 kV/m, which is considerably below the unperturbed maximum field of 4.3 kV/m.

For the EFEM, data in Table 5 are given in terms of time measured in a field range. From these data, bins with maximum exposure time can be identified and a median field estimated. By computing accumulated exposure, field ranges with the highest accumulated exposure can be identified, total accumulated field can be estimated, and an equivalent field can be estimated.

TABLE 5A. Exposures Measured by Vest Exposure Meter for Bucket-Truck Task Simulation. Elapsed time: 810 seconds.

Range, kV/m	Accumulated exposures, (kV/m)h
0 - 0.05	0
0.05 - 0.24	0.001
0.24 - 1.22	0.081
1.22 - 6.11	0.218
6.11	0.002
Total:	0.30 (kV/m)h
Equivalent Field:	1.33 kV/m

TABLE 5B. Exposures Measured by Shirt-Pocket EFEM Exposure Meter for Bucket-Truck Task Simulation. Elapsed time: 810 seconds.

Bin	Range, kV/m	Recorded time, sec	Estimated Exposure (kV/m)sec	
			Minimum	Maximum
0	0 - 0.28	208	0	58
1	0.28 - 0.85	348	97	296
2	0.85 - 1.70	148	126	252
3	1.70 - 2.83	52	88	147
4	2.83 - 4.24	48	136	204
5	4.24 - 5.94	0	0	0
6	5.94 - 7.92	0	0	0
7	7.92 - 10.19	0	0	0
x	10.19	0	0	0
Total (kV/m sec):		804	447	957
Total (kV/m h):			0.12	0.27

Equivalent field (minimum): 0.6 kV/m
(maximum): 1.2 kV/m
Median equivalent field: 0.6 kV/m

TABLE 5C. Exposures Measured by Armband EFEM Exposure Meter for Bucket-Truck Task Simulation. Elapsed time: 810 seconds. Excess recorded time denoted by parentheses.

Bin	Range, kV/m	Recorded time, sec	Estimated Exposure (kV/m)sec	
			Minimum	Maximum
0	0 - 0.27	0 (120)	0	0
1	0.27 - 0.82	84 (104)	23	69
2	0.82 - 1.63	168	138	274
3	1.63 - 2.72	184	300	500
4	2.72 - 4.08	308	838	1257
5	4.08 - 5.71	68	277	388
6	5.71 - 7.62	0	0	0
7	7.62 - 9.79	0	0	0
x	9.79	0	0	0
Total (kV/m sec):		812 (952)	1576	2488
Total (kV/m h):			0.44	0.69

Equivalent field (minimum): 1.9 kV/m
(maximum): 3.1 kV/m
Median equivalent field: 2.5 kV/m

TABLE 5D. Exposures Measured by Hard-Hat EFEM Exposure Meter for Bucket-Truck Task Simulation. Elapsed time: 810 seconds. Excess recorded time denoted by parentheses.

Bin	Range, kV/m	Recorded time, sec	Estimated Exposure (kV/m)sec Minimum	Estimated Exposure (kV/m)sec Maximum
0	0 - 0.33	20 (124)	0	7
1	0.33 - 0.98	504	166	494
2	0.98 - 1.97	196	192	386
3	1.97 - 3.28	52	102	171
4	3.28 - 4.92	40	131	197
5	4.92 - 6.89	0	0	0
6	6.89 - 9.18	0	0	0
7	9.18 - 11.81	0	0	0
x	11.81	0	0	0
Total (kV/m) sec:		812 (916)	591	1255
Total (kV/m) h:			0.16	0.35

Equivalent field (minimum): 0.7 kV/m
(maximum): 1.6 kV/m
Median equivalent field: 0.8 kV/m

At the armband location the EFEM measured higher exposure, by a factor of about two, compared with the other EFEM locations, probably because of the position of the subject relative to the grounded tower. During a significant portion of the task, the subject was facing toward the tower, looking down at his hands. In this position, the front of the body (shirt-pocket and hard-hat locations) would be shielded more than the side of the body (armband location).

In terms of average effective field and total integrated exposure, the hard-hat EFEM compared most favorably with the vest. The armband values were higher, and the shirt-pocket values lower, than comparable values from the vest. Again, these differences may be accounted for by the shielding effects of the predominant orientation. The vest is shielded, to some extent, by orientation and also by the metal railings of the work platform.

The results in Table 5 are indicative of the range of exposure measurements expected from various sensors. Integrated exposure and estimated average field vary by at least a factor of two.

Ground-Task Simulation

A task similar to that performed in the bucket was also performed on the ground by subject G; the difference was that the ground clamps were placed and removed using an insulated hot-line maintenance tool. The elapsed time for this task was 608 sec. The fields near the tower base, where the task was performed, are given in Figure 1B.

A summary of the measured exposures for the ground-level task is given in Table 6. These are cumulative measures of exposure. The detailed exposure and time distributions for this task demonstrate similar characteristics to the distributions for the bucket-truck simulation.

TABLE 6. Measured Exposure for Ground-Level Electricians' Tasks. Elapsed time: 608 seconds.

Vest		
Total accumulated exposure: 0.41 (kV/m)hr		
Equivalent field: 2.4 kV/m		
EFEM, shirt pocket		
	Minimum	Maximum
Total accumulated exposure:	0.18	0.31 (kV/m)h
Equivalent field:	1.0	1.8 kV/m
Median equivalent field:	1.0 kV/m	
EFEM, armband		
Total accumulated exposure:	0.38	0.58 (kV/m)h
Equivalent field:	2.1	3.4 kV/m
Median equivalent field:	2.6 kV/m	
EFEM, hard hat		
Total accumulated exposure:	0.52	0.75 (kV/m)h
Equivalent field:	2.9	4.4 kV/m
Median equivalent field:	2.9 kV/m	

For the ground-level task, the hard-hat location measured larger exposures than the vest. The range of possible exposures measured at the armband location was consistent with measurements made with the vest. The shirt-pocket data were, again, low when compared with those from the vest and the other EFEM locations. Shielding while facing the tower during a significant portion of the task accounts for the relatively low exposures measured at the shirt pocket. However, the relative difference between hard-hat and armband measurements is different from those measured for the bucket-truck task. Without repetitive and more detailed observations of both tasks, the source of this change cannot be identified explicitly. One possible explanation lies in the orientation of the subject's head during the two tasks. For the bucket-truck operation, work was performed at about waist or chest height, and the head was tilted forward. For the ground-level task, the work was performed overhead with a long insulated tool, and the subject's head was tilted back to observe the work location. This latter position would tend to increase the enhancement factor at the hard-hat location.

The results (Table 6) again demonstrate the amount of variation that can be expected in exposure measurements made with different instruments during the performance of even a simple task; the estimates of equivalent and of maximum integrated exposure vary by more than a factor of two.

The measured exposures for the ground-level task are higher than those for tasks in the bucket truck except for the ones measured with the armband EFEM. This is surprising, because the unperturbed fields at the bucket location are greater, and the time for the bucket task was 33% longer than for the ground- level task. The result emphasizes how dramatic the effects of shielding and body position can be when working in and near grounded objects.

Substation Inspection Simulation

The most extensive dynamic exposure measurements were made during the simulated inspection of the 230-kV BPA Ross Substation. Four subjects (B, C, E and F) participated in the simulated substation inspection, wearing the vest and three EFEM simultaneously. Responses of the instruments when the subjects were standing in the reference position are given in Table 3.

The elapsed time for the simulated substation inspections ranged from 15 to 17 min, which corresponded to the amount of time the vest was switched on and was recording data. Recorded times for the EFEM were longer than for the vest; presumably, this excess occurred in the substation control house during the initial placing of the instruments or during readout.

The fields measured at 10-sec intervals along the inspection route were described in Figure 2. The mean measured field, 2.1 kV/m, and the median measured field, 1.7 kV/m, were used to construct hypothetical exposures for comparison with the actual measurements.

A summary of the accumulated exposure measurements for each subject is given in Table 7. These values have been normalized to a 1070-sec inspection for all subjects by assuming a linear relationship between exposure and time.

The total accumulated exposures measured by the vest agree well for all individuals. The average measured exposure of 0.42 (kV/m)h represents a reduction by a factor of 0.67 from that predicted from electric-field measurements. A large portion of this 0.67 activity factor for the substation inspection can be attributed to shoe resistance; factors for shoes for the various subjects on asphalt ranged from 0.7 to 0.8. We assumed these values to be valid also for the dry rock, asphalt and concrete in the substation.

Total accumulated exposure estimates from the EFEM were fairly consistent across subjects for each EFEM location. However, the ranges of total exposure exhibited by the shirt-pocket EFEM were lower than exposures measured at the two other locations or with the vest. The various activities involved in the substation inspection, such as walking, with arm movement, and approaching equipment, shielded the shirt-pocket location more than the others.

The normalized total exposures from the hard-hat and armband locations were consistent within and across subjects. The normalized exposure ranges for the EFEM in these two locations (with two exceptions) encompassed all exposures measured with the vest on all subjects.

The mean and median equivalent fields calculated from the total accumulated exposure data and from the time distribution by EFEM bin, respectively, are lower than the mean and median of the measured field. These lower values from exposure data are, of course, another manifestation of inadvertent shielding of the meters.

TABLE 7. Summary of Exposure Data from Substation Inspection. Total exposure data normalized to 1070 sec for all subjects. The electric field exposure meter (EFEM) locations, shirt pocket, armband, and hard hat, are denoted SP, AB, and HH, respectively. The sensitivity of the shirt pocket EFEM was twice that of the EFEM used in other locations.

Total integrated exposure, (kV/m)h
Predicted from field measurements: 0.62 kV/m

Subject:	B	C	E	F	Average
Vest	0.46	0.42	0.39	0.39	0.42
EFEM-SP	0.21 - 0.42	0.15 - 0.30	0.23 - 0.47	0.13 - 0.31	0.28
EFEM-AB	0.31 - 0.55	0.29 - 0.53	0.21 - 0.45	0.26 - 0.52	0.39
EFEM-HH	0.32 - 0.57	0.48 - 0.75	0.31 - 0.59	0.30 - 0.58	0.49

Average Equivalent Field, kV/m
Predicted from field measurements: 2.1 kV/m

Subject:	B	C	E	F	Average
Vest	1.6	1.4	1.3	1.3	1.4
EFEM-SP	0.7 - 1.4	0.5 - 1.0	0.8 - 1.6	0.4 - 1.0	0.9
EFEM-AB	1.0 - 1.8	1.0 - 1.8	0.7 - 1.5	0.9 - 1.7	1.3
EFEM-HH	1.1 - 1.9	1.6 - 2.5	1.0 - 2.0	1.0 - 2.0	1.6

Median Equivalent Field, kV/m
Predicted from field measurements: 1.7 kV/m

Subject:	B	C	E	F	Average
EFEM-SP	0.8	0.5	0.8	0.6	0.7
EFEM-AB	1.1	1.0	0.8	0.9	1.0
EFEM-HH	1.0	1.3	1.1	1.2	1.2

Percent of Exposure Time Above EFEM Threshold
Predicted from field measurements: 88%

Subject:	B	C	E	F	Average
EFEM-SP	80	73	77	69	75
EFEM-AB	91	82	79	88	85
EFEM-HH	89	86	80	86	85

Comparison with Predicted Exposures

Because the field distribution was measured along the route, it is possible to predict the response of the exposure meters on a bin-by-bin basis. Predicted exposures for the various field ranges for the vest are shown in Figure 3. These predictions are based on a 1070-sec walkthrough of the substation. Also shown are the measured values, normalized to 1070 sec of total elapsed time for each of the four subjects. The largest predicted exposure occurred in the 1.34- to 1.67-kV/m range and coincided with the largest measured exposure. Measured exposures in the lower bins also agreed fairly well with predicted levels. However, the lack of measured exposure above 6.7 kV/m did not correspond to the predicted results for a perfectly grounded subject. If the activity factor of approximately 0.70 for shoes is included in the prediction, then no exposure would be expected in the highest range; this is, in fact, what was observed.

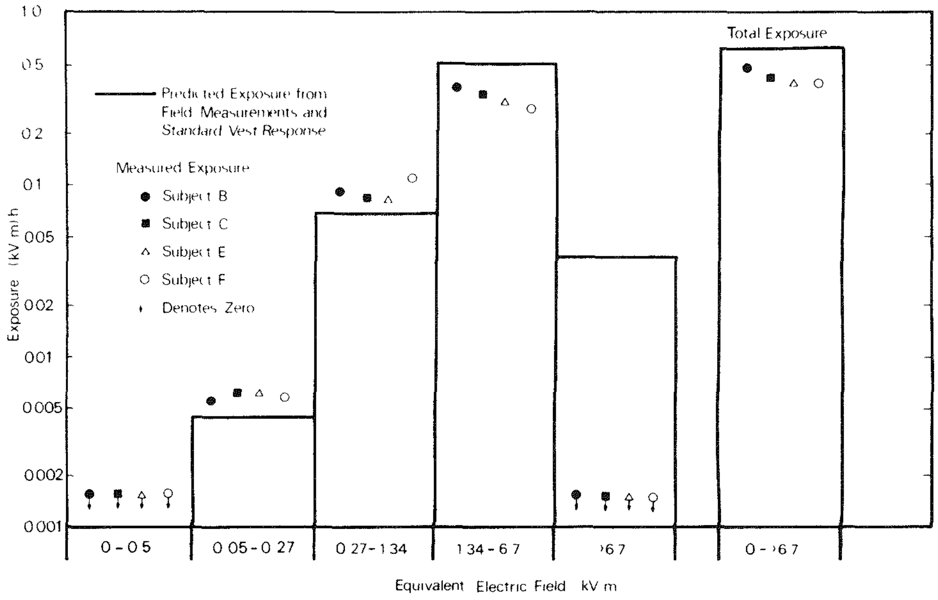

Figure 3. Measured and Predicted Integrated Exposures for Simulated Inspection of 230-kV Substation: *Measurements Recorded by a Vest Designed for the Purpose. Measured* exposures normalized to 1070-sec exposure.

Similar results are seen when the predicted and measured times are compared on a bin-by-bin basis for the EFEM in the shirt-pocket, armband and hard-hat locations, respectively, as shown in Figures 4, 5 and 6. The distribution of times measured in the EFEM bins was shifted lower than the predicted times, and very little time was observed in the higher bins, especially for the shirt-pocket location. Only the hard-hat location *showed consistent measured time in the higher bins.*

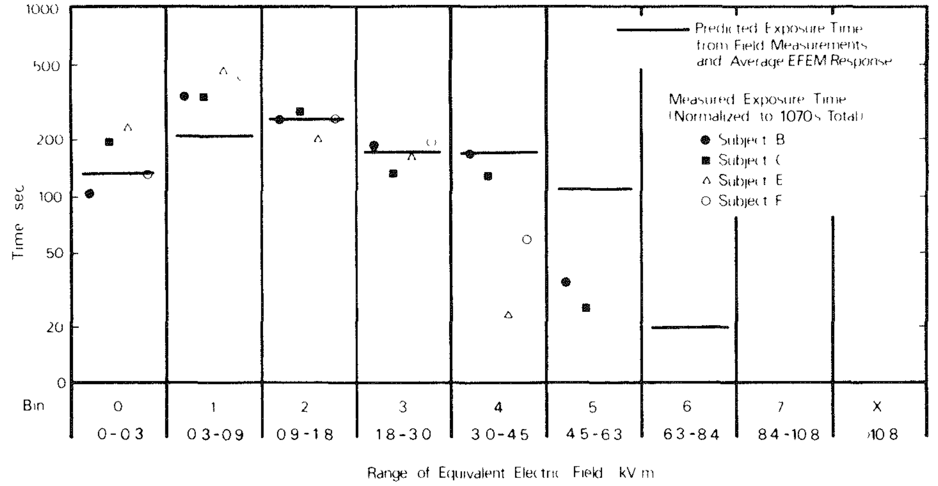

Figure 4. Measured and Predicted Exposure Times for Simulated Inspection of 230-kV Substation: Measurements Recorded by a Shirt-Pocket Electric Field Exposure Meter (EFEM). Measured time normalized to 1070 sec total elapsed time.

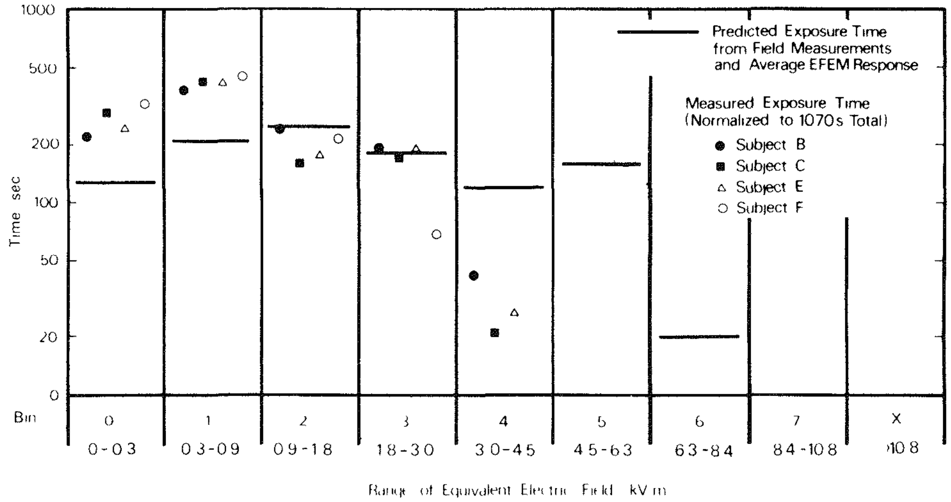

Figure 5. Measured and Predicted Exposure Times for Simulated Inspection of 230-kV Substation: Measurements Recorded by an Armband Electric Field Exposure Meter (EFEM). Measured time normalized to 1070 sec total elapsed time.

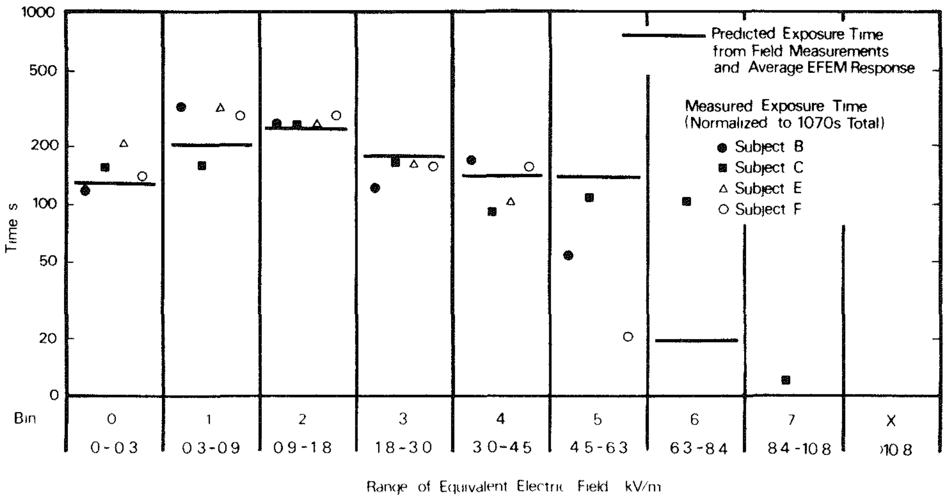

Figure 6. Measured and Predicted Exposure Times for Simulated Inspection of 230-kV Substation: Measurements Recorded by a Hard-Hat Electric Field Exposure Meter (EFEM). Measured time normalized to 1070 sec total elapsed time.

In summary, both the vest and EFEM showed general agreement with the predicted measurements for the substation inspection. If the measured effects of shoe soles are factored into the predictions, then the predicted and measured values would agree more closely. The differences between measured and predicted values were larger for the EFEM than for the vest.

CONCLUSIONS

Two electric-field exposure meters were evaluated in a limited series of exposure situations during a 3-day measurement field day. The meters were designed for different purposes and accumulated exposure in terms of different parameters. Nevertheless, the following conclusions can be drawn about their performances, comparability and consistency in measuring exposures to occupational electric fields.

- Measured electric-field exposures were lower than predicted. The accumulated exposures measured with the vest were 60 to 75% of the predicted exposures. The accumulated exposures estimated from EFEM measurements were 45 to 80% of predicted levels.

- A large portion of the lower-than-predicted values can be attributed to insulation provided by shoes, asphalt and dry rock in the substation.

- Total exposures measured with the vest were quite consistent across the subjects that performed the simulated substation inspection.

- Total exposures measured with the EFEM were fairly consistent across subjects for a particular EFEM location; however, the EFEM exhibited more variation than the vest.

- Exposures measured on the armband and hard hat were consistent with vest measurements. However, exposures measured at the shirt-pocket location were consistently lower than those measured with the vest and at other locations.

- The measured accumulated exposure profile of the vest and the time histogram of the EFEM reflected the unperturbed electric-field distribution with a shift to lower fields. The EFEM with the larger number of bins was better able to define this shift.

- Variations in measured exposure with the EFEM for even a simple, well-defined task can be large (± 30%) because of variations in shielding and peculiarities in body orientation.

- Given the large observed variations in both exposures and exposure measurements, both meters are sufficiently accurate to provide consistent quantification of electric-field exposure at occupational field levels.

ACKNOWLEDGMENTS

This project was supported by the Electric Power Research Institute (EPRI) under Contract RP 799-19. The support and encouragement of the EPRI project managers, Robert Kavet and Gordon Newell, are very much appreciated. This project would not have been possible without the support and assistance of the Division of Laboratories of the Bonneville Power Administration, who provided the facilities and support personnel for the field day. The author is indebted to the participants in the field day for their contributions. Special thanks go to Mike Silva, Don Deno, Paul Wong and Vern Chartier, who provided exposure-measuring devices for use in the testing.

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NUMERICAL CALCULATION OF INDUCED CURRENTS IN HUMANS AND EXPERIMENTAL ANIMALS EXPOSED TO ELF ELECTRIC FIELDS

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ABSTRACT

We have developed a charge simulation method for calculating induced currents in humans and experimental animals exposed to extremely low-frequency (ELF) electric fields. The induced currents are obtained from the cross-sectional area of the electric tube of force, which contains the same number of electric lines of force at each cross-section. The currents induced in the bodies of a human and of a mouse are calculated using the new method.

To assess the biological effects of extremely low-frequency (ELF) electric fields, the currents induced in the biological bodies may be as important as the surface electric fields. Some theoretical and experimental approaches have been taken to establish a general method to obtain the induced body currents (Kaune and Phillips, 1980; Guy et al., 1982; Deno, 1977; Spiegel, 1976 and 1981; Chiba et al., 1984; Shiau, 1981).

This paper proposes a new method for calculating the currents induced in humans and experimental animals exposed to ELF electric fields. The induced currents are obtained from the cross-sectional area of the electric tube of force (flux tube), which contains the same number of electric lines of force at each cross-section. Two tests of the calculation method were conducted. First, the current induced in a human body was calculated, assuming the body is axially symmetrical. Agreement between the calculation and actual measurement using a human model was reasonable. Second, the current induced in the body of a mouse was calculated using the three-dimensional shape of the body.

CALCULATION METHOD

Induced currents in an area, S, on the surface of the body can be obtained by the following equation:

$$I = j\omega \int_S \sigma \, dS, \qquad (1)$$

where σ is the surface charge density, given by

$$\sigma = \varepsilon_0 \bar{n} \cdot \bar{E} - \varepsilon \bar{n} \cdot \bar{E}_i \cong \varepsilon_0 \bar{n} \cdot \bar{E}, \text{ and} \tag{2}$$

ε_0 and ε are the permittivities of the air and the organ tissue, respectively; $\bar{E}$ is the surface electric field on the body; E_i is the electric field inside the body; and $\bar{n}$ is a vector of unit length perpendicular to the body surface. Substituting σ into Eq. (1), it becomes

$$I \cong j\omega \int_S \varepsilon_0 \bar{n} \cdot \bar{E}\, dS = j\omega \int_S \bar{n} \cdot \bar{D}\, dS, \tag{3}$$

where $\bar{D}$ is the surface flux density. As can be seen in Eq. (3), the induced current, I, is proportional to the sum of the surface fluxes that fall into the area S. Here, the value of $\int_S \bar{n} \cdot \bar{D}\, dS$ in Eq. (3) is constant at any cross- sectional area of the tube of force that contains the same number of electric lines of force.

In order to improve the accuracy of the calculation, the surface integral should be calculated at the place where $\bar{n} \cdot \bar{D}$ is constant. If $\bar{n} \cdot \bar{D}$ is constant and given as D_C, $\int_S \bar{n} \cdot \bar{D}\, dS$ becomes $D_C \times S_C$. Since D_C is a known value, the problem is reduced to obtaining the cross-sectional area, S_C, of the tube of force at the place where $\bar{n} \cdot \bar{D}$ is constant.

At this point in the calculation, the charge simulation method (CSM) is used to obtain the electric field. The details of the CSM are described elsewhere (Yializis et al., 1978). In the calculations for both the human and mouse, the assumption is made that they are standing on the ground, and that the uniform electric field, E_0, is vertical. For calculating the electric fields, the distributed charges on the surface of the biological body, which is assumed to be a perfect conductor (Kaune and Gillis, 1981), are replaced by n fictitious charges, arranged inside the body. In order to determine the magnitude of these charges, n contour points on the surface of the body were chosen. At any of these points, i, the potential resulting from the superposition of these charges must be equal to the given surface potential ϕ_C; i.e.,

$$\sum_{j=1}^{n} P(i,j) \cdot Q(j) = \phi_C - E_0 z(i), \tag{4}$$

where Q (j) is the discrete charge, P (i,j) is the associated potential coefficient, and z (i) is the z-component of the i-th contour point.

The application of this equation to n contour points leads to a system of n linear equations for n charges; i.e.,

$$\begin{bmatrix} P(1,1), & P(1,2), & \ldots, & P(1,n) \\ \vdots & \vdots & & \vdots \\ P(n,1), & P(n,2), & \ldots, & P(n,n) \end{bmatrix} \begin{bmatrix} Q(1) \\ \vdots \\ Q(n) \end{bmatrix} = \begin{bmatrix} \phi_C - E_0 z(1) \\ \vdots \\ \phi_C - E_0 z(n) \end{bmatrix} \tag{5}$$

After the charge Q(j) is obtained from this equation, the potential and the electric field intensity at a point k outside or on the surface of the body can be calculated by

$$\phi(k) = \sum_{j=1}^{n} P(k,j) \cdot Q(j) + E_0 z(k) \tag{6}$$

$$E_x(k) = \sum_{j=1}^{n} F_x(k,j) \cdot Q(j) \tag{7}$$

$$E_y(k) = \sum_{j=1}^{n} F_y(k,j) \cdot Q(j) \tag{8}$$

$$E_z(k) = \sum_{j=1}^{n} F_z(k,j) \cdot Q(j) - E_0, \tag{9}$$

where $F_x(k,j)$, $F_y(k,j)$ and $F_z(k,j)$ are the electric coefficients for x-, y- and z-directions, respectively.

The electric line of force that starts from an arbitrary point on the surface of the body can be calculated by iteration.

RESULTS

Induced Currents in a Human Body

The currents induced in a human body are calculated, assuming the body is axially symmetrical. The subject is a man about 160 cm tall. The outline profile of the man was obtained, using several image processing techniques (Kobayashi et al., 1982). Figure 1 shows the arrangements of the contour points and the fictitious charges (1 point charge, 25 ring charges and 4 line charges [Yializis et al., 1978] are used in the calculation). The same number and kinds of image charges occur at the opposite side of the ground.

Since the cross-section of the electric tube is a circle in this case, the induced currents at a height z in a human (whose total height is h) in an erect position with the feet grounded is given by

$$I(z) = j\omega\varepsilon_0 E_0 \cdot \pi r^2{}_0(z) = 2j\pi^2 f \varepsilon_0 E_0 r^2{}_0(z), \tag{10}$$

where $r_0(z)$ is a radius of the circular tube of force at the position where the electric field is considered to be a uniform value, E_0.

Therefore, the induced currents can be calculated by merely obtaining the distance of the electric line of force from the axis of rotation. Figure 2 shows some of the electric lines of force obtained.

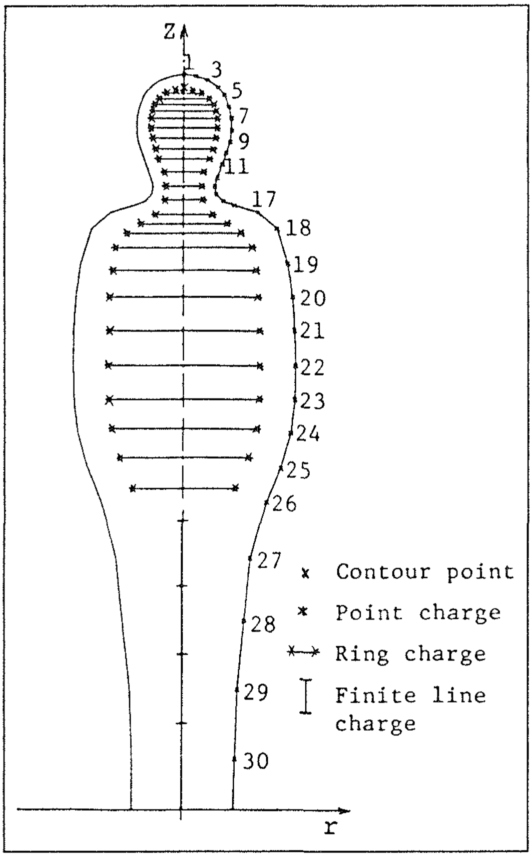

Figure 1. Arrangement of the Contour Points and Fictitious Charges for a Body Shape Obtained by Image-Processing Techniques. One point charge, 25 ring charges and 4 finite line charges were used.

If $z = 0$ in Eq. (10), the current is called a short-circuit current (I_{SC}). Figure 3 shows both calculated and measured I_{SC}. In the measurement, we used a phantom brass model (21.8 cm tall), which is axially symmetrical and has the same profile as that in the calculation. The model is divided into 11 parts perpendicular to the axis of rotation of the body, i.e., 11 thick disks. A parallel-plate electrode system was used to generate the vertical ELF electric field. Each electrode measures 2.0 x 2.0 m, and the upper electrode is supported 1 m above the lower electrode by four insulating posts. The model is placed at the center of the lower electrode.

In the measurement, the field intensity is varied from 0.0 through 37.5 kV/m. As can be seen in Figure 3, the results show good linearity. The average difference between measured and calculated intensity is about 5.4%. This is small enough to evaluate the I_{SC} in practice.

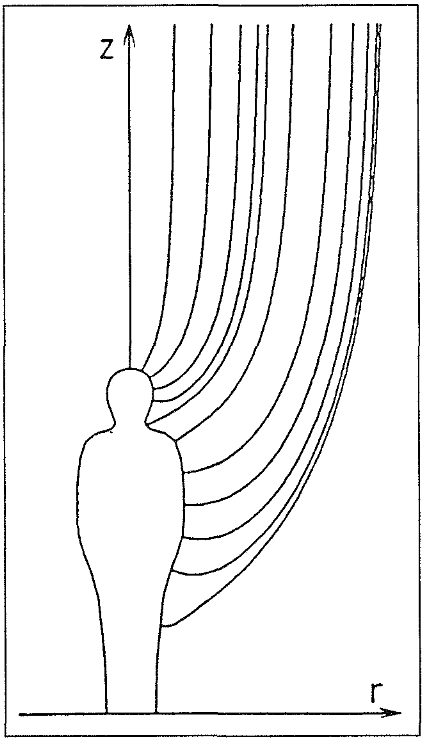

Figure 2. Calculated Electric Lines of Force.

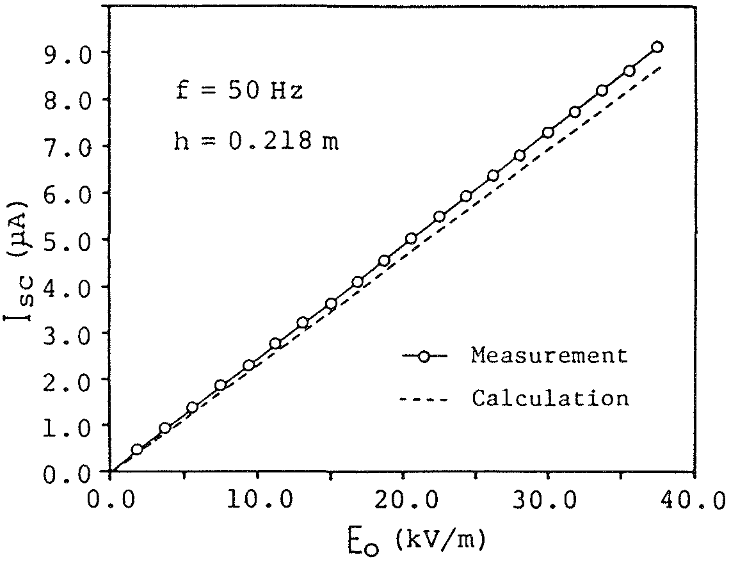

Figure 3. Induced Short-Circuit Current (I_{SC}). The electric field (50 Hz) was applied from 0.0 through 37.5 kV/m. The broken line is the calculated value.

Figure 4 shows the current distribution inside the body; the solid line indicates the calculated results. Agreement between measured and calculated values is reasonable.

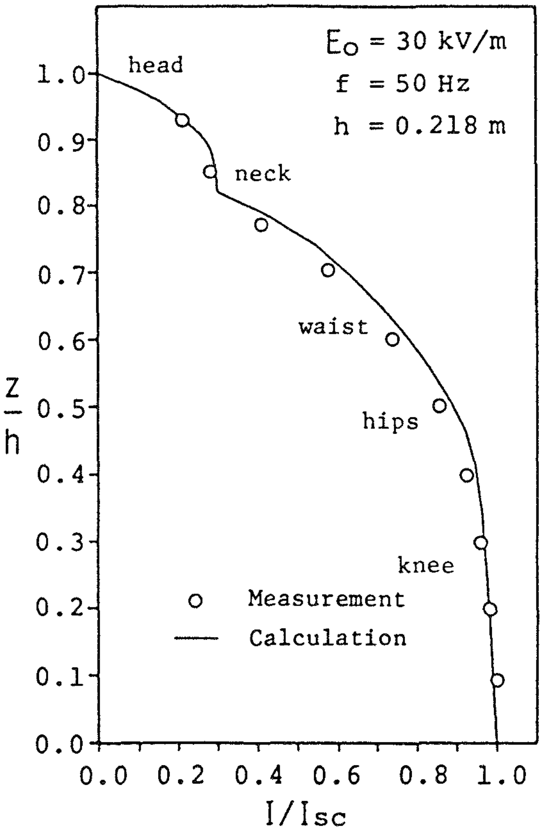

Figure 4. Induced Current Distribution Inside the Human Body. The solid line indicates the calculation. The intensity of the applied, unperturbed electric field was 30.0 kV/m.

Figure 5 shows the calculated induced current density in the body. We assumed that the induced current is distributed uniformly at each horizontal cross-section of the body. As shown in this figure, the current density is large at the neck and the legs.

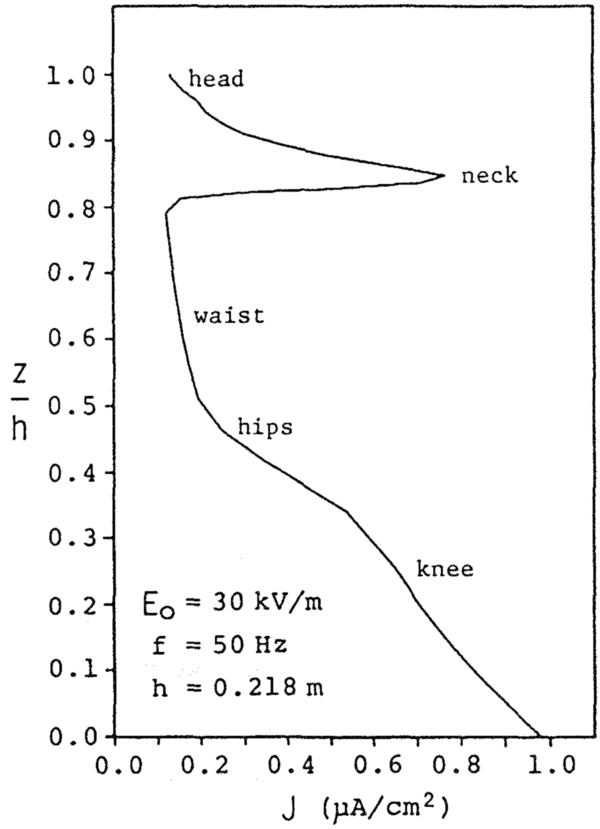

Figure 5. Calculated Induced Current Density Inside the Human Body. The intensity of the applied, unperturbed electric field was 30.0 kV/m.

INDUCED CURRENTS IN A MOUSE

The currents induced in the body of a mouse were calculated, using a male mouse about 20 weeks old, weighing 43 g. The mouse was allowed free movement and was photographed with 35-mm monochromatic film. The image on the film was transformed into a digital image (sampling matrix, 512 x 512, gray level, 7 bits), using a flying spot scanner. Figure 6 shows a photograph of the original digital image. In order to calculate the electric field and currents within the three-dimensional shape of the body, a 3-D phantom model (Figure 7) had to be made from this image. The image of the mouse was sliced vertically, and each slice was replaced with an appropriately sized circle that was considered to be the cross-section of the model.

After the 3-D geometry was obtained, certain contour points and fictitious charges were arranged (on the image) on the surface of the body and inside the body, respectively. In this calculation, 202 point-charges were used as the fictitious charges. The mouse was assumed to be on the ground with the feet grounded. Figure 8A shows the calculated cross-sectional area, S_C of the tube of force at the place where $\bar{n} \cdot \bar{D}$ is considered to be constant (20.0 cm above the ground). Each section corresponds to a tube that enters one of four parts of the body (divided into four segments by the planes at the neck, abdomen and tail). As mentioned before, the induced currents can be calculated directly from the S_C by

$$I = j\omega\varepsilon_0 E_0 S_C. \tag{11}$$

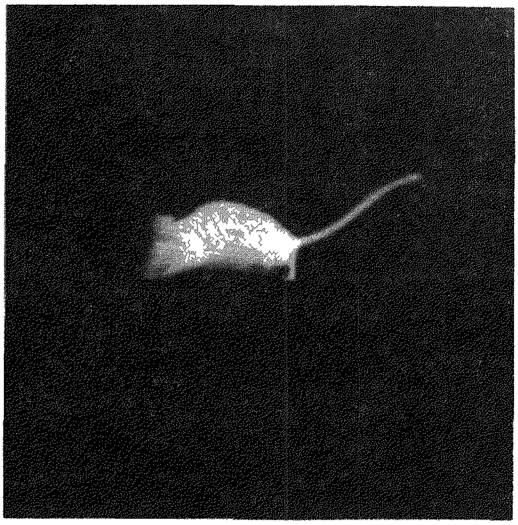

Figure 6. Original Digital Image of a Mouse, Used for Calculation.

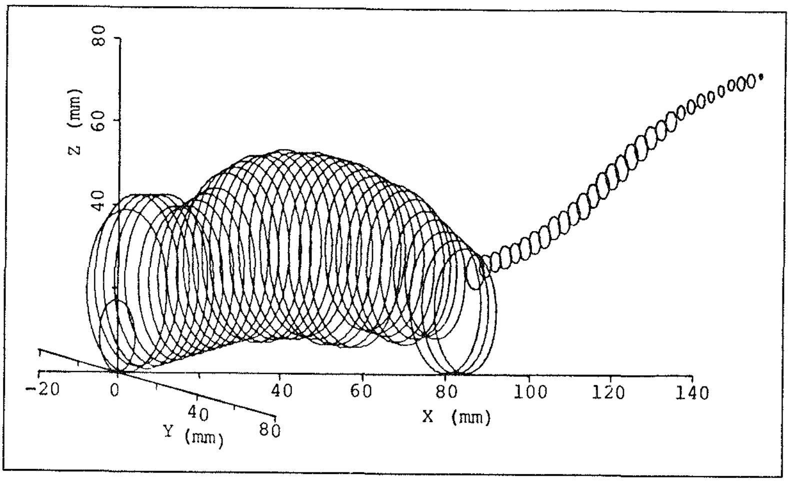

Figure 7. The Three-Dimensional Shape of a Mouse Obtained from the Original Image.

Figure 8B shows the percentage of the calculated currents induced in each part of the mouse's body which is exposed to a 50-Hz, 10-kV/m electric field.

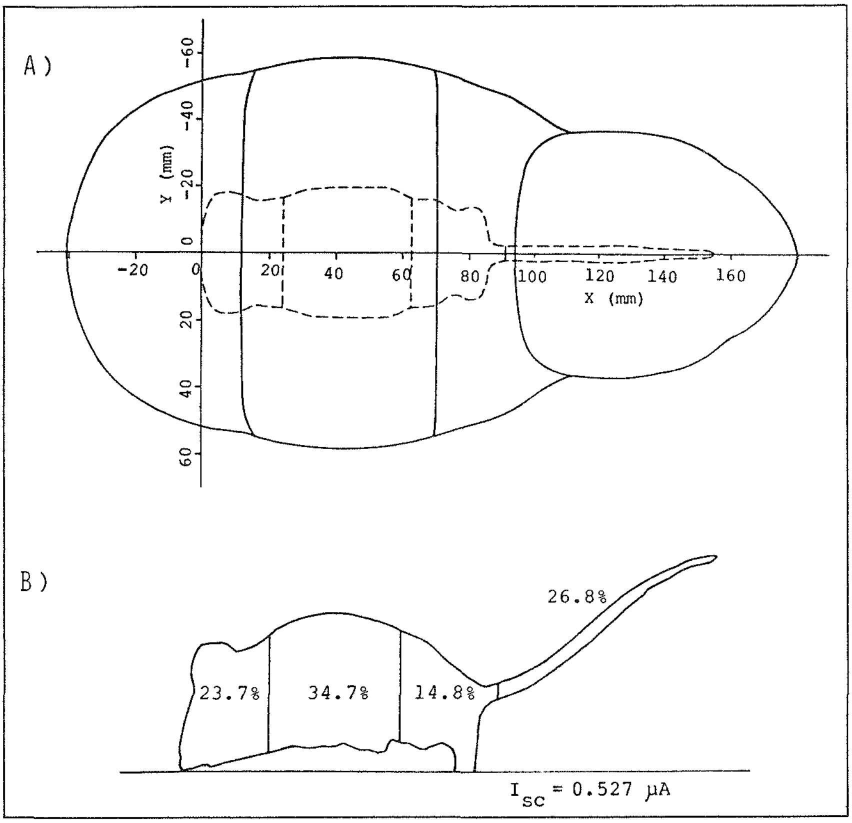

Figure 8. A. Calculated Cross-Sectional Area of the Electric Tube of Force at the Place where $\bar{n} \cdot \bar{D}$ is Considered Constant (20.0 cm above the ground). The broken line shows the top view of the mouse. B. Calculated Currents Induced in a Mouse Exposed to a 50-Hz, 10-kV/m Electric Field.

CONCLUSIONS

A method was developed for calculating induced currents in a body exposed to ELF electric fields. The induced currents were obtained from the cross-sectional area of the electric tube of force that contains the same number of electric lines of force at each cross-section. This method was first applied to a human body that was assumed to be axially symmetrical. To verify the validity of this method, the induced currents were measured using a small phantom model. Agreement between calculated and measured values was reasonable. Currents induced in a mouse were then calculated by means of a three-dimensional shape of the body. This calculation method enabled us to obtain the induced currents, using a few unknown quantities, in a comparatively short time.

ACKNOWLEDGMENT

The authors express their sincere appreciation to Dr. Hiroshi Nakamura of the Central Research Institute of Electric Power Industry for his valuable discussions.

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RESULTS OF EXPERIMENTAL AND THEORETICAL ANALYSES OF INDUCED CURRENTS FROM A UNIFORM POWER-FREQUENCY ELECTRIC FIELD IN HUMANS

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ABSTRACT

This paper describes the experimental results of induced currents in two human models. Model 1 was a cylinder surmounted by a hemisphere; Model 2 was a modification of Model 1 that more closely resembled the human form. These axisymmetrical models, which had maximum diameters of 27 cm and heights adjustable from 150 to 180 cm, were covered with aluminum foil. Results of the experiments, which were performed at indoor and outdoor testing sites, were obtained with fairly good reproducibility. Comparisons between the experimental results and theoretical calculations of induced currents and induced current densities indicates that the model was an electrostatic equivalent of the human body. The finite-element method was applied to the theoretical analysis of induced current densities inside the models. Also described are experiments that investigated the electric-field-shielding effect of one person on another. Results showed that the induced current decreased by approximately 15% when the two were 1 m apart.

The highest transmission-line voltage in use at present in Japan is 500 kV. To increase power transmission capacity in the future, voltages as high as 1200 kV have been studied, and a voltage of 1100 kV will probably be accepted as the ultrahigh-voltage (UHV) level. In the United States, voltages as high as 2000 kV have been investigated, but 1500 kV is the highest level at which research has been extensive. Among the technical problems associated with such an increase in line voltages, problems associated with electrostatic induction have been of major concern. A related problem is the direct effect of electric fields on humans. Research in this field has been actively supported by the U.S. Department of Energy (Bulawka et al., 1982), and the Electric Power Research Institute (Kavet, 1982).

Information on internal field strengths or induced current densities inside human bodies has been obtained through experiments using a scaled human model (Kaune and Phillips, 1980) and a full-size mannequin (Zaffanella and Deno, 1978). A mathematical method of modeling humans by using simplified shapes such as a sphere or spheroid has also been proposed (Spiegel, 1976; Barnes, McElroy, and Charkow, 1967; Shiau and Valentino, 1981). Calculation of the induced currents of grounded human models by both the "method of spheres" (Diplacido, Shih, and Ware, 1978) and by the charge-simulation method (Kobayashi, Shimiza, and Matsumoto, 1984) agreed well with the experimental results. A computer-modeling method has also been proposed in which the complicated biological organisms were represented by blocks (Spiegel, 1981).

The primary objective of this work is to develop techniques for calculating the internal electric fields (current densities) and the surface electric fields of human bodies or laboratory animals in 60-Hz electric fields. This paper describes the experimental results of determining, by the finite-element method, the total induced currents and induced current densities of two erect human models in electric fields. In addition, some results of a preliminary experiment on the shielding effect of two adjacent human bodies are described.

METHODS

Human Models

Schneider et al. (1974) reported the use of a metallic cylinder with a hemisphere on top of it as the first approximation of a human body. Following their example, our Model 1 was composed of a 27-cm-diameter cylinder and a 25-cm-diameter hemisphere. The 85-cm circumference of the chest (equivalent diameter, ~27 cm) was acceptable for an adult, but the 25-cm diameter for the head seemed too large; a diameter of ~20 cm would have been adequate. Therefore, this model was used only for a rough estimate of the total induced currents.

To estimate induced current densities at horizontal cross-sections of the model, we used data on body dimensions of adults (including measurements of head, neck, waist, ankle, etc.) to construct an axisymmetrical human model (Model 2). The configurations of Models 1 and 2 are shown in Figure 1.

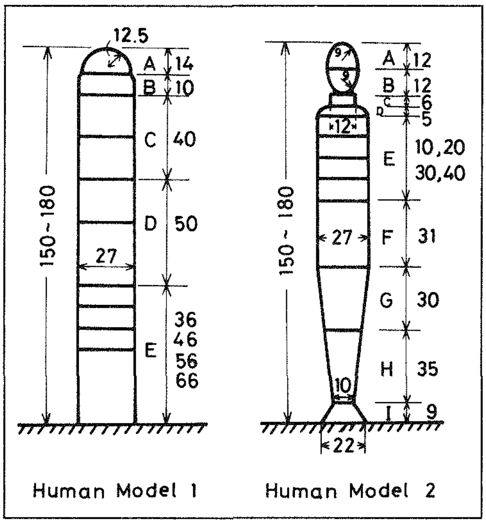

Figure 1. Configurations of Two Types of Human Models Employed for the Induced Current Measurements (units, cm).

Model 1 was divided into five parts, designated, from top to bottom, A, B, C, D, and E, respectively. In the same manner, Model 2 consisted of nine parts, A, B, C, D, E, F, G, H, and I. The heights of both human models could be adjusted to 150, 160, 170, or 180 cm by inserting or removing the 10-cm-high cylinders in part E. Figure 2 shows the front and side views of a person standing beside Models 1 and 2; all heights are 170 cm. The profile of Model 2 is very similar to that of a person, but the front view is quite different from a human in shape.

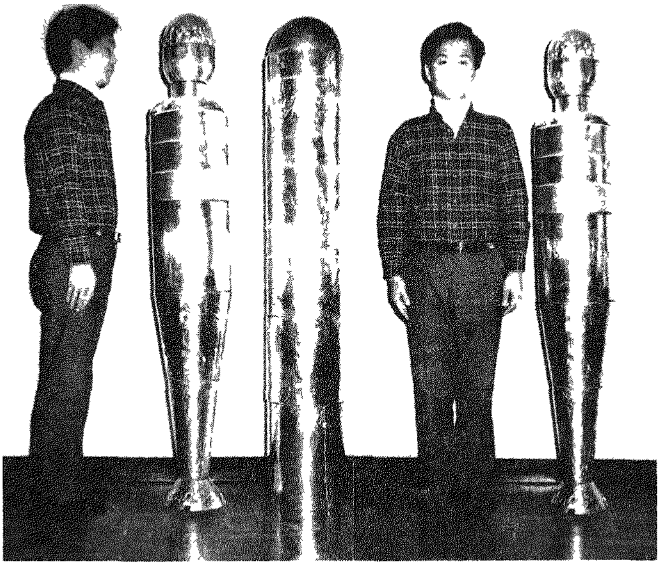

Figure 2. Comparison of Configurations of Models 1 and 2 with the Side and Front Views of a Man; *All Are 170 cm High.*

Induced Current Measurements

The induced current measurements were made at two testing sites: the indoor high-voltage laboratory of Chugoku Electric Power Company, Inc. and the outdoor testing site of NGK Insulators, Ltd. In the indoor experiment (experiment A), a conductor, 20 m long and 0.2 m in diameter, was stretched at a height of 6.6 m above the floor. In the outdoor experiment (experiment B), three horizontal conductors (each 2 cm in diameter and 15 m long) installed, 1 m apart, at a height of 6.7 m above ground. The characteristics of the field strengths, at 1 m above ground, parallel to the test line and normal to the line at the line center, are illustrated in Figure 3. In experiment A, the electric-field strength at the line center, where the models were placed, was 2.8 kV/m; in experiment B the field strength was 4.0 kV/m. For physical reasons, it was impossible to obtain uniform field conditions; however, the electric fields around the line center may be considered uniform with regard to the dimensions of the models employed. When measuring the currents induced in the various parts of the models, each part was grounded individually through the microampere meter, while the remaining parts were solidly grounded.

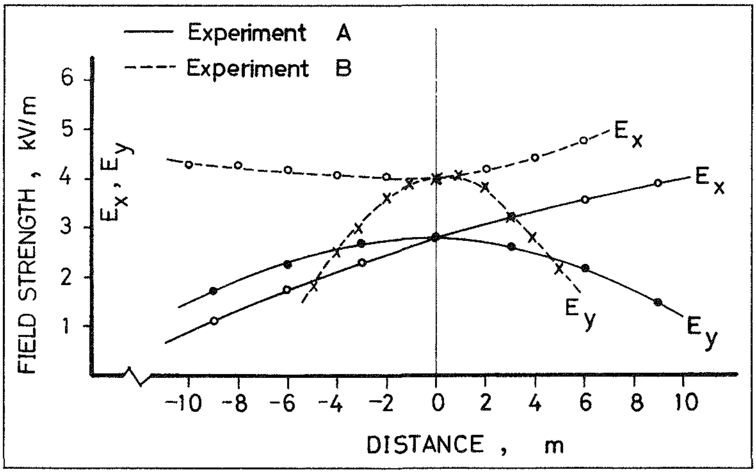

Figure 3. Distributions of Electric Field Strengths at 1 m Above Ground Under the Test Lines in Experiments A (Indoor) and B (Outdoor). E_x is the field distribution along the line; E_y is the field distribution in the direction normal to the line at the center point, where the models were placed.

ANALYSIS BY FINITE-ELEMENT METHOD

The pioneering work in computer-modeling of electric-field coupling to biological tissue was done by Spiegel (1981), who used blocks to simulate complicated biological organisms. His predicted results and experimental results obtained by measuring induced current densities in a mannequin (Zaffanella and Deno, 1978) were similar but not identical.

We have explored another technique, the finite-element method, by which the internal current densities of an axisymmetrical human model can be calculated (Chiba et al., 1984). Our computer program is capable of predicting the distributions of not only the internal current densities but also of the surface electric fields of the human model that consist of axisymmetrical, heterogeneous tissues. For reference, the data on the conductivities and dielectric constants of the body tissues are plotted in Figure 4. As a preliminary study of the scaling factors, the induced current concentration factor will be discussed with regard to the electrical constants of body tissues (Isaka et al., 1984).

In order to calculate the induced currents of Models 1 and 2 in a uniform electric field, it is assumed they are standing at the center of the ground-side electrode of circular, parallel-plate electrodes, 30 m in diameter, with 10 m of clearance above the models. Energizing the high-voltage electrode at 10 kV results in an electric field of 1 kV/m. For Model 1, the region that includes the electrode system and the model was divided into 49 curvilinear, quadrilateral, axisymmetrical elements. For Model 2, the region was composed of 102 elements. The No. 5 and No. 10 elements were allotted to Models 1 and 2, respectively. The division pattern inside Model 2 and in its vicinity is illustrated in Figure 5.

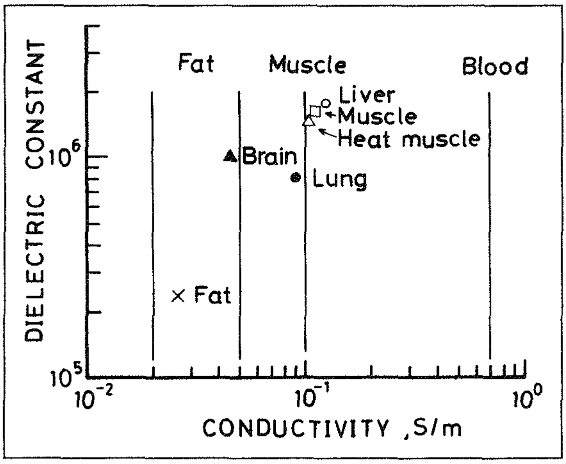

Figure 4. Electrical Constants of Various Body tissues.

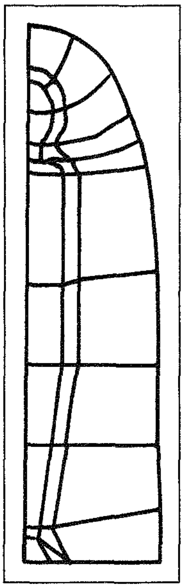

Figure 5. Division Pattern of Axisymmetrical Model 2 and its Vicinity, for the Finite-Element Analysis.

RESULTS AND DISCUSSION

Induced Currents

Figure 6 shows the total induced currents (in μA/[kV/m]) per unit external field of Models 1 and 2 as measured in experiments A and B. The experimental results were fairly reproducible, although the electric-field characteristics were somewhat different at the two testing sites. Also plotted in Figure 6 are the results, calculated using the following expression (Zaffanella and Deno, 1978):

$$I_{SC} = 5.4 \cdot H^2 \cdot E \cdot f/60, \mu A, \quad (1)$$

where I_{SC} is the induced current (in μA), H is the height of a person (in m), E is the external electric field (in kV/m), and f is frequency, in Hz. This expression applies to a person with his hands by his sides, and is believed to best fit the experimental results of measuring the total induced currents in humans. It follows from Figure 6 that the total induced currents in Model 2 are almost as large as those calculated using Equation 1 (Curve C); however, the total induced currents in Model 1 are larger than those in Model 2, mainly because of the difference in their head dimensions.

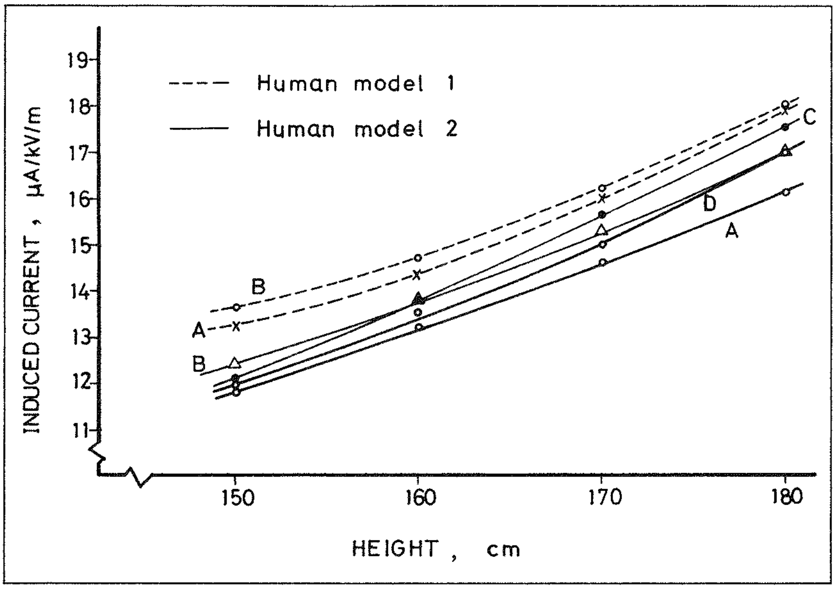

Figure 6. Total Induced Currents of Models 1 and 2 in Experiments A and B. Shown also are results calculated using Eq. 1 in the text (Curve C) and results obtained by the finite-element method (Curve D).

Figure 7 illustrates the induced currents integrated from the top of the head to specific sections of Models 1 and 2. The experimental results of measuring induced currents in a 175-cm-high mannequin (Zaffanella and Deno, 1978) are shown for comparison. The characteristics of the mannequin are nearly midway between those of the models, which are 170 and 180 cm high, respectively. If the shoulder portion of Model 2 had been wider, its induced current would have been more similar to that of the mannequin.

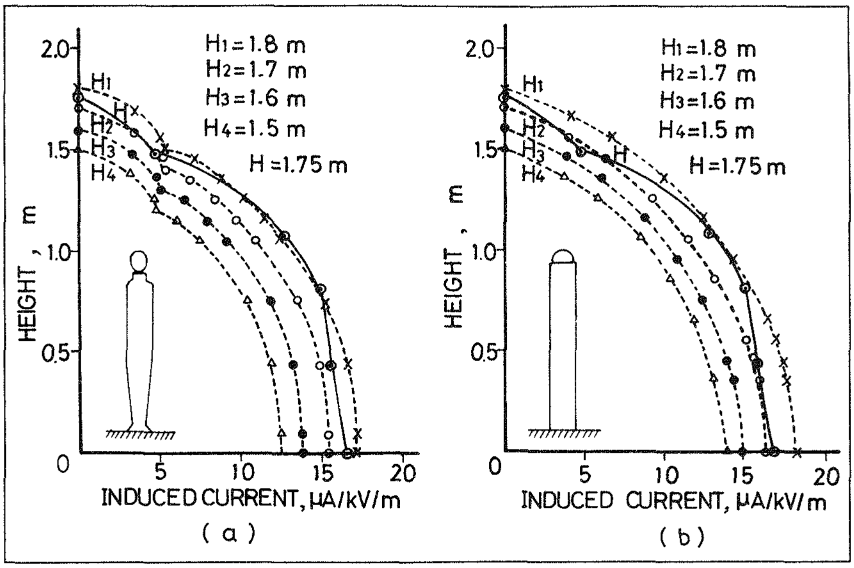

Figure 7. Induced Currents Integrated from the Top of the Model's Head to a Specific Body Part. For reference, the data obtained using the mannequin (height, 175 cm) are also plotted.

Comparisons between Experimental and Theoretical Results

The total induced current in a model can be calculated using the following equation:

$$I_{SC} = \omega E_0 \int E_i \, ds, \qquad (2)$$

where E_0 is the permittivity of free space, $\omega = 2\pi f$ (f: frequency, 60 Hz in this calculation), E_i is the local electric field strength on the model's surface, and s is the surface area. Table 1 shows comparisons of the experimentally and theoretically derived total induced currents in Models 1 and 2. The induced current measured in the various sections (and therefore the total induced current) is very similar in the metallic models to that measured in homogeneous tissue having the conductivity and dielectric constant shown in Figure 4. This is because the impedance of the air surrounding the models is much larger than that around the body tissue. Therefore, the metallic model can be regarded as an electrostatic equivalent of a human body.

TABLE 1. Comparison of Experimentally and Theoretically Derived Total Induced Currents Measured in Human Models 1 and 2

Model Number	Height (cm)	Experiment 1 (μA)	Experiment 2 (μA)	Finite-Element Analysis
1	150	13.3	13.6	13.9
	160	14.4	14.7	15.5
	170	16.0	16.2	16.8
	180	17.9	18.0	18.4
2	150	11.9	12.4	12.1
	160	13.2	13.7	13.5
	170	14.7	15.3	15.0
	180	16.3	17.0	16.9

The induced current density, J, in tissue can be calculated using the following equation:

$$J = (\sigma + j\omega\varepsilon) E', \tag{3}$$

where E′ is the internal electric field of a tissue, calculated directly by the finite-element method, and σ and ε are the conductivity and permittivity of that tissue, respectively. Table 2 summarizes the average induced current densities at the neck, pelvis, and ankle portions of Model 2 in a 1-kV/m electric field. It was assumed, in the finite-element analysis, that the model was filled with homogeneous tissue. Repeated calculations showed that the induced current densities hardly changed when the electrical constants of the body tissue varied within the region shown in Figure 4; Table 2 shows that the experimental results agree with those calculated.

TABLE 2. Comparison of Experimentally and Theoretically Derived Total Induced Current Densities [$\mu A/cm^2/(kV/m)$] of Human Model 2

Model Height (cm)	Body Part	Experiment 1	Experiment 2	Finite-Element Analysis
170	Neck	46.6	47.6	46.2
	Pelvis	22.5	23.4	22.7
	Ankle	186.6	195.4	191.6
180	Neck	49.1	50.0	48.6
	Pelvis	25.3	26.7	25.5
	Ankle	206.7	218.4	210.5

Enhancement Factor

The electric-field strengths on the surfaces of Models 1 and 2 were also calculated by the finite-element method. An example of the calculated field strengths on the surface of Model 1 is shown in Figure 8. The enhancement factor at the top of a 150-cm-high model is 12.0; for Model 2, it is 16.0. The relationship between the enhancement factor at the top of the head and the model's height is roughly expressed by the following equation:

$$Y_1 = 0.15\ X_1 - 10.5 \quad \text{for Model 1, and} \tag{4}$$

$$Y_2 = 0.777\ X_2 + 4.5 \quad \text{for Model 2,} \tag{5}$$

where Y is the enhancement factor, and X is the height of the model. The enhancement at the top of Model 2 when it is 180 cm high is 18.3; this was the tallest height considered.

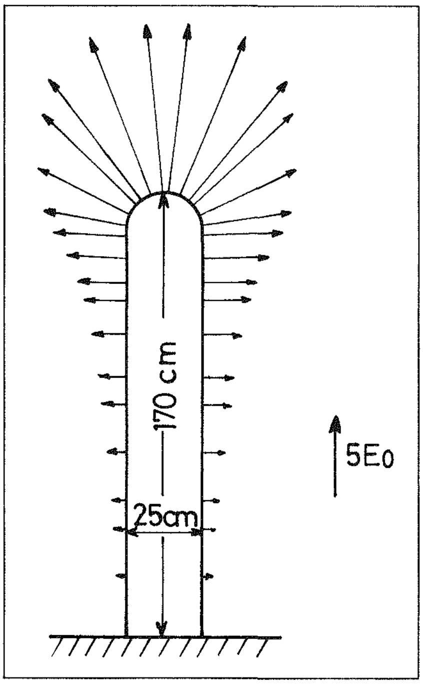

Figure 8. An Example of Electric-Field Distribution on the Surface of Model 1, 170 cm in Height.

Effect of Model Diameter

The diameter of the model is a key factor in estimating induced current densities. From finite-element analysis we found that, when the trunk diameter of Model 1 (height, 170 cm) was increased from 25 to 30 cm, the total induced current increased by about 8%, and the maximum induced current density decreased by 25%.

SHIELDING EFFECTS

The electrostatic shielding effect of one or two persons on another person was also studied. As a preliminary investigation, the induced current in one person (A) was measured when another person (C) approached A; C faced the side of A. Then another person (B) was added and faced the other side of A. The results (Figure 9) were that the induced current decreased by about 15% when each person was 1 m apart from the other, and the shielding effect was doubled (30% decrease in induced current) when B and C were 1 m away from A. A's height was 172 cm; B and C were both 170 cm tall.

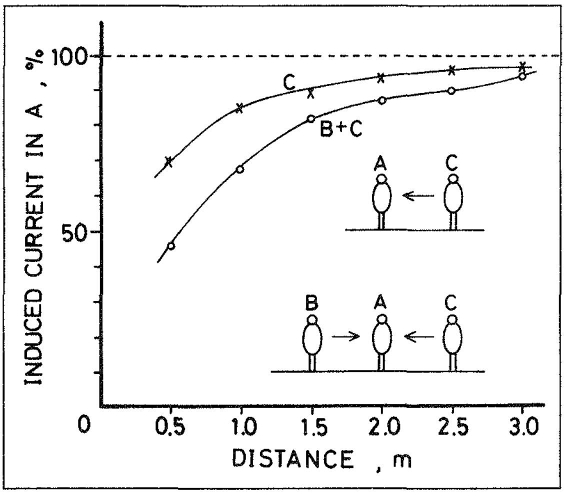

Figure 9. Shielding Effect on Induced Current Measurements.

ACKNOWLEDGMENT

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MOTION OF COUNTERIONS ON A CYLINDRICAL CELL SURFACE: A POSSIBLE MECHANISM FOR THE ACTION OF LOW-FREQUENCY, LOW-INTENSITY MAGNETIC FIELDS WHICH DISPLAY UNSUSPECTED FREQUENCY DEPENDENCE

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ABSTRACT

In an attempt to answer the question "Can surface bound counterions be responsible for extremely low-frequency or audiofrequency magnetic-field effects on cell preparations?", we have examined the motion of counterions under the influence of such fields, oriented parallel to the axes of cylindrical cells. Results show that the induced current on the surface of an isolated cell is below thermal noise but can exceed thermal noise when cells interact within a sufficiently large radius. In a group of cells, the axial time-varying magnetic field will induce a small inhomogeneity in the density of counterions on the surface of each cell; the magnitude and position of that inhomogeneity *becomes independent of the frequency of the applied field above the dielectric counterion relax*ation frequency.

Several investigators have recently reported effects of extremely low-frequency (ELF) or audiofrequency magnetic fields at relatively low intensities (∿10 G) on DNA synthesis in cell culture (Liboff et al., 1984), growth of bacteria (Ramon et al., 1983), development of *Drosophila* (Ramirez et al., 1983), motor excitability of monkeys (Delgado et al., 1983) and development of injured chick embryos (Sisken et al., 1983). The dependence of these effects on the amplitude and frequency of the applied field is not clear, but in at least one case it was shown (Liboff, 1984) that neither the threshold intensity for the appearance of the effect nor the magnitude of the effect (in that case DNA synthesis of human fibroblasts measured by thymidine uptake) showed a dependence on the product of frequency and intensity of the applied magnetic field. Such dependence would be expected if the mechanism involved was linearly dependent on an induced electric current, which, in a medium with simple ohmic conductivity, is directly proportional to that product.

In this analysis we examined counterion motion, because theoretical work on counterion behavior of spherical cells (Schwarz, 1962) has explained very well the low-frequency *dielectric* dispersion of some biological substances (Einolf and Carstensen, 1973). We selected counterions on the surface of a cylindrical cell because that geometry represents a better approximation for fibroblasts, and it is also mathematically more tractable in the case of an applied *magnetic* field.

The analysis begins with the expression for a diffusion-limited current density:

$$\bar{J} = uqN\bar{E} - ukT\,\nabla N, \qquad (1)$$

where u = electric mobility, q = ionic charge, N = number density of charge per unit volume, $\bar{E}$ = induced electrical field, k = Boltzman's constant, and T = absolute temperature. Using charge conservation, $\nabla \cdot \bar{J} = -(\partial \rho / \partial t)$, where $\rho = Nq$ = volume charge density. Applying the constraints of motion exclusively in the surface (and not perpendicular to the surface), and assuming a magnetic-field vector along the cell axis, one is led to the following equation for the "disturbance" $\tilde{n}$, i.e., the time- and space-dependent part of the total surface number density:

$$-\frac{\partial \tilde{n}}{\partial t} = \omega\beta \sin \omega t \frac{\partial \tilde{n}}{\partial \Phi} - \partial \frac{\partial^2 \tilde{n}}{\partial \Phi^2}, \tag{2}$$

where the total ion surface density, n, and the time- and space-independent part n_o are related to $\tilde{n}$ by

$$n = n_o + \tilde{n}, \tag{3}$$

and $\beta = \frac{uB_o}{2}$, $\alpha = \frac{kTu}{qR^2}$, B_o peak amplitude of applied magnetic flux density, $\omega = 2\pi f$ = radian frequency of applied field, Φ = angle measured along surface of cylinder in plane perpendicular to applied field, R = radius of cylinder, n = N Δ, and Δ = thickness of the assumed ion sheath with uniform radial distribution. The quantity α is equal to (1/2) of the counterion dielectric relaxation frequency derived by Schwarz (1962) for spherical cells.

At ELF or audiofrequencies and magnetic flux densities below 1T $\omega\beta << \alpha$ in equation (2). Since we will also find that $(\partial \tilde{n}/\partial \Phi)$ and $(\partial^2 \tilde{n}/\partial \Phi^2)$ are of the same order of magnitude, we note that the magnetic field term in (2) represents only a minor modification of the diffusion equation,

$$\frac{\partial \tilde{n}}{\partial t} = \alpha \frac{\partial^2 \tilde{n}}{\partial \Phi^2}, \tag{4}$$

which has the solution

$$\tilde{n}_D = n_1 e^{-\alpha t} \cos(\Phi - \xi), \tag{5}$$

where n_1 and ξ are constants determined by boundary conditions. Clearly, $\tilde{n}_D = 0$ for all t unless some external cause has produced an initial disturbance, n_1, i.e., an inhomogeneity in the Φ-direction, which will then decay exponentially. However, with a uniform axial magnetic flux density, $B = B_o \cos \omega t$, the induced electric field in the Φ-direction is (to a very good approximation, at ELF and for media with electrical conductivities $\sigma < 10$ S/m).

$$E_\Phi = \frac{r\omega B_o}{2} \sin \omega t, \tag{6}$$

which was used in obtaining equation (2). Since E_Φ is independent of Φ, it cannot produce the required inhomogeneity. Therefore, we expect that the solution of equation (2) will have a form similar to that of equation (4): any disturbance initially present will again decay exponentially in the presence of the magnetic field. Thus the appropriate solution of equation (4) is

$$\tilde{n} = n_2 e^{-\alpha t} \cos(\Phi - \zeta + \beta \cos \omega t), \tag{7}$$

indicating that the effect of the magnetic field is only a time-dependent change in angular position of any pre-existing disturbance. This displacement could be physically significant only if it took place before $\tilde{n}$ has decayed substantially; that is, only if $\alpha << \omega$. However, any significant displacement would also require an enormously large magnetic field since

$\beta \simeq 10^{-10}$ for $B_o \simeq 10^{-3}$ T.

In evaluating the effect of a time-varying magnetic flux one needs to investigate not only changes in surface charge distribution but also the magnitude of the steady-state circulating counterion current which will be produced by E_Φ on the surface of each cell. From equations (1), (6) and (7) it follows that this current is

$$(i_\Phi)_{ss} = uqn_o \ell \; B_o R\,(1/2)\, \omega \sin \omega t \tag{8}$$

on a cell of radius R and length ℓ. It is of interest to compare this induced current with the mean square thermal noise current, i_n, flowing into the counterion sheet at physiological temperatures, which is given by

$$i_n^2 = 4GkT\,(\delta f), \tag{9}$$

where δf is the noise bandwidth, k = Boltzman's constant, and G is the conductance of the sheet,

$$G = \frac{\sigma \ell \Delta}{2\pi R} = \frac{n_o q u \ell}{2\pi R}, \tag{10}$$

with σ the electrical conductivity of the sheet. The ratio of the induced to the thermal noise current is, then,

$$\frac{i_{ss}}{i_n} = \left[\frac{\pi u q n \ell_o}{8kT\delta f}\right]^{1/2} \omega B_o R^{3/2}. \tag{11}$$

This ratio is plotted against ωB_o on Figure 1 for unit bandwidth ($\delta f = 1$), mobility, $u = 3.6\ (10^{-7})\ m^2/Vs$; surface charge density, $n_o = 2(10^{17})\ m^{-2}$, and various values of R and ℓ that are representative of cell dimensions. It is clear that, for ωB_o below 10^3, the magnetically induced current on a single cell is well below thermal noise.

In addition to examining the effects of a time-varying magnetic flux on an isolated cylindrical cell, we considered the situation illustrated by Figure 2. A group of cells is shown along the circumference of a circle of radius a, and it is assumed that an infinitesimally small fraction of the counterions from each cell surface can move through the resistance of the intercellular medium to the adjacent cell. To evaluate the electric field tangential to the wall of an individual cell of radius R we must now apply Faraday's law, $\int \bar{E} \cdot d\bar{\ell} = -\partial/\partial t \int\int \bar{B} \cdot d\bar{s}$, to a path of radius a (the radius of the cell sample). Since the amount of enclosed magnetic flux differs, depending upon whether the path is taken along the "inside" or the "outside" of an individual cell, the emf = $\int_A^B \bar{E} \cdot d\bar{l}$ between points such as A and B on Figure 2 will differ along the two paths. If the angle Φ indicates the position on the circumference of an individual cell, the electric field on the surface of that cell is then a function of Φ, given by

$$E = -\frac{\omega B_0}{2} \sin \omega t\,(a \cos \Phi - R), \tag{12}$$

and the surface current density is

$$j_s = -uq(n_0 + \tilde{n}) \frac{\omega B_0}{2} \sin \omega t\,(a \cos \Phi - R) - \frac{ukT}{R} \frac{\partial \tilde{n}}{\partial \Phi}\,. \tag{13}$$

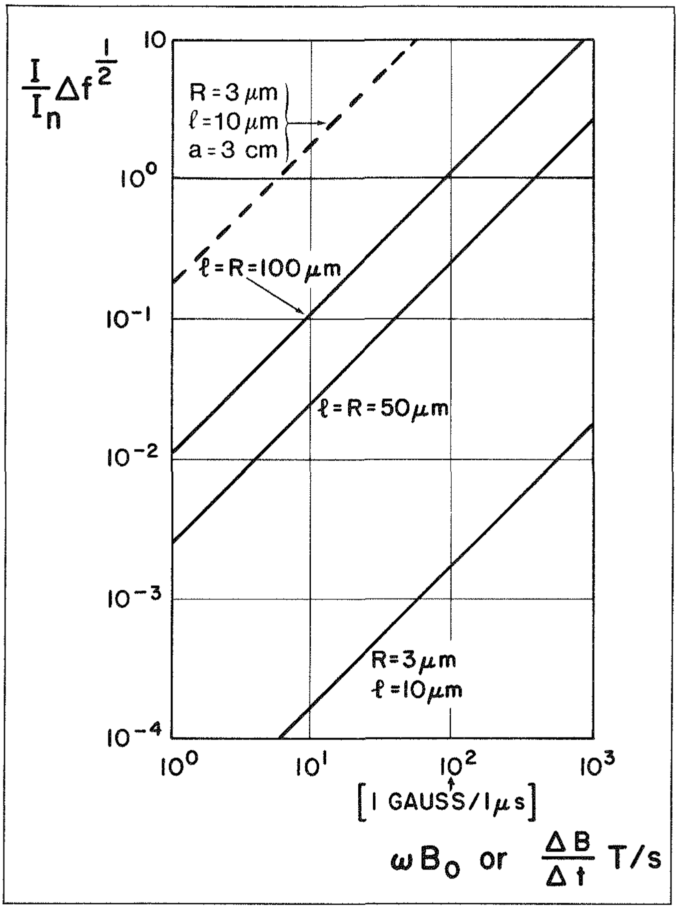

Figure 1. Ratio of Induced Counterion Current to Thermal Noise Current on Cylindrical Cells Versus ωB_0: Solid Lines, Isolated Cells; Dashed Line, Single Cell in a Cell Sample of 3-cm Radius (A in Figure 2).

Substitution into the charge conservation equation (given in the text below equation 1) then gives

$$\frac{\partial \tilde{n}}{\partial t} = u\,\frac{\omega B_O}{2R}\sin\omega t\,(a\cos\Phi - R)\,\frac{\partial \tilde{n}}{\partial \Phi} - u\tilde{n}\,\frac{\omega B_O}{2R}\,a\sin\omega t\sin\Phi$$

$$-un_O\,\frac{\omega B_O}{2R}\,a\sin\omega t\sin\Phi + \frac{ukT}{qR^2}\,\frac{\partial^2 \tilde{n}}{\partial \Phi^2}\,. \tag{14}$$

Before proceeding further, we compare the magnitudes on the righthand side of this equation: if $\tilde{n}$ is some trigonometric function of Φ, the first two terms containing, respectively, $(\partial \tilde{n}/\partial\Phi)$ and $\tilde{n}$ are roughly of the same order of magnitude. However, if we assume that the variable, $\tilde{n}$, represents only a small perturbation of n (an assumption to be tested after the solution for $\tilde{n}$ is obtained), so that $\tilde{n} << n_O$, the third term is much larger than either of the first two. Comparing this term with the fourth, we note that $(kT/qR^2) \simeq 4(10^9)$ for a cell radius of 3 μm, while $\omega B_O a/2R \sim 1.7(10^4)$ if $\omega = 10^4\,s^{-1}$, $B_O \simeq 10^{-3}$ T, and $a = 10^{-2}$ m; therefore, even if $n_O >> \tilde{n}$, the fourth term (diffusion term) cannot be disregarded. Using the definitions of α and β given below equation (3) and defining

$$F = \frac{u\omega B_O a}{2R}\,n_O\ s^{-1}m^{-2}\,, \tag{15}$$

equation (14) can be approximated by

$$\frac{\partial \tilde{n}}{\partial t} = \alpha\,\frac{\partial^2 \tilde{n}}{\partial \Phi^2} - F\sin\omega t\sin\Phi, \tag{16}$$

which has the solution

$$\tilde{n} = \frac{F\sin\Phi}{\sqrt{\omega^2 + \alpha^2}}\left[\cos(\omega t + \zeta) - e^{-\alpha t}\cos\zeta\right]\,,\ \text{and} \tag{17}$$

$$\tan\zeta = \frac{\alpha}{\omega}\,. \tag{18}$$

From equations (15) and (17) it is apparent that, for the case when the signal frequency ω is substantially larger than the dielectric counterion relaxation frequency α, in the steady state one obtains ($e^{-\alpha t} \rightarrow o$)

$$\tilde{n} \approx \frac{un_O a}{2R}\,B_O\sin\Phi\cos\omega t, \tag{19}$$

which represents a "standing wave" of charge density around the circumference whose magnitude and position are independent of the signal frequency. The charge distribution indicated by equation (19) is illustrated on Figure 3. When interpreting this result, note that $\tilde{n}$, as defined by equation (3), represents a perturbation in the total surface charge density. The ratio,

$$\frac{|\tilde{n}|}{n_O} = \frac{uaB_O}{2R}\,, \tag{20}$$

will usually be small. Thus for $u \approx 4\ (10^{-7})\ m^2/Vs$, $a = 2$ cm, $B_0 = 10^{-3}$ T and $R = 4\ \mu m$, one obtains $(| \tilde{n} | / n_0) = 10^{-6}$. Nevertheless, for larger flux densities or larger sample radii "a," the fixed nonuniformity in surface charge distribution indicated by equation (19) could possibly influence ion transfer across the cell membrane.

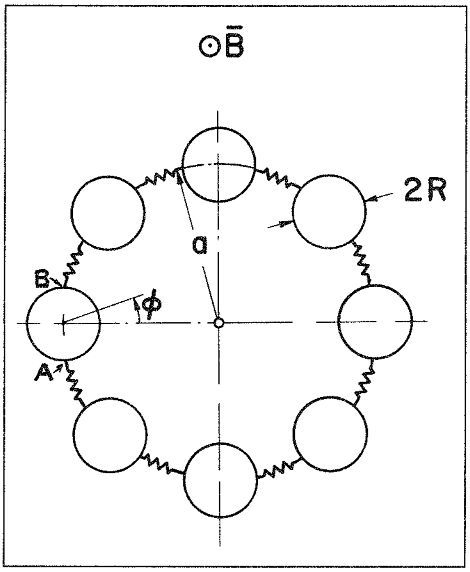

Figure 2. Schematic Representation of Cylindrical Cells with Infinitesimal Counterion Current Between Cells.

As for the isolated cell, it is also useful to compare the steady-state surface current with the thermal noise current in the counterion sheet. In view of equation (12) and noting that $a >> R$, the result analogous to equation (11) is

$$\frac{i_{ss}}{i_n} = \frac{1}{4} \left[\frac{\pi u q n_0 \ell}{kT \delta f} \right]^{1/2} \omega B_0\, a \sqrt{R}\,, \tag{21}$$

using the maximum value of E, considering only the noise generated within the counterion sheet, and taking for the extent of that sheet the region $0 \leqslant \Phi \leqslant \pi$ rather than $0 \leqslant \Phi \leqslant 2\pi$, which was appropriate for the circulating current in the isolated cell. A numerical example of this ratio is shown as the dashed line on Figure 1, indicating that for sufficient sample size the counterion surface current can exceed thermal noise.

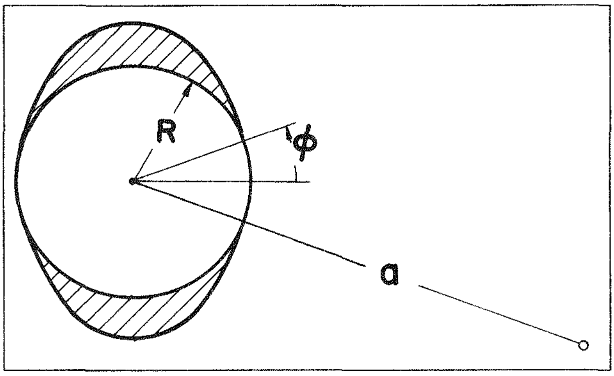

Figure 3 Steady-State Perturbation in Counterion Distribution on the Surface of One of the Cells Shown in Figure 2

CONCLUSIONS

The counterion current induced by a time-varying ELF or audiofrequency magnetic field oriented parallel to the axis of a cylindrical cell will be below thermal noise when the cell is isolated but may exceed thermal noise when cells within a sufficiently large radius can interact Thus, any effect on cell behavior of such a counterion current would depend on sample size. In a group of cells (but not in a single isolated cell) an axial time-varying magnetic field can also induce a small inhomogeneity in the distribution of counterions on the surface of each individual cell. At frequencies sufficiently larger than the dielectric counterion relaxation frequency α, the magnitude and position of that inhomogeneity become independent of the frequency of the applied magnetic field.

Any effect on cell behavior which depends on the magnetic-field-induced motion of counterions will be affected (if the cell is not spherical) by the relative orientation of cell axis to the magnetic field. It will depend on sample size (for example, the size of the Petri dish used) and will lose its frequency dependence above the counterion dielectric relaxation frequency. As a first step to establishing whether changes in counterion distribution play a role in developmental changes of a cell sample under the influence of an ELF or audiofrequency magnetic field, it would therefore be desirable to measure dielectric permittivity versus frequency of that sample

Although all numerical examples in this paper refer to cells, it may also be possible to apply the analytical results given here, with a suitable change of scale, to rather crude cylindrical (rather than helical) models of large organic molecules.

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COMPARISON OF THE COUPLING OF GROUNDED AND UNGROUNDED HUMANS TO VERTICAL 60-Hz ELECTRIC FIELDS

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ABSTRACT

Total induced currents and average induced axial current densities have been published in the literature for human models exposed to 60-Hz electric fields The results of these studies have been quite useful, but they deal with a somewhat idealized exposure situation that ignores the insulating effects of most types of footwear This paper describes a new laboratory technique for studying the relationship between grounded and ungrounded exposure of humans A conducting model of the body of a 40-cm-tall man was electrically divided into seven segments Wires connected to the conducting surfaces of these segments were routed horizontally through shielded cable to remote, battery-powered electronics The "common" potential of the electronics was biased to the electric-field-induced potential of the model, allowing us to accurately measure the current induced in each body segment of the model The method was tested by measuring the current induced in the upper hemisphere of an ungrounded sphere agreement between theory and measurement was excellent Measurements were made with the human model located at 15 positions, ranging from touching ground to remote from ground (i e , in free space) The ratios of free space to grounded currents crossing horizontal sections through the body were neck, 0 58, chest, 0 40, abdomen, 0 39, thigh, 0 36, ankle, 0 17

Most experimental data published on extremely low-frequency (ELF; 30- to 300-Hz) electric-field dosimetry pertain to grounded humans exposed to vertical fields. There are several reasons why this case has received the most attention. 1) It simulates several aspects of the most common way that humans are exposed to strong ELF electric fields; namely standing on the ground near electric-power generation and distribution facilities, where the field is approximately vertical and uniform. 2) Several potential sources of error involved in making measurements on ungrounded models are avoided by addressing only this case However, because of the insulating character of most types of footwear (EPRI, 1975), it is not necessarily correct to assume that a person is *electrically* grounded just because he or she is standing on the ground. Measurements relating currents and fields induced in grounded and ungrounded humans are needed to evaluate realistic exposure situations in the environment.

Two theoretical papers have been published which give calculated data on induced-current distributions in ungrounded and grounded humans exposed to vertical electric fields. Spiegel (1977) simulated a standing human with a system of cylinders, consisting of an upright cylinder that modeled the torso, head, and legs, and two smaller horizontal cylinders that modeled the arms. Using a moment-method technique, the induced current in the body was calculated as a function of height above the feet. DiPlacido, Shih, and Ware (1978) simulated a man by means of a cylindrically symmetrical figure whose radius-versus-height profile was adjusted to approximate the legs, torso, neck, and head. The vertical current induced in the model was calculated using the "method of spheres." The agreement between the calculations of Spiegel and DiPlacido et al. is fairly good, and the discrepancies that exist can be attributed to the different shapes of their models (Kaune and Phillips, 1985).

Based on measurements made with a full-sized human mannequin, Deno (1977) developed formulae which give the induced-current distribution in ungrounded humans. Let d be the clearance between the bottoms of the feet and ground. For $d > 2.5$ cm,

$$I(p/h) = [2.47 \times 10^{-9}\ \mathrm{A/(Vm)}]\, h^2 E_o f(p/h,d), \tag{1}$$

where I is the vertical induced current at a height p inside a human body of height h, E_o is the unperturbed vertical electric-field strength, and f(p/h,d) is an empirical function that is given in Deno's paper. For values of $d < 2.5$ cm, or where there are additional impedances between the feet and ground (e.g., the resistance of shoe soles), Deno gives the following alternative formula:

$$I(p/h) = [5.4 \times 10^{-9}\ \mathrm{A/(Vm)}]\, h^2 E_o f_1 (p/h) \times \left[1 - \frac{V_{og}}{E_o (h/2)} f_2 (p/h)\right], \tag{2}$$

where V_{og} is the induced voltage of the body relative to ground, and f_1 and f_2 are empirical functions that are also given in Deno's paper.

Guy et al. (1982) used a resonant cavity to generate vertical, nearly uniform, 57.3-MHz electric fields, to which they exposed homogeneous models of humans and pigs. The induced current-density distributions in these models were measured using thermographic techniques. By keeping the linear dimensions of the models fairly small relative to one wavelength, the authors were able to extrapolate their data to 60 Hz. The accuracy of this extrapolation was verified using homogeneous spheroidal models: 60-Hz current-density distributions extrapolated from their radiofrequency data were in good agreement with theoretical prediction. These researchers found that the ratio of ungrounded-to-grounded current density varied from about 0.6 in the neck to 0.2 in the ankle.

This paper describes a new technique for measuring currents induced in an ungrounded human body. The technique is usable when the clearance between the model and ground is small. Measurements of the current induced between the upper and lower hemispheres of an ungrounded sphere are presented and compared with theory to experimentally verify the accuracy of the experimental technique. This paper also presents induced-current data for a seven-segment human model located at various elevations above ground. These data are used to calculate the currents crossing transverse sections through the neck, upper arm, chest, abdomen, thigh, and ankle of a human for 15 elevations of the model above ground.

METHODS AND MATERIALS

Exposure System

The exposure system used for the measurements reported in this paper consisted of two parallel, 1.8-m x 1.8-m conducting plates that were positioned with a vertical spacing of 1.02 m between them. The lower electrode was grounded. Nine guard rings were used to increase the uniformity of the electric field between these two electrodes. Details of this system have been published elsewhere (Kaune and Forsythe, 1985).

Spherical Model

A sheet of Mylar was placed between two 5.02 ± 0.03-cm-radius solid-aluminum hemispheres, and the assembly was glued together to form the spherical model used in this work. Current induced in the two hemispheres was routed to external electronics via two wires enclosed in a metal-foil shield. The model was suspended from the upper electrode of the exposure system, using nylon monofilament line.

Calculation of Current Induced in a Sphere

This section briefly describes the theoretical technique we used to calculate the current induced by a 60-Hz electric field between the upper and lower halves of a sphere.

Let a sphere (radius = a) be located with its center lying on the z axis a distance h above the xy plane, which we assume is the ground plane. Let the sphere be exposed to a vertical, uniform electric field with strength E_O. For $h >> a$, the potential, Φ, outside the sphere is (Reitz and Milford, 1960; Spiegel, 1976):

$$\Phi = -E_O z + \frac{E_O a^3 (z - h)}{[x^2 + y^2 + (z - h)^2]^{3/2}} . \tag{3}$$

The first term on the right-hand side of this expression is due to the unperturbed field, and the second term is the potential produced by an electric dipole with moment $\mathbf{P}_o = 4\pi\varepsilon_O a^3 E_O \hat{\mathbf{z}}$, located at the center of the sphere. In this equation $\hat{\mathbf{z}}$ is a unit vector in the z direction (Reitz and Milford, 1960).

Now reduce h so that the sphere is no longer remote from ground. We must find a solution for Φ which satisfies the following five conditions: 1) $\nabla^2 \Phi = 0$; 2) the plane $z = 0$ is a zero-voltage equipotential; 3) the surface of the sphere is an equipotential; 4) the total charge induced on the surface of the sphere is zero; 5) the total electric field becomes equal to $E_O\hat{\mathbf{z}}$ at large distances from the sphere. Such a solution can be obtained, iteratively, as follows.

The first iteration simply places an image dipole, $\mathbf{P}_{gO}$, equal to $\mathbf{P}_o$ at $z = -h$. This addition renders the $z = 0$ plane a zero-voltage equipotential, but it also distorts the potential in the neighborhood of the sphere so that its surface is no longer an equipotential.

In the second iteration, the sphere is again made into an equipotential by imaging the dipole, $\mathbf{P}_{gO}$, placed below the ground plane in the previous iteration, into the sphere. This requires that a dipole $\mathbf{P}_{s1} = (a^3/8h^3)\mathbf{P}_{gO}$ and a point charge $Q_{s1} = -(a/4h^2)\mathbf{P}_{gO}$ be located on the z axis a distance $a^2/2h$ below the center of the sphere. To keep the total induced charge on the sphere at zero, it is also necessary to place a second point charge, $Q'_{s1} = -Q_{s1}$, at the center of the sphere. The second iteration terminates with the imaging into the ground plane of $\mathbf{P}_{s1}$, Q_{s1}, and Q'_{s1}.

The iterative process described in the previous paragraph was continued until convergence was obtained. We gauged convergence by calculating the potentials at the top and bottom poles of the sphere, Φ_t and Φ_b, respectively, then requiring that the quantity $| \Phi_t - \Phi_b | /(E_o\, a)$ be less than 10^{-6}.

Once convergence was obtained, the charge Q induced on the surface of the upper hemisphere by the image charges and dipoles located inside the sphere was calculated. The current, I_h, induced between the hemispheres was calculated using the relationship $I_h = \omega Q$, where ω was angular frequency.

Human Model

A 40-cm-tall human model was made by pouring polyester resin into a styrofoam mold (Kaune and Forsythe, 1985). After the resin had solidified, the mold was removed, and the surface of the model was finished with a small grinder. It was then divided into seven parts (Figure 1), and each part was painted with a silver-based conducting paint. Wires connected to the surfaces of each of the seven parts were routed through the interior of the body to the navel, where they emerged. These wires were routed outside the body within a metal-foil-shielded cable and were connected to remote electronics as described below.

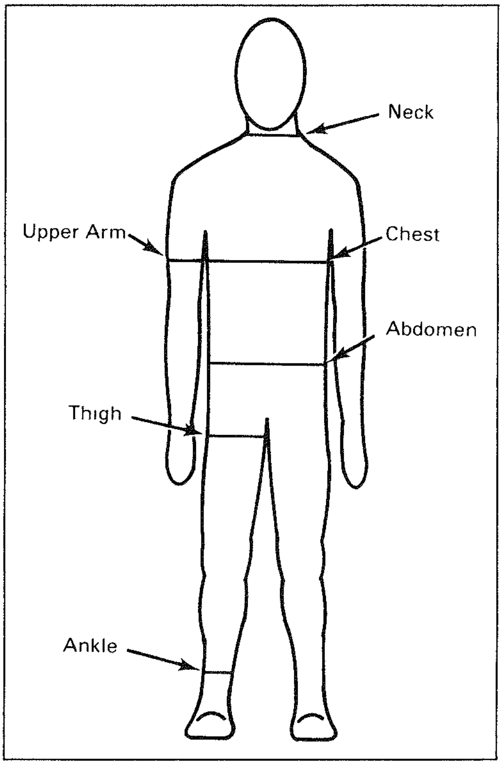

Figure 1. Polyester Resin Model with Conducting Paint Surface. Body is divided into seven segments by the six horizontal sections shown in figure.

Induced-Current Measurements

Induced-current measurements were made using a modification of a method developed by Misakian, Kotter, and Kahler (1978). As described above, a shielded cable connected the various segments of the model to a remote current-to-voltage (I-to-V) converter (transresistance = 99.6 MΩ). This unit was located just outside the exposure volume on an insulated stand. The common side of the battery-powered I-to-V converter was connected to the metal box in which it was enclosed; the box was, in turn, connected to the tap on a 1-MΩ potentiometer. (The common side of a circuit is usually connected to ground.)

This potentiometer was energized from the same source used to power the exposure electrodes. In this way, the converter's common voltage could be biased to any value between 0 and the voltage applied to the upper electrode of the exposure system.

The current induced in a particular segment of the body, say the k^{th} segment, was measured as follows. Using appropriate switches, the model was divided into two parts: the k^{th} segment and the remainder of the body. An additional switch enabled the input of the I-to-V converter to be connected to either the k^{th} segment, the remainder of the body, or to both (i.e., to the entire body). The first step in the measurement process was to connect both sections of the model to the input of the I-to-V converter, then to adjust the 1-MΩ potentiometer to null the output of the converter. This produced a situation in which current induced in the k^{th} segment passed through the shielded cable to the input junction of the I-to-V converter and then, without actually entering the converter, passed back through the shielded cable to the remainder of the body. The switches described above were then set to measure the current induced in the k^{th} body segment alone.

The only difference between the situation described in the previous paragraph and a truly isolated body–the situation we were trying to model–was that induced current did not flow directly from the k^{th} body segment to the remainder of the body but, instead, was routed between the two through an external cable. The optimal routing of this cable would have been along the equipotential surface that had the same space potential as the cable's voltage, V_c. (V_c was equal to the bias voltage applied to the I-to-V's common side because the cable shield was connected directly to this point, and the signal conductors inside the cable were also connected to it, either directly or through the low-impedance input of the converter.)

Unfortunately, field perturbations from the conducting body of the model rendered the position of the V_c equipotential surface uncertain. We therefore adopted a somewhat different procedure, in which the cable was routed along a well-defined horizontal path, then along horizontal paths at other elevations in order to estimate uncertainties in the measured induced currents resulting from uncertainties in the correct location of the cable. The nominal horizontal path was chosen so that the *unperturbed* space potential at its height was equal to the cable voltage.

We found that the effect of the signal-cable elevation was small in all measurements except those involving currents very close to zero. In the data analysis, we used our measured data to estimate the uncertainty resulting from the uncertain cable position as the change in the induced currents that would result from a vertical displacement of the signal cable by ± 25% of the 40-cm body height of the model.

Calculation of Sectional Currents

The six horizontal sections that divided the body of the human model into seven segments are shown in Figure 1. The currents crossing these sections were calculated using Kirchoff's laws and the measured induced segment currents.

RESULTS

Currents Induced in a Sphere

The current, I_h, induced between the upper and lower hemispheres of a sphere of radius a was measured as a function of the distance, h, of the center of the sphere above ground. The exposure-system voltage for these measurements was 150 V, which corresponded to an unperturbed electric-field strength of about 145 V/m. Measured values of the normalized quantity I_h/E_0 are given in Figure 2 as a function of h/a - 1. The smooth curve given in this figure was calculated using the numerical method described in the previous section. Within measurement errors, the measured and calculated values are in agreement except for small deviations when $h/a<1.01$.

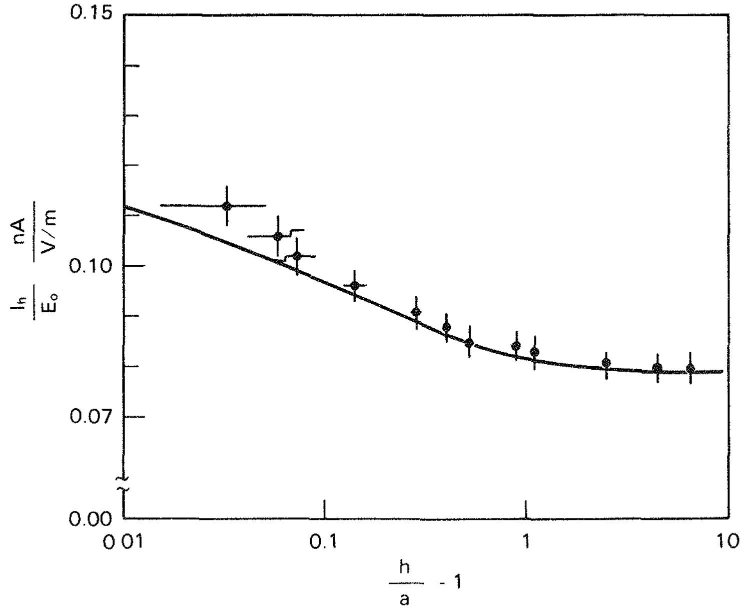

Figure 2. Current, I_h, Induced in Upper Hemisphere of Sphere (radius = a) Exposed to Vertical, 60-Hz Electric Field, E_0. The elevation of the center of the sphere above ground is given by h.

Currents Crossing Sections Through the Human Body

Table 1 gives calculated currents crossing horizontal sections through the neck, upper arm, chest, abdomen, upper thigh, and ankle of the body of a 1.7-m-tall human exposed to a 1-kV/m, 60-Hz electric field. Positive values in this table represent currents which are flowing vertically *downwards* in the body. The estimated uncertainties given in

Table 1 contain contributions from the following sources: 1) uncertainty in the unperturbed electric field; 2) calibration uncertainties in the I-to-V converter; 3) uncertainties in the bias voltage, V_C; and 4) uncertainties in the routing of the cable which connected the model to the I-to-V converter.

TABLE 1. Currents (μA) Crossing Sections Through the Body of a 1.7-m-Tall Human Exposed to a Vertical 1-kV/m, 60-Hz Electric Field. Positive values designate currents which are flowing vertically downward toward the ground. Values for h given in cm

Section	h = 124	h = 79	h = 60	h = 36.3	h = 25.8	h = 17.7	h = 12.8
Neck	3.13 ± 0.11	3.15 ± 0.11	3.16 ± 0.11	3.18 ± 0.11	3.22 ± 0.11	3.26 ± 0.11	3.32 ± 0.12
Upper Arm	0.04 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.02	0.01 ± 0.02	-0.03 ± 0.02	-0.06 ± 0.02
Chest	5.41 ± 0.18	5.45 ± 0.18	5.50 ± 0.18	5.58 ± 0.19	5.69 ± 0.19	5.85 ± 0.20	6.05 ± 0.20
Abdomen	5.66 ± 0.18	5.71 ± 0.19	5.76 ± 0.19	5.85 ± 0.19	5.98 ± 0.20	6.15 ± 0.20	6.37 ± 0.21
Upper Thigh	2.83 ± 0.09	2.86 ± 0.09	2.89 ± 0.10	2.94 ± 0.10	3.01 ± 0.10	3.11 ± 0.10	3.22 ± 0.11
Ankle	1.47 ± 0.10	1.48 ± 0.10	1.51 ± 0.10	1.56 ± 0.10	1.62 ± 0.10	1.72 ± 0.10	1.84 ± 0.10

TABLE 1 Continued

Section	h = 8.6	h = 6.6	h = 4.38	h = 3.48	h = 2.21	h = 1.10	h = 0.34	h = 0.00
Neck	3.37 ± 0.12	3.43 ± 0.12	3.54 ± 0.12	3.61 ± 0.13	3.76 ± 0.13	4.04 ± 0.14	4.67 ± 0.17	5.37 ± 0.17
Upper Arm	-0.10 ± 0.02	-0.15 ± 0.02	-0.21 ± 0.02	-0.26 ± 0.02	-0.36 ± 0.02	-0.57 ± 0.03	-0.98 ± 0.05	-1.49 ± 0.05
Chest	6.27 ± 0.21	6.48 ± 0.22	6.85 ± 0.23	7.09 ± 0.24	7.64 ± 0.26	8.71 ± 0.30	10.89 ± 0.38	13.54 ± 0.43
Abdomen	6.61 ± 0.22	6.84 ± 0.23	7.25 ± 0.24	7.51 ± 0.25	8.11 ± 0.27	9.29 ± 0.31	11.68 ± 0.50	14.59 ± 0.46
Upper Thigh	3.36 ± 0.11	3.50 ± 0.11	3.73 ± 0.12	3.87 ± 0.13	4.17 ± 0.14	4.72 ± 0.16	6.10 ± 0.29	7.76 ± 0.25
Ankle	2.03 ± 0.10	2.19 ± 0.10	2.49 ± 0.10	2.69 ± 0.11	3.12 ± 0.12	3.99 ± 0.14	6.00 ± 0.28	8.49 ± 0.27

Data on sectional currents may be used to estimate average axial current densities in the human body (Deno, 1979; Kaune and Phillips, 1980). The data in Table 1 can thus be used to construct the ratios of current density measured at a height h and at ground level. The results are given in Figure 3. These data demonstrate clearly that the grounded configuration leads to the maximum induction of electric currents, and hence fields, inside the body.

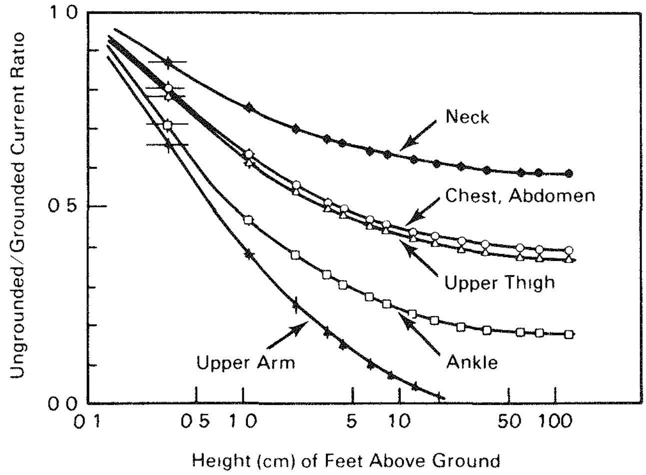

Figure 3. Comparison of Sectional Currents and Average Vertical Current Densities in Grounded and Ungrounded Human Models Exposed to Vertical, ELF Electric Fields.

DISCUSSION AND CONCLUSIONS

Comparison to Other Experiments

Grounded sectional currents from Deno (1977) and from this experiment are given in Table 2. Values measured by us are higher than Deno's by 8 to 23%. These discrepancies are probably due to differences in the shapes of our respective models.

TABLE 2. Currents Crossing Sections Through the Body of a 1.7-m-Tall Man. Data are given for both grounded and free-space conditions and for an electric-field strength of 1 kV/m. The data labeled "Deno" are from Deno (1977); h is the clearance between the feet and ground.

	Current (μA) Crossing Section				Ratio	
	Grounded		In Free Space		Free Space/Grounded	
Section	Deno	Our Data	Deno[a]	Our Data[b]	Deno[a]	Our Data[b]
Neck	4.4	5.4	2.9	3.1-3.3	0.66	0.58-0.62
Chest	11.2	13.5	5.5	5.4-6.0	0.49	0.40-0.45
Abdomen	13.1	14.6	6.2	5.7-6.4	0.47	0.39-0.44
Upper Thigh	7.2	7.8	2.9	2.8-3.2	0.40	0.36-0.41
Ankle	7.8	8.5	1.4	1.5-1.8	0.18	0.17-0.22

[a] $h \geq 12.7$ cm

[b] $h = 124$ cm for first column of values, and $h = 12.8$ cm for second column

Table 2 also gives sectional currents for free-space (i.e., remote from ground) exposure and ratios relating free-space and grounded sectional currents. Deno gives just one set of sectional currents for all elevations of the feet above ground greater than 12.7 cm. Since our sectional-current data vary over this range, data for both h = 124 cm and h = 12.8 cm are given in the table. It is evident that our data for h = 12.8 cm are in better agreement with Deno's than our data at h = 124 cm. This suggests that Deno may not have elevated his model far enough above ground to truly simulate free-space conditions.

Deno (1977) presents an empirical formula which gives sectional currents when $h < 2.5$ cm; this formula is reproduced as Eq. (2). Sectional currents, calculated using Deno's formula, and our measurements of these quantities are given in Table 3 for the four values of h we studied that were less than 2.5 cm. Our data show a significantly stronger dependence on body height than Deno's. In view of the close agreement between experiment and theory obtained in the spherical measurements described earlier in this paper, we believe that the error bars given in Table 1 accurately indicate the uncertainties in our data. The discrepancy between Deno's and our data must, therefore, be due to some difference in the exposure situation, in the models used, or to experimental uncertainty.

TABLE 3. Currents Crossing Sections Through the Body of an Ungrounded Human Exposed to a 1-kV/m, 60-Hz Electric Field. Data are from Deno (1977) and our work. Values of h given in cm.

	Current (μA) Crossing Section Through Body							
	h = 0.0		h = 0.34		h = 1.11		h = 2.21	
Section	Deno	Our Data	Deno	Our Data	Deno	Our Data	Deno	Our Data
Neck	4.4	5.4	4.2	4.7	4.1	4.0	4.0	3.8
Chest	11.2	13.5	10.8	10.9	10.4	8.7	10.2	7.6
Abdomen	13.1	14.6	12.5	11.7	12.1	9.3	11.8	8.1
Upper Thigh	7.2	7.8	6.8	6.1	6.5	4.7	6.4	4.2
Ankle	7.8	8.5	7.2	6.0	6.6	4.0	6.4	3.1

Current densities measured by Guy et al. (1982) in the neck, knee, and ankles of grounded and ungrounded human models are given in Table 4. Ratios of ungrounded-to-grounded current density, calculated using the data of Guy et al. and our data, are also given in this table. The agreement between these two sets of ratios is good. (Since current flow in the erect human is predominantly vertical, the comparison made here of Guy's total current densities and our vertical current densities is appropriate.)

TABLE 4. Current Densities in Grounded and Ungrounded Human Models Exposed to a Vertical, 1-kV/m, 60-Hz Electric Field. Data are from Guy et al. (1982) and from our work.

	Current Density (nA/cm^2) from Guy et al. (1982)		Ratio Free Space/Grounded	
Location	Grounded	Ungrounded	Guy et al.	Our Work
Neck	43	26	0.60	0.58
Thigh	–[a]	–[a]	–[a]	0.36
Knee	126	27	0.21	–[b]
Ankle	200	39	0.20	0.17

[a] Not given in paper

[b] Not measured

SUMMARY

This paper has presented the results of an experiment to measure the currents induced in seven segments of the body of an ungrounded human model exposed to a vertical, uniform, 60-Hz electric field. From these data, currents crossing horizontal sections through the neck, upper arm, chest, abdomen, thigh, and ankle were calculated. The latter currents are directly related to average vertical current densities in these parts of the body and, hence, to vertical electric fields induced in the body. The data show that induced sectional currents increase substantially as the body nears ground. The largest change was observed in the ankle, where the vertical current increased by a factor of 5.8 as the body neared and, finally, contacted ground.

Probably the most important use of these data will be to extrapolate to ungrounded exposure situations the more extensive data base for grounded exposure. Figure 4 gives the results of extrapolating grounded current-density data given by Kaune and Phillips (1980) to ungrounded exposure situations.

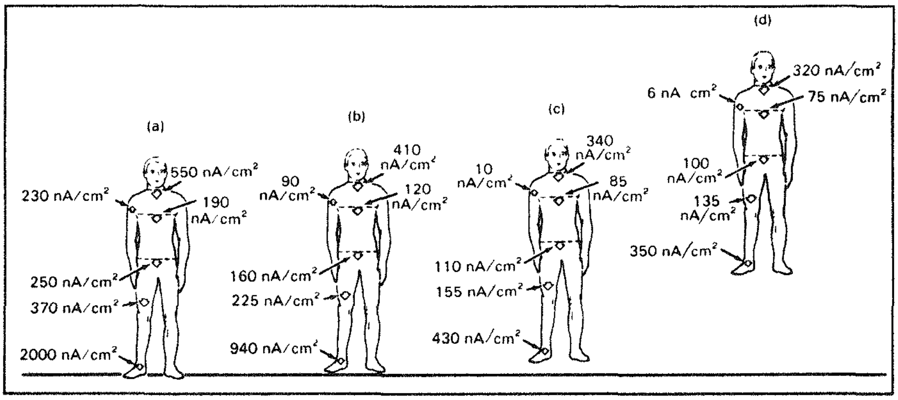

Figure 4. Average Vertical Current Densities Induced in Human Exposed to Vertical, 10-kV/m, 60-Hz Electric Field. Data are shown for four positions of model relative to ground plane: (a) electrically grounded; (b) feet 1.1 cm above ground, approximately simulating human standing on ground with insulating footwear; (c) feet 12.8 cm above ground; (d) feet 124 cm above ground.

The induced-current data given in this paper are valid for any conducting body which has the shape of a human (Kaune and Gillis, 1981). They can therefore be extrapolated from the conducting models used in our research to actual humans, with errors arising only from differences in body shapes. Furthermore they may be extrapolated to other frequencies, f, by multiplying them by the quantity f/60 (Kaune and Gillis, 1981). This extrapolation is valid for frequencies up to at least 10 MHz.

The experimental technique described in this paper allowed measurement of both induced currents and electrical capacitances. The capacitance data are currently being analyzed and will be presented in a future publication. When these results are available, it will be possible to analyze exposure situations where 1) the subject is grounded through parts of his body other than the feet, 2) the subject is grounded through a nonzero resistance, or 3) the subject is insulated from ground by a lossy dielectric.

ACKNOWLEDGMENTS

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MAGNETIC AND ELECTRIC POWER FREQUENCY FIELDS IN THE HOME

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This paper is based on a contribution to a panel discussion held at the Symposium, "Sources and Structure of Magnetic and Electric Fields in the Home."

We assume for this discussion that one is interested in knowing the domestic magnetic and electric fields to help determine whether exposure to them causes ill health and, in particular, to provide a measure of the electromagnetic environment for an epidemiological survey. First, we consider the various factors to be borne in mind concerning fields, exposure, and the kinds of measurement that should, perhaps, be made in the home. Then we remark on the sources of these fields and, finally, comment on approaches to quantitative surveys. There are difficulties apparent at the outset: it is not known what aspect of the fields may be important and, in addition, the situation is more complex than that outdoors.

FIELD AND EXPOSURE CONSIDERATIONS

Electric Fields

In the circumstances in which strong electric fields are encountered (i.e., under extremely high-voltage (EHV) electric power transmission lines and in substations) the fields are predominantly vertical, with strengths of a few kilovolts per meter. In homes they are much weaker, typically, 10 V m^{-1}, but perhaps rising to 200 V m^{-1}, and with directions which may be far from vertical. As in outdoor exposures, if one supposes that the stronger the field and the longer one stays in it the more marked (for better or worse) the effect is likely to be, then the simple time-integrating technique pioneered by Deno (1977) to give an exposure in kV m^{-1} hr may seem appropriate.

It was realized early on that there could be thresholds for possible effects and that a given exposure (in kV m^{-1} hr) was likely to be more severe if the field were high for part of the period of exposure and low for the rest than if it were at an intermediate level throughout. There was no rule to say what form a trade off between duration and strength might have. In the hope that future knowledge might clarify the issue, meters that recorded exposure times in different bands of field strength were introduced. Thus, several values are needed to characterize exposure.

At the low fields encountered in the home some in vitro cell studies suggest biological "windows," i.e., that only a particular range of field is effective. If this feature is confirmed, there is a risk that any measurement bands chosen today may later prove to have been unsuitable. We judge this risk to be small.

Magnetic Fields

Domestic magnetic fields from power equipment typically range from about 10 mA/m (approximately 0.1 mG) to perhaps 10 A/m. However, they have no predominant direction; so, at the very least, we must double the amount of data, i.e., we need to record exposures to both vertical and horizontal fields.

Estimation of exposure to magnetic fields is further complicated because currents in power systems rise and fall by orders of magnitude, whereas the voltages fluctuate by only a few percent. This means that the magnetic field at a given location must be characterized by its temporal variation. Figure 9 in the paper by Male, Norris, and Watts (this volume) shows this variation at one house for a period of a few days. The large fluctuations illustrate the pointlessness of spot measurements. However, measurements with a personal exposure meter reduce the importance of the temporal variability problem since, for a moving person, temporal and spatial variations are equivalent. However, exposure over a period of days, weeks or, possibly, seasons may be needed to give an accurate picture.

The mechanisms of action of magnetic fields at these recorded levels are virtually unknown. For the time being, it is most reasonable to assume that the internal electric fields and current flows induced by the changing magnetic field may affect tissue, rather than that the magnetic field acts directly on molecules or cells. However, in the home, induced internal currents are of the same order of magnitude for both electric and magnetic fields. For example, assuming typical values, let's compare currents at 50 Hz as a result of a vertical electric field of 10 V/m and a vertical magnetic field of 80 mA/m (1 mG), for a person of height 1.8 m, radius 0.1 m, with electric conductivity 0.2 S/m. Adapting formula (12) of Deno (1977) for the total body current from the electric field, we find a current density of

$$\frac{1.44 \times 10^{-11}\, \omega h^2 E}{\pi r^2} = 4.7\, \mu\text{A m}^{-2}$$

The peripheral current density induced by the magnetic field is

$$(\omega B r \sigma)/2 = 0.3\ \mu\text{A m}^{-2}.$$

Thus, it would be imprudent to estimate exposures to magnetic fields without also measuring exposure to electric fields.

Other Factors

Both electric and magnetic fields induce in the body internal currents proportional to frequency. Higher harmonics of the power frequency can therefore be important even though their magnitude is normally only a fraction of that of the fundamental. Fortunately, most magnetic and electric exposure meters are also proportionately more sensitive to higher frequencies. In our experience, television sets are a major source of high harmonic fields in the home, increasing the "total" induced currents by a factor of about two by the harmonic content.

Another difficulty is that for cancer, the one major disease on which it has been suggested that domestic magnetic fields may have an influence, there is a variable latency period. This means that the disease is not apparent until some time, often years, after it has been initiated.

Summary

Thus, one way to obtain a rough approximation of the exposure to electric and magnetic fields in the home would be to measure the duration of exposure over several bands of field strength and include both the primary harmonic and the sum (in some sense) of higher harmonics measured over a number of periods. To account for the temporal variability of these fields, these periods should last for, perhaps, a couple of weeks, spaced throughout the year, over a number of years.

We venture to say we shall have to be content with an even rougher approximation or another approach. For instance, we might postulate that allegations concerning the effects of these fields are improbable. Consider, as Bernhardt (1979) has done, the naturally occurring fields inside the body created by its own neural and muscular activity. At most places in the body, these fields swamp currents induced by domestic fields of the strengths typically encountered. Only if the domestic fields are at some resonant frequency is any effect likely. Perhaps further investigation should wait until someone demonstrates (e.g., in vitro) a biological resonance at a power frequency; the question merits further debate.

SOURCES OF FIELDS IN THE HOME

Internal

The principal internal domestic sources are appliances, which produce mainly magnetic fields. The most important are televisions (especially for harmonics), ranges, blankets, washing machines, heating systems (including under-floor systems), wiring and lamps (which give rise to electric as well as magnetic fields) and water and gas pipes (which will give rise to magnetic fields if they carry any stray current). Figures 1 and 2 show examples of the fields from a few of these sources. These measurements are merely illustrative, and should not be taken as definitive. Notice the rapid fall-off in field as one moves away from the appliance and the general background level—at least in the house where measurements were taken—on the order of 1 mG (~100 mA/m).

External

The most common external sources of fields are overhead power lines, underground cables and substations. The highest voltage lines pass near only a small proportion of homes and are thus likely to be infrequent sources of fields. External electric fields are screened by the fabric of the house by a factor of about 10 or more, but magnetic fields are not reduced in this way. The magnetic field from an overhead line falls off inversely as the square of the distance for a balanced supply (see Appendix). For the largest lines in the UK, an average field beneath the line is about 10 to 20 A/m, with occasional peaks of about 100 A/m. At a distance of 25 m these fields would be reduced about fivefold.

Urban and suburban power supplies in the UK are almost always distributed by three-phase cable buried in the street; rural supplies are often also buried. The conductors within the cable are laid in a helical pattern (to facilitate cable bending), and the magnetic field resulting from balanced currents in such a cable falls off exponentially at distances more than the pitch length of the helix away from the cable (see second part of Appendix). However, if the vector sum of the currents in the cable conductors (usually three-phase conductors and a neutral, and perhaps a screen or sheath) is not zero, the magnitude of the field due to the residual or unbalanced current will be proportional to the unbalance and will fall off inversely to the first power of the distance from the cable. This behavior has often been observed. It is very difficult to predict the degree of unbalance simply from cable loading.

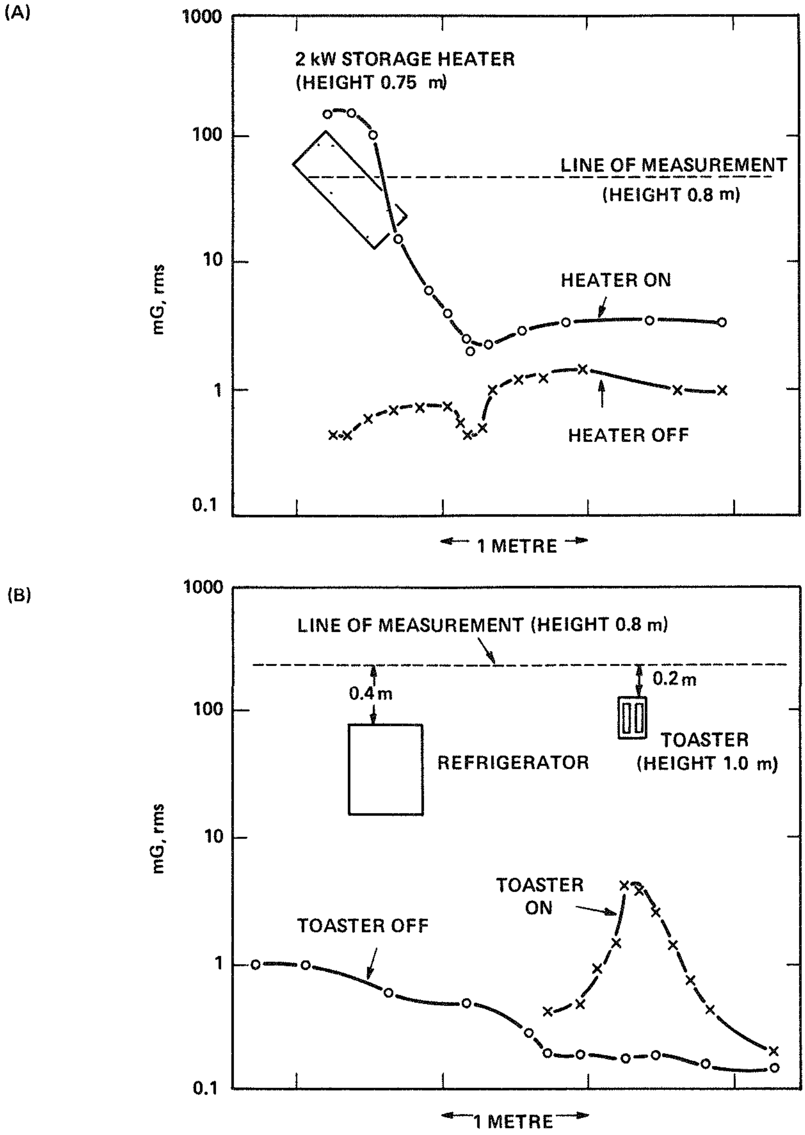

Figure 1A and B. Magnetic Field Strengths Close to Domestic Electrical Equipment. The line of measurement is shown in plan view. Note the increased background at locations remote from the storage heater probably due to currents in the wiring below the floor.

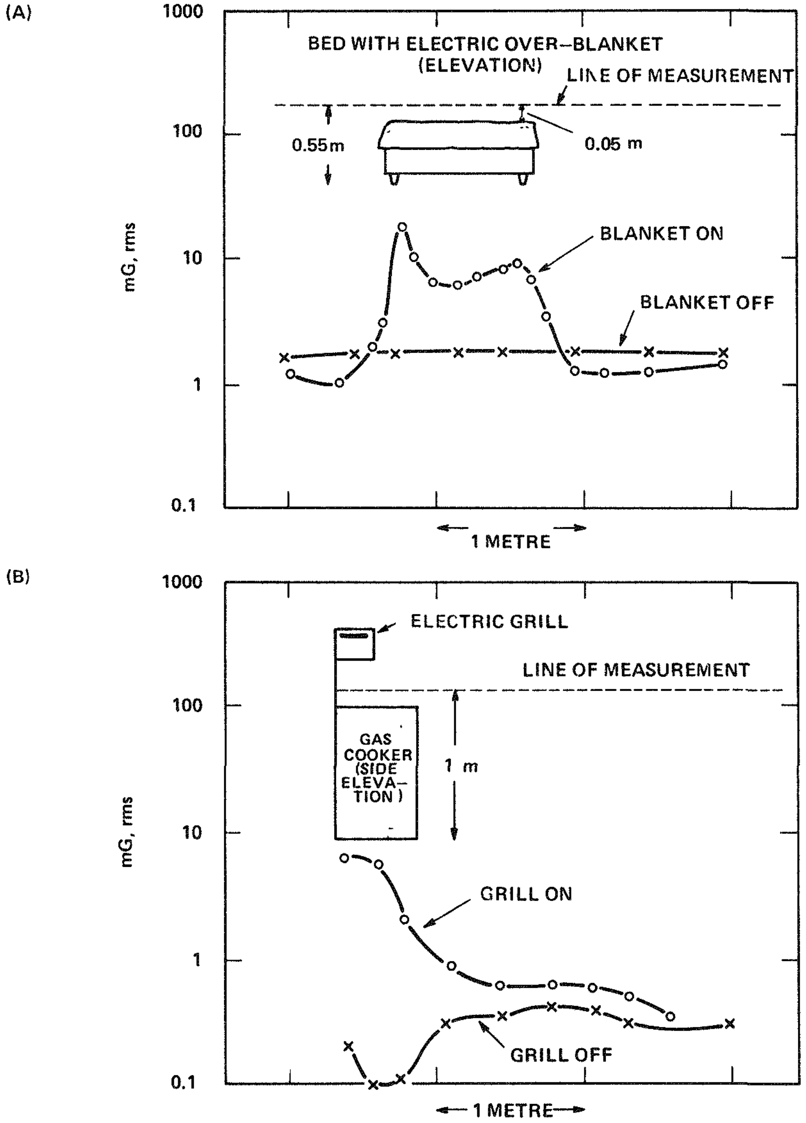

Figure 2A and B. Field Strengths Close to an Electric Blanket and an Electric Grill. Note the reduction in field strength at locations remote from the blanket when it is on, presumably due to interference effects.

Figure 10 in Male, Norris, and Watts (this volume) shows the variation of the three components of magnetic field over a period of time in a house on a street with distribution cables along both sides. The field component parallel to the cables is negligible; the other two components show wide but correlated fluctuations. The negligible parallel component suggests that the cables are the dominant source of domestic fields in this case. Figure 11 in the same article shows the vertical field within the house at various distances from the street. Again, the fields fluctuate together, with the amplitude falling off approximately at a rate consistent with a net current of a few amperes in the cables in the street. To examine this feature further, Male, Norris, and

Watts measured the field about 2 m directly above a buried distribution cable and calculated the field in an adjacent house, assuming a fall-off inversely proportional to distance. They repeated this for 24 houses and compared their estimates with the values actually measured in the houses (their Figure 12). Agreement was reasonable at high fields but, not surprisingly, worse at low fields, to which other unregistered sources will have contributed.

The net current carried by the cable must return somewhere. It is likely to either be dispersed in the earth or to flow via other service links, such as metallic water pipes. Current in a water pipe is equivalent, as far as the magnetic field it produces is concerned, to a cable carrying the same net current.

High-power transmission cables, with each phase in a separate cable and the cables laid parallel to each other,will produce a significant field without any unbalanced current flowing, but this sort of cable is infrequently found.

Field strengths measured at a substation are shown in Figure 3. Very close to some cables within the substation, fields approaching 100 A/m were recorded, but they fell rapidly to about 100 mA/m only a few meters outside the wall of the station.

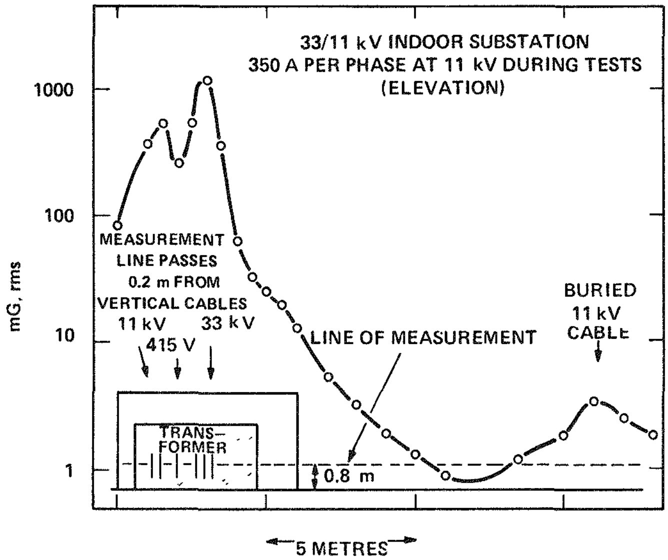

Figure 3. Field Strengths near an Urban Indoor Substation; Inside the Building, Levels may be as High as 1000 mG; 5 m from the Outside Wall, they are 1mG.

A STAGED APPROACH TO SURVEYS OF MAGNETIC FIELDS

Stage 1

Using Occam's Razor*, assume that only the highest fields are important. These arise from nonhelically wound cable systems and overhead lines close enough to produce fields larger than, say, 80 mA/m (1 mG), which seems to us, based on a moderate number of measurements, to be about the highest level in a house resulting from the overall wiring and other background sources at places remote from particular appliances. Count, then, the fields from just these strong external sources. If UK experience is a guide, only about 10% of homes will be affected. There may be data available on historic line loadings to allow estimating the field in earlier years.

Stage 2

Any refinement is bound to add to the difficulty and complexity. A relatively simple one, mentioned in the paper by Male, Norris, and Watts (this volume), arises from the fact that distribution cables are often installed (at least in Britain) on only one side of the street. If one suspected that magnetic fields cause effects one might look for a preponderance of cases on that side. Although this method is crude, it does mean that more homes would be included in a survey than by using only Stage 1, and the method seems free of several forms of bias (e.g., sociological). However, the ratio of the fields on the two sides of the street could be as low as 2:1.

Stage 3

Attempts to characterize what we might call ambient fields in various types of home may be taken a step further by installing a recording meter at a place near the center of the house, remote from large in-house sources of field, for a period of, say, 2 weeks on a few occasions during a year to get seasonal variations. This might be done at different addresses to represent various kinds of housing: urban, rural, flats, terrace, and individual. By scrutinizing the results, one might be able to classify them by general level of field. A study of different distribution cable designs and their use, to see what features lead to unbalanced current might be even more profitable. For both this stage and stage 4, the choice of how many bands to use in measurement and, for this stage, what field components to measure is best decided as late as possible to take advantage of the newest insights.

Stage 4

Personal magnetic and electric-field-exposure surveys can be performed in homes with different ambient levels. Data can be collected on the number of electrical appliances, electricity consumption, etc., and correlations can be attempted between these factors and exposure measurements. Again, this must be done in a variety of types of residences. Attempts should be made to find a mechanistic explanation for

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*Entia non sunt multiplicanda praeter necessitatem. (The best explanation is that with the fewest suppositions.)

any correlation that may occur. Armed with a data bank of this kind, one might then predict field exposures for people in homes at periods in the past, based on knowledge of loads in local lines and of factors such as the use of appliances. But one may also find "noise" limits, where too much random fluctuation prohibits discrimination.

We cannot foresee the outcome of this last stage of the approach; one needs to be careful when interpreting the results. For example, the use of electricity is also a measure of class and wealth, and this may be a more important determinant of disease, or the absence of it, since electricity is overwhelmingly beneficial.

At present, only stages 1 and 2 are being used in our work. Plans are being made to use stages 3 and 4, but they may require a great deal of work and the outcome is uncertain.

ACKNOWLEDGMENTS

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APPENDIX

Magnetic Fields From Arrays of Conductors

For a typical three-phase overhead line, consider three long, straight, horizontal and mutually parallel conductors arranged vertically, one above the next, with a spacing between them of s. Let the current in each be I.

Approximate formulae for the horizontal and vertical components of the magnetic field at a point a distance r from the middle conductor are given below under "vertical array" for $r >> s$ and $r >> t$, where t is the distance of the point above or below the horizontal plane through the middle conductor.

Current	Vertical array		Horizontal array	
	H_{horiz}	H_{vert}	H_{horiz}	H_{vert}
Positive or negative sequence	$\sqrt{3}sI/2\pi r^2$	$2\sqrt{3}tsI/2\pi r^3$**	$2\sqrt{3}tsI/2\pi r^3$	$\sqrt{3}sI/2\pi r^2$
Zero sequence, dispersed return*	$3tI/2\pi r^2$	$3I/2\pi r$	$3tI/2\pi r^2$	$3I/2\pi r$
Zero sequence with return conductor***	$6sI/2\pi r^2$	$12tsI/2\pi r^3$	~ 0	~ 0

*The return current is assumed to be dispersed through the ground.

**As t approaches 0, the field falls to $s^2I/2\pi r^3$ rather than to zero.

***For the vertical array, the return conductor is an additional, neutral conductor at a distance s above the top conductor or below the bottom conductor and carries a current of 3I. For the "horizontal array," each conductor is assumed to have its own sheath return, which carries a current I.

For a horizontally disposed arrangement of the three conductors (typical of underground transmission with one cable for each phase, or of some overhead lines), approximate formulae are given under horizontal array for the same conditions.

When remote from the vertical array of conductors, the horizontal component of the field dominates for positive, negative and zero-sequence currents with a return neutral. If there are unbalanced zero-sequence currents, the vertical component dominates and falls off only as 1/r rather than $1/r^2$.

When remote from the horizontal cable array, the vertical component dominates for positive, negative and unbalanced zero-sequence currents.

MAGNETIC FIELDS FROM THREE-PHASE CABLES

Here, we are interested in cables used under the street for distribution, to a row of houses, for example. Such cables usually contain (at least in the UK) either three 120°-sector-shaped conductors within a sheath acting as the neutral conductor, or four 90°-sector conductors. The conductors are laid in a helix.

The pattern of the magnetic field generated by a helical cable is complex, especially near to it. However, by considering the azimuthal distribution of current over the cross-section as a number of Fourier components, and by making some modest approximations, we can show that the field arising from positive and negative sequence currents of I per phase is predominantly horizontal. It can be approximated as $\frac{I}{2\pi} q^2 r_0 e^{-qr}/\sqrt{(qr)}$ for $r >> 1/q$, where r is the distance from the cable (radius r_0) and $q = 2\pi/p$, p being the pitch length of the helix.

By modeling the cable as two parallel conductors transposed at regular intervals, we can obtain an exact solution. This confirms the exponential behavior and shows that the field from any zero-sequence current returned within the cable also falls off in this way. A zero-sequence current of I per phase with a dispersed return will give a predominantly vertical field of $3I/2\pi r$. The model also shows that any marked deviations from uniformity of conductor spacing or pitch length, such as could occur at tee joints, may give rise to the field in their vicinity, falling off only as $1/r^3$ rather than exponentially.

SOURCES AND STRUCTURES OF MAGNETIC AND ELECTRIC FIELDS IN THE HOME

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INTRODUCTION

Six years ago, at the 18th Annual Hanford Life Sciences Symposium, I presented a paper entitled "Monitoring of Personnel Exposed to a 60-Hz Electric Field" (Deno, 1978). At that time, exposures of 5 to 10 kV/m and 10 to 20 A/m were of concern. Today, at the 23rd Hanford Symposium, we are concerned with household exposures of 5 to 10 V/m and magnetic fields of 0.01 to 0.02 A/m. These levels are one-thousandfold less than the earlier ones, which brings into consideration a group of sources that were not previously considered. The purpose of this paper is to put into perspective the dominant electric and magnetic fields to which people are exposed.

FIELDS

The electric and magnetic fields to which humans are exposed are grouped here to afford us a perspective of their characteristics so that measurements of exposure can be planned for meaningful applications.

QUASI-STATIC ELECTRIC FIELDS

Quasi-static fields are those that can be analyzed using static theory techniques. Generally, but not always, this excludes propagating fields. When object length is small relative to the propagating wavelength and skin depth is large relative to an object's cross-section, quasi-static field theory applies. Quasi-static electric fields are illustrated in Figures 1, 2 and 3.

Figure 1 shows a typical cross-section of the earth's field in which we walk; this field changes very slowly. Currents are induced in our bodies when we rotate in the field. Household 60-Hz fields are typified by the potential profile shown in Figure 2. Not shown are the tremendous static fields that build up on clothing and synthetic materials in the household environment. In dry weather the crackling of synthetic-material clothing indicates the ionization of air as a result of local fields that exceed one million V/m. Static charge collected by humans from carpeting often results in potentials of 4 kV; spark discharge current can exceed 1 A.

The field around a very large, 765-kV transmission line is shown in Figure 3 for conditions of 70-ft clearance (Deno, 1976). The potential in space is highest at the boundary surface of the conductor and zero at ground. The rms potential distribution is shown by the contour lines of 12.5 kV, 25 kV, 50 kV, 100 kV, and 200 kV. Electric-field profiles are shown for 1 m and 3 m above ground. The electric field is always perpendicular to a potential boundary surface such as that of the earth at ground potential. Around the three-phase line, the electric field is a rotating vector, as shown by the ellipses in Figure 3.

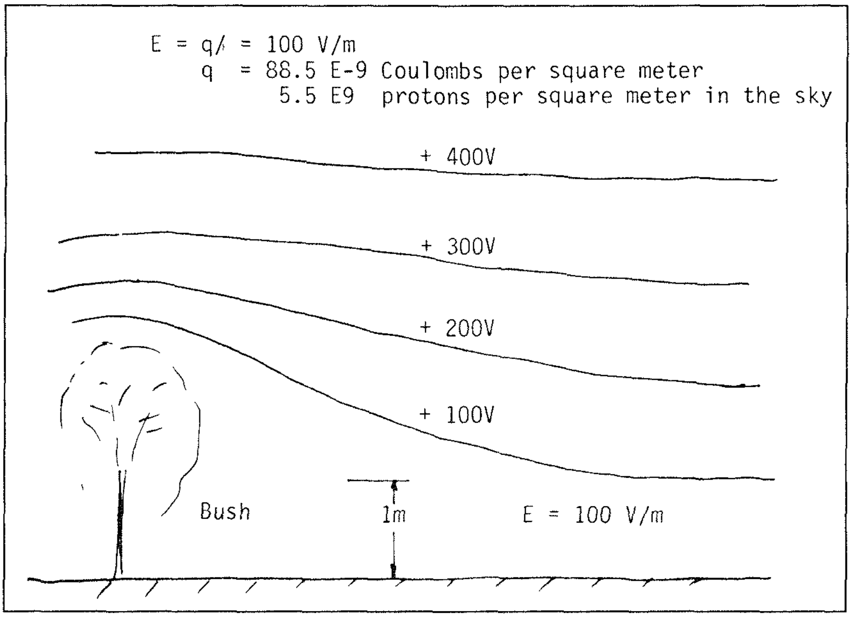


Figure 1. The Earth's Electric Field.

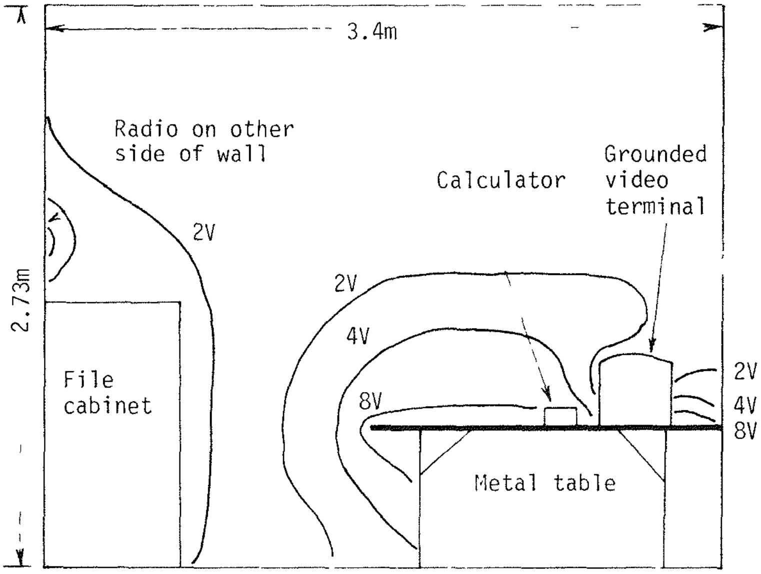
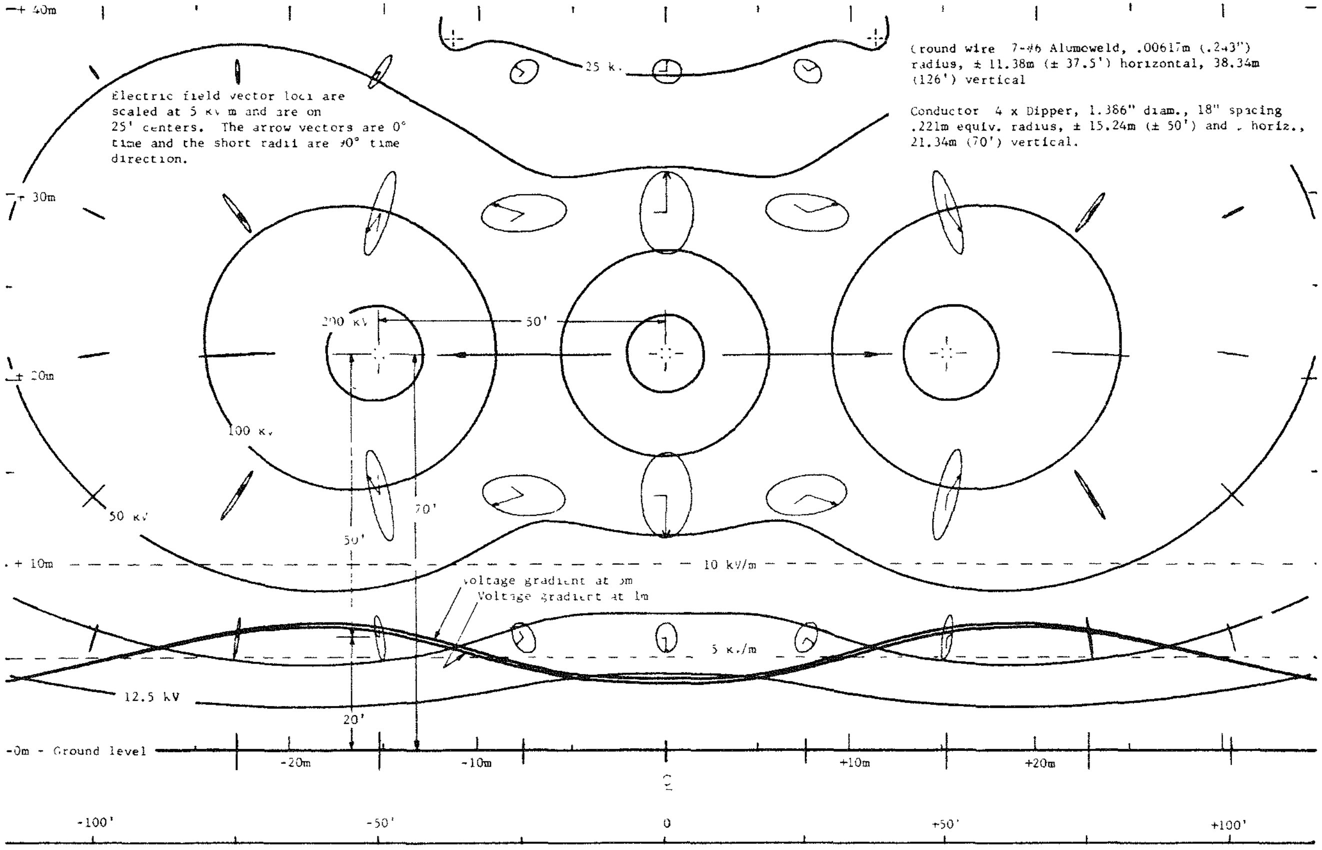


Figure 2. A Typical Office Electric Field.



Electric field vector loci are scaled at 5 kV m and are on 25' centers. The arrow vectors are 0° time and the short radii are 90° time direction.

Ground wire 7-#6 Alumoweld, .00617m (.243") radius, ± 11.38m (± 37.5') horizontal, 38.34m (126') vertical

Conductor 4 x Dipper, 1.386" diam., 18" spacing .221m equiv. radius, ± 15.24m (± 50') and . horiz., 21.34m (70') vertical.

765 kV line at 70' height: space potential map, electric field vector loci, and voltage gradient magnitude at 1m and 3m.

Figure 3. A Power-Line Electric Field.

QUASI-STATIC MAGNETIC FIELDS

Table 1 lists the dominant magnetic fields that we are exposed to. Two of the sources of these fields are shown in Figures 4 and 5; not illustrated is the dominant component, the earth's field. The earth field component is essentially constant. The power-frequency phasor rotates to form an elliptical locus, which changes around sources such as electrical appliances. Radiowave-field vectors are much smaller in magnitude than earth and power-frequency field vectors and add to them. Because of the much lower angular frequency, the earth's time-derivative field vectors are negligible compared to the power-frequency and radiowave-frequency time-derivative field vectors. Since the spectra of the various fields are not coherent, their vector sum forms an ill-defined trajectory that is impractical to illustrate. The dot product of the vector sum with a surface normal vector contributes to the induced voltage and current on a plane surface, such as inside a man, who is a resistive material. Figure 4 shows how a house ground loop can contribute to local magnetic fields. Practically, this kind of magnetic-field source is found in unexpected places as a dominant local source.

TABLE 1 Summary of Typical Electric, Magnetic and Radiated Fields

Source	Frequency	Strength	60-Hz Average Equivalent Induction Field	Comments
Electric				
Earth field		+ 100 V at 1 m height		Very low induced current
Clothing		up to 1×10^6 V/m	2 V/m	Extremely variable. Increases with low humidity. Corona can be seen when rubbing fabric
Household	60 Hz	2 V/m		
Powerlines	60 Hz	5 kV/m nominal maximum		Very short periods of exposure
Magnetic				
Earth field	0.2 rad/sec[a] 1 rad/sec[a]	44 A/m	0.02 A/m[a] 0.11 A/m[a]	Common motion while walking [a] Active body rotation [a]
Household	60 Hz	0.02 A/m, 0.2 A/m		Background, kitchen[a]
Powerlines	60 Hz	40 A/m, 2 to 20 A/m		Worst-case analysis, under real lines. Very short periods of exposure
Radiated Fields				
Radiowaves	1×10^6 Hz	0.1 mV/m 0.2 x 10^{-6} A/m	1.6 V/m 0.0034 A/m	Constant exposure. For human induction, 60-Hz quasi-static field analysis is appropriate
Sunlight	50×10^{12} Hz	300 V/m, 0.81 A/m		Assumed 400 W/m^2

[a] Body motion equivalent effects

Figure 5 shows the magnetic field around a high-power 765-kV line. Magnetic fields are negligibly influenced by both the earth and living tissues. These fields are 60-Hz sinusoids near the line, but away from the line, the balanced components cancel one another. The unbalanced component that goes through the earth return forms a large loop. It can produce magnetic fields even at some distance. The unbalanced component often consists largely of 60-Hz harmonics that make it identifiable on an oscilloscope. This unbalanced component often comprises the background 60-Hz coherent spectrum of a magnetic field.

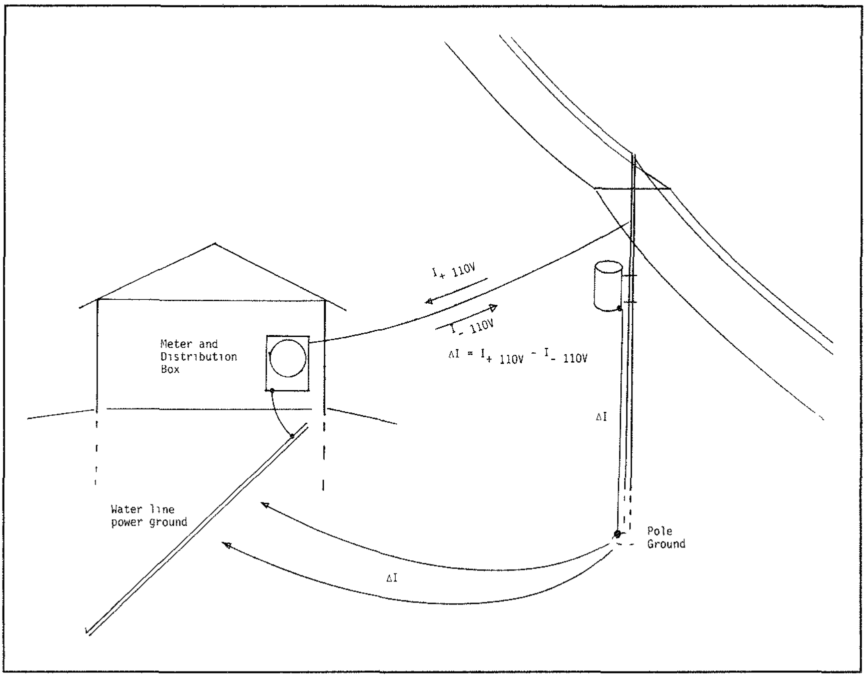


Figure 4. A Power Distribution Ground Loop.

PROPAGATING (RADIATED) FIELDS

Radiated fields are those which propagate through a medium at the velocity of light, Υ, where Υ is given by

$$\Upsilon = \frac{1}{\sqrt{\varepsilon \times \mu}} = 3 \times 10^8 \text{ m/sec,} \tag{1}$$

where ε is the permittivity of the material and μ is its permeability.

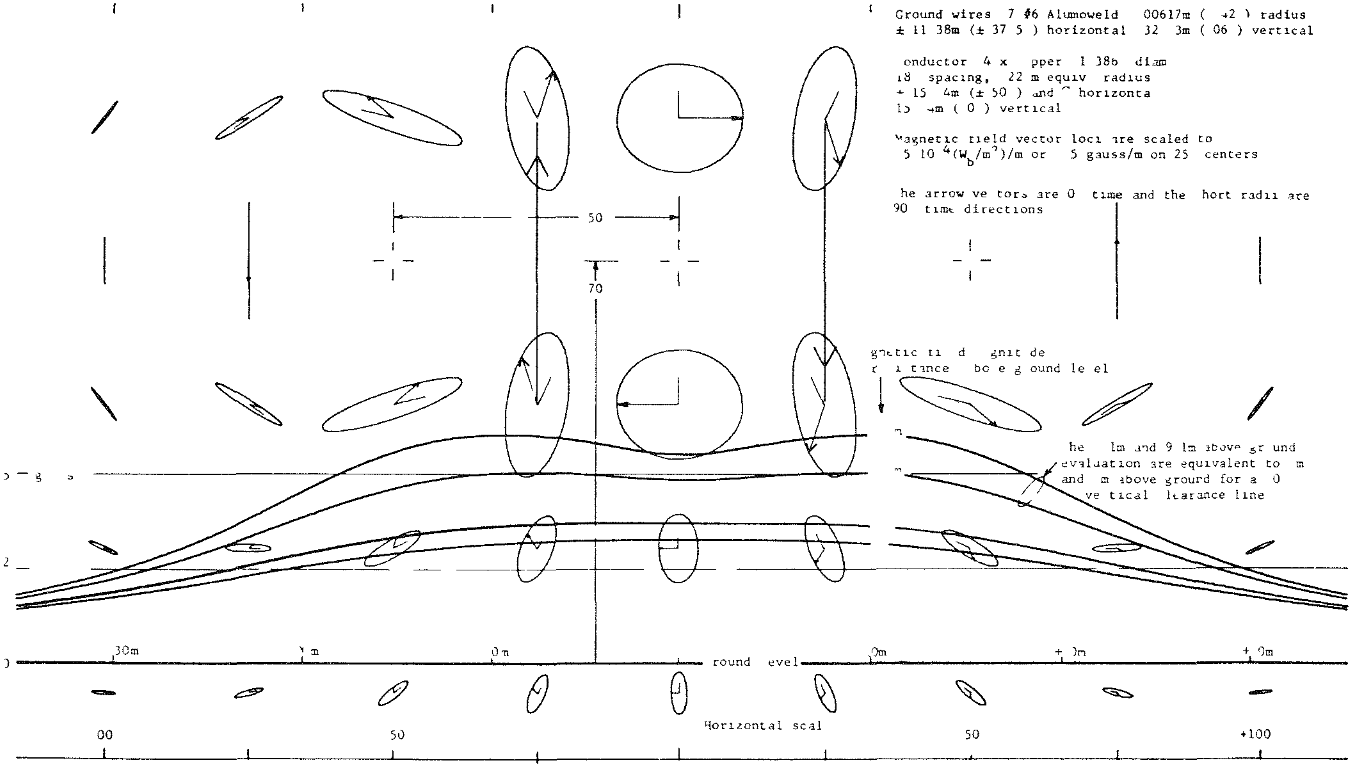
The electric and magnetic fields are coupled by the surge impedance (Z) of free space,

$$Z = \sqrt{(\mu/\varepsilon)} = 377\,\Omega. \tag{2}$$

Also, for a propagating wave, there is an energy flux (P) defined by

$$P = E^2/Z, \text{ or equivalently,} \tag{3}$$

$$P = I^2 Z. \tag{4}$$



765 kV line carrying 4000A at 70 heigh magnetic field vector loci magnetic field magnitude at 1m 3m 7 1m and 9 1m

Figure 5 A Power-Line Magnetic Field

The choice of the appropriate method of analyzing the interaction of an object with a radiating field depends on the wavelength of the field (λ) relative to the object's size and also on the object's skin depth (δ). The skin depth of an object such as a human, with a resistivity of $\rho = 10\ \Omega$ - m, is given by

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{5}$$

where $\mu = 4\pi \times 10^{-7}$ Henry/m, the permeability of free space. If the wavelength is much larger than the skin depth, then the analysis can be done in the same way as for 60-Hz calculations. If not, skin-surface calculation methods are appropriate.

Radio signals are an example of a common radiated wave; their significant levels are found in the range of $1\ \mu\text{V/m} < E < 1\ \text{mV/m}$. Since the current induced by an electric field is proportional to its frequency of oscillation, a 1-MHz radio signal at a field strength of 0.1 mV/m induces a current equivalent to a 60-Hz electric field of 1.6 V/m.

A similar relationship holds for magnetic fields. The radiofrequency magnetic field is related to its electric field by $H = E/Z$. The 0.1-mV/m radiowave then has a magnetic field of 0.26×10^{-6} A/m. The equivalent 60-Hz magnetic field is 0.0044 A/m, again related to the ratio of the frequencies of the fields.

The eddy-current skin depth for the 1-MHz wave is 1.6 m, which is large compared to any human-body cross-section. Its wavelength is 300 m, which is large compared to the length of a person. Therefore, the propagating radiowave interaction with a human can be analyzed using the same quasi-static techniques as those used with 60 Hz (Deno, 1977).

Sunlight, which includes the frequency of 3×10^{14} radians/sec (5×10^{13} Hz), is another example of a common electromagnetic radiated field. Assuming the radiated energy flux is $P = 400\ \text{W/m}^2$ in sunlight, then, from (3) and (4),

$$E = \sqrt{PZ} = 400\ \text{V/m}, \tag{6}$$

$$I = \sqrt{P/Z} = 1.0\ \text{A/m}. \tag{7}$$

The eddy-current skin depth for this frequency is 230 μm, which is small compared to any human-body cross-section. The wavelength is 6.3 μm, which is small compared to the length of a person. Therefore, for sunlight analysis we cannot use quasi-static techniques as with 60 Hz. Sunlight-radiated energy couples effectively to human skin, inducing significant voltage and currents that can cause sunburn.

FIELDS AND TIME-DERIVATIVE INDUCTION CURRENT

Magnetic Induction from Low-Frequency and Earth Fields

Magnetic induction of current in a resistive medium such as a biological system at low frequency is proportional to the induced voltage. The induced voltage can come from time rate of change of the field or rotational motion of the medium, for example, normal body motion.

The magnetic field intensity can be expressed as

$$\bar{H} = \bar{H}(\omega) + \bar{H}_e. \tag{8}$$

$H(\omega)$ = the 60-Hz magnetic field, usually expressed in six variables, real and imaginary, in three cartesian coordinates. Coordinates can be rotated to describe the rotating vector in two orthogonal coordinates with four variables for a steady-state single frequency.

$\bar{H}_e$ = the earth's field, essentially nonvarying. Usually expressed in three cartesian components. Coordinates can be rotated to one component, which is approximately 44 A/m. The maximum variation is 1% during any one day.

The electric induction from a magnetic field can be expressed as the time rate of change of the flux density, $B = \mu H$, which is the electromotive force, emf, = $d(\mu H)/dt$; or, more elegantly, $\nabla \times E = -\partial B/\partial t$; the curl of E equals the partial of B with respect to time. If the magnetic field is measured along a sensitive axis, the curl of E is around that axis. After all the other calculations are made, the permeability constant can be added to obtain the voltage.

The net magnetic field intensity can be measured along a sensitive axis, S; it is shown by equations (9 and 10):

$$H = \bar{H} \cdot S \tag{9}$$

$$= \bar{H}(\omega) \cdot \bar{S} + \bar{H}\mathrm{e} \cdot \bar{S}. \tag{10}$$

The magnetic-field-induced voltage per unit area perpendicular to S is obtained from (8) and (10):

$$\text{emf} = \mu \frac{\partial H}{\partial t}$$

$$= \underbrace{\mu \bar{S} \cdot \omega \bar{H}(\omega)}_{\text{The power frequency induction}} + \underbrace{\mu \bar{H}(\omega) \cdot \bar{S} \frac{d\Theta_\omega}{dt} + \bar{S} \cdot \mu \frac{d\bar{H}_e}{dt}}_{\text{These terms are negligible}} + \underbrace{\frac{\bar{S} d\Theta_e}{dt} \cdot \bar{H}_e}_{\text{The motion induction from the earth's field}} \tag{11}$$

$\bar{H}$ is the magnetic field intensity vector in A/m,
$\bar{H}(\omega)$ is the frequency component vector of the magnetic field,
$\bar{H}_e$ is the earth's magnetic-field-intensity vector, ∼40 A/m,
$\bar{S}$ is the subject area's normal vector,
Θ_ω = the angle between $\bar{H}(\omega)$ vector and area normal vector, and
Θe = the angle between the earth's field vector, H_e, and area normal vector.

If the time derivative of the magnetic field is normalized to the 60-Hz magnetic field, calculation of the induced current density in A/m² can proceed as follows:

$$i = (\mu dH/dt)(\text{Area}/\text{Resistance})/(\text{Circumference}) \tag{12}$$

$$= (\mu\omega H_{rms})(\pi r^2/R)/(2\pi r) \tag{13}$$

$$= (377\,\mu H_{rms})(r/2R). \tag{14}$$

Assume that the resistivity of the medium is $R = 10\ \Omega/\text{meter}$; the current density at the radius of the cross-section is then:

$$i = 23.74 \times 10^{-6}\ H_{rms}\ \text{A/m}^2. \tag{15}$$

The induced voltage is $377\mu H$ times a cross-section area. Current densities are shown in equations (16) and (17) for an assumed magnetic field intensity of $H = 0.1$ A/m. These currents are in the range of ions in a wetted contact. For humans, the induced current density in typical cross sections of the body is:

$$\text{Torso radius } r = 0.145\text{ m},\ i = 3.45 \times 10^{-6}H = 0.345 \times 10^{-6}\ \text{A/m}^2,\text{ and} \tag{16}$$

$$\text{Calf radius } r = 0.056\text{ m},\ i = 1.3 \times 10^{-6}H = 0.13 \times 10^{-6}\ \text{A/m}^2. \tag{17}$$

Electric Induction From Static Fields and Phasor Fields

The combined electric induction from a static electric field and a manmade phasor electric field is similar to the combined magnetic induction from the earth's magnetic field and a manmade phasor magnetic field. The representation here is a simplified symbolic form, to avoid the detailed surface normal electric field complication around humans.

Starting from the concept $E = V/S$, where S is the spacing,

$$V = \bar{E} \cdot \bar{S} \tag{18}$$

$$= \bar{E}(\omega) \cdot \bar{S} + \bar{E}(\text{static}) \cdot \bar{S}. \tag{19}$$

The induced body currents from the dV/dt function are:

$$dV/dt = \partial/\partial t[\bar{E}(\omega) \cdot \bar{S} + \bar{E}(\text{static}) \cdot \bar{S}] \tag{20}$$

$$= \underset{\substack{\text{Phasor field}\\ \text{component}}}{\underleftrightarrow{\omega \cdot \bar{E}(\omega) \cdot \bar{S}}} + \underset{\text{Neglect these terms}}{\underleftrightarrow{\bar{E}(\omega) \cdot d\bar{S}/dt + d\bar{E}_s/dt \cdot \bar{S}}} + \underset{\substack{\text{From body}\\ \text{motion in}\\ \text{clothing}}}{\underleftrightarrow{\bar{E}_s \cdot d\bar{S}/dt}}. \tag{21}$$

The rapid body motion that induces a current in a static electric field is equivalent to the induction in a 60-Hz vertical electric field of a few V/m.

ELECTRIC AND MAGNETIC FIELDS IN ONE DAY IN THE LIFE OF DON DENO

An hourly recording of electric- and magnetic-field exposure is provided in Figures 6 and 7. This type of data, accompanied by oscilloscope recordings of field waveforms and their time derivatives, provides a background reference to assure valid interpretation of dosimetric or other data.

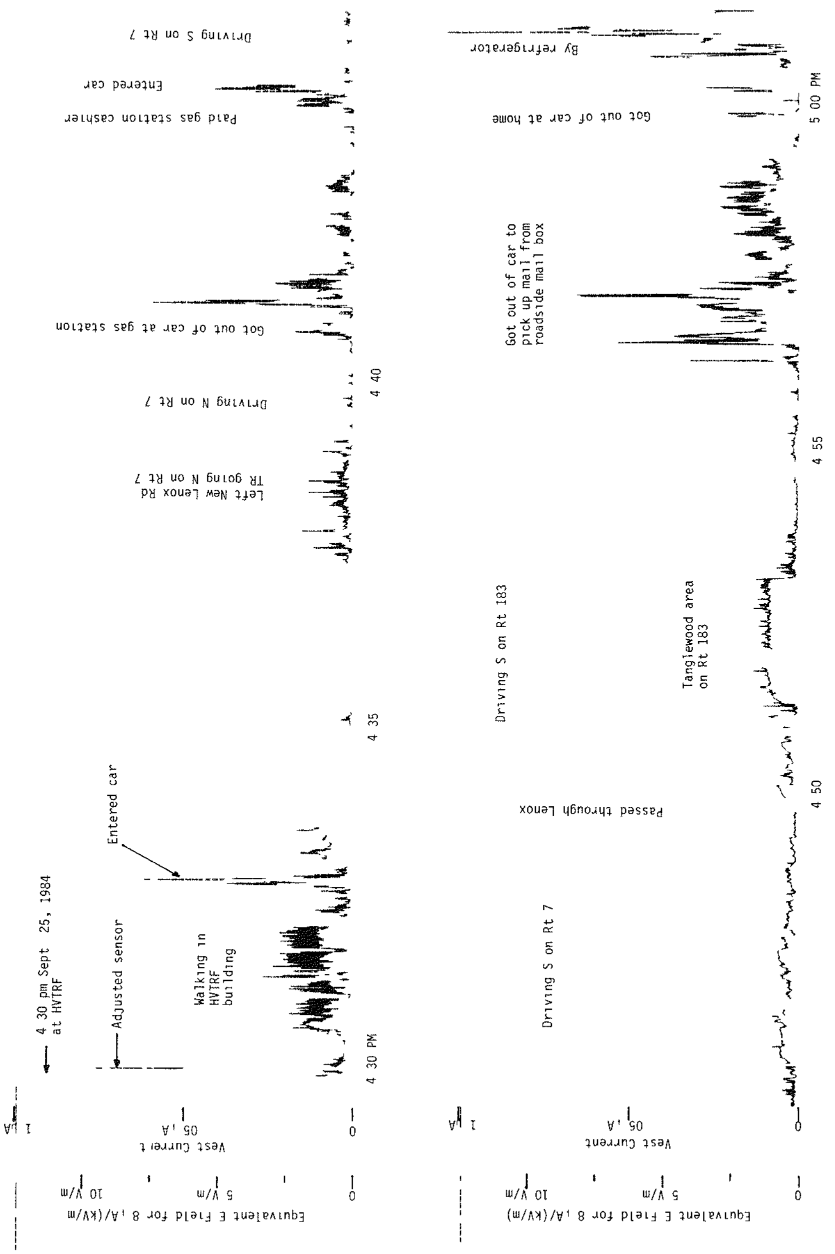


Figure 6. Electric-Field-Induced Current on a Human during 1 hr.

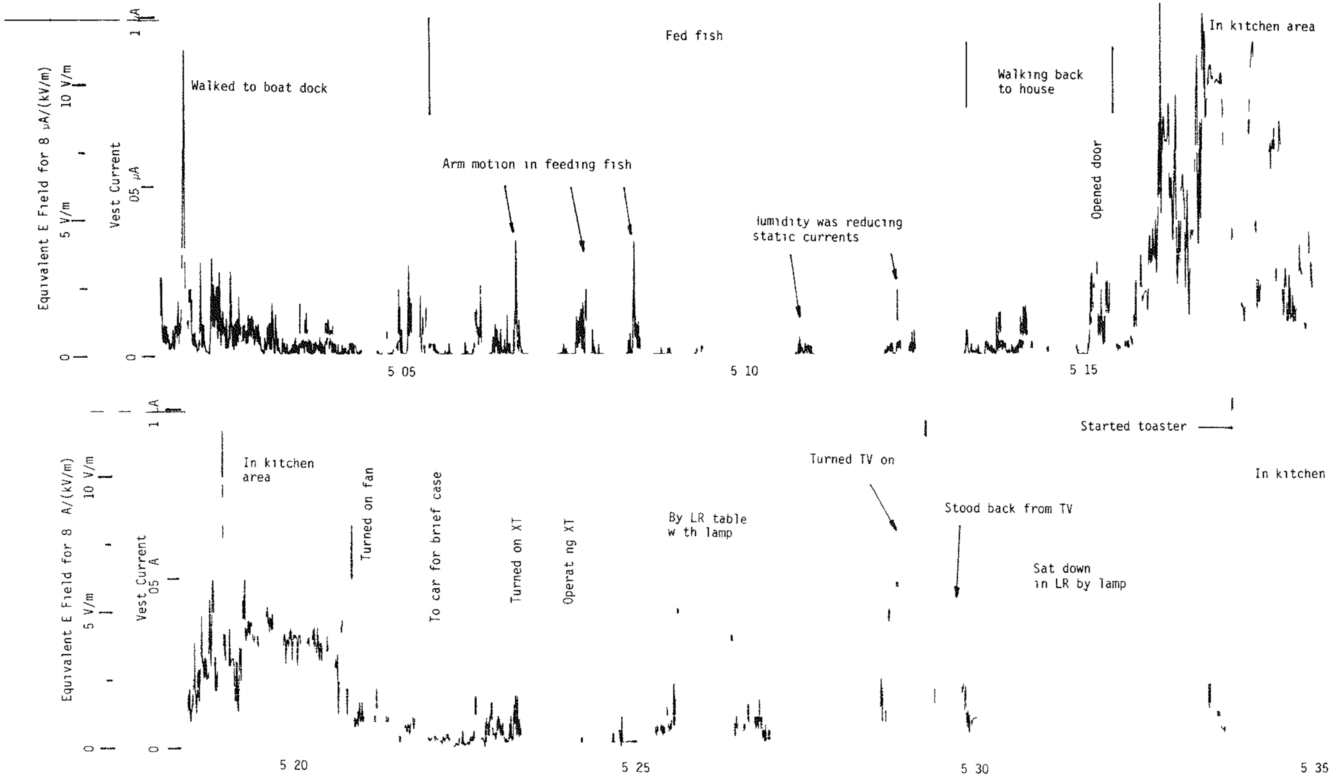


Figure 6 Continued

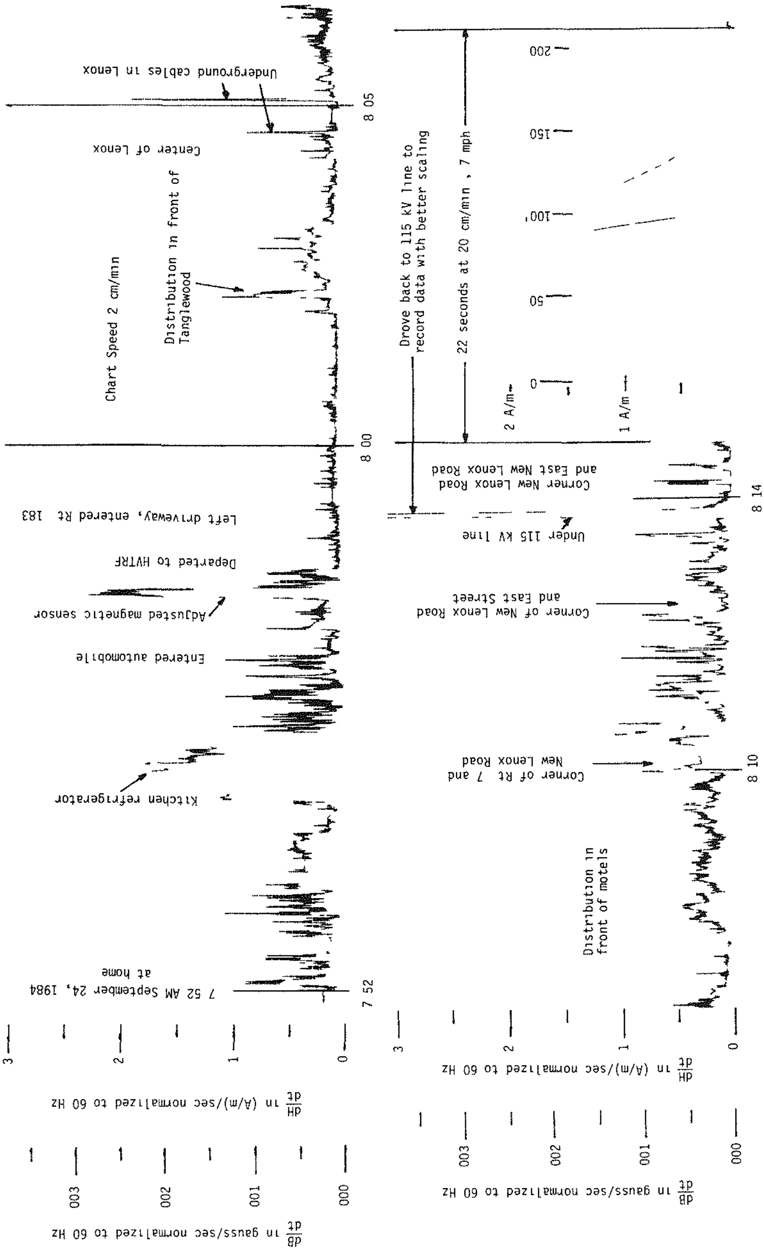


Figure 7. Magnetic-Field-Induced Current in a Human during 1 hr.

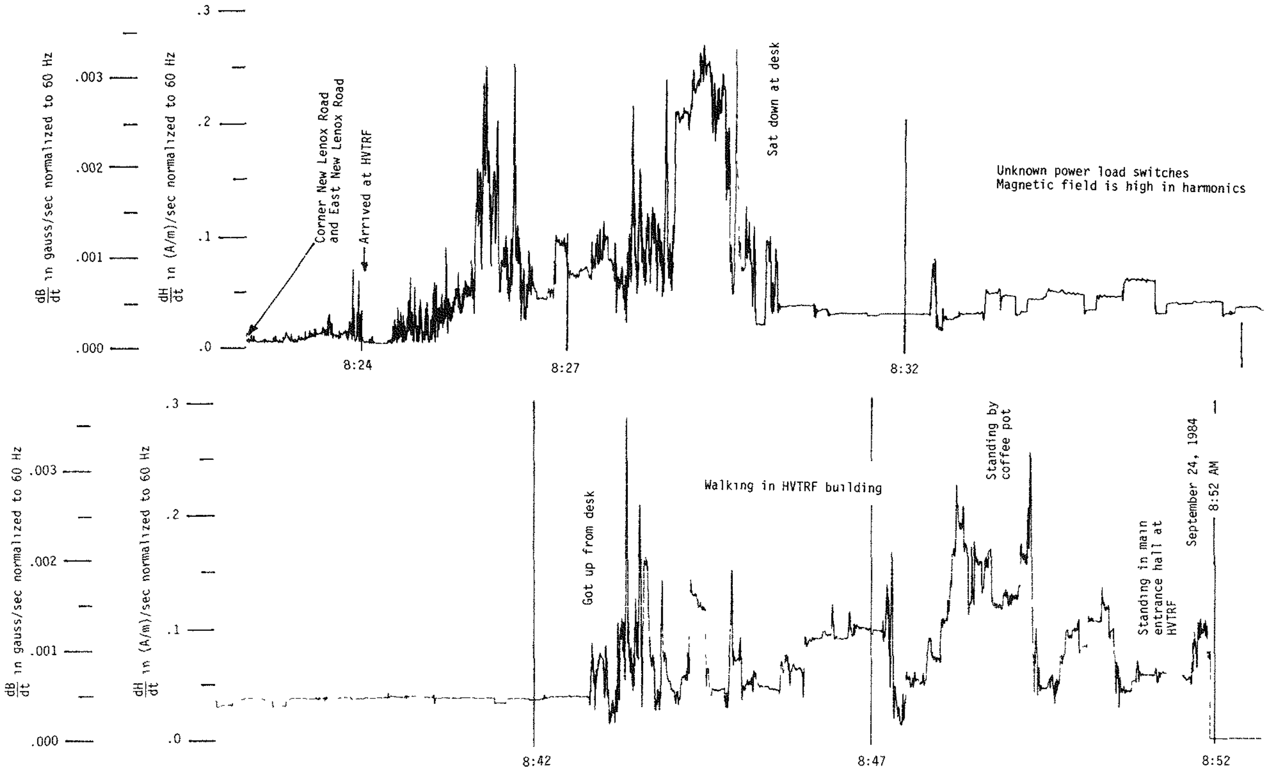


Figure 7. Continued

The electric-field recording shown in Figure 6 was made by means of a conductive cloth vest worn inside a jacket. The current flowing from the vest to the body of the human was measured. This current is proportional to the time derivative of the electric field, averaged over the surface of the vest. The vest current had a correspondence of 8 μA/(kV/m) while the wearer was grounded and standing in a vertical electric field. The sensed current was processed according to the following transfer function:

Detected Signal		Postdetection		
$[s/(s + 1 \times 10^6)]$ ·	$[3.77 \times 10^5/(s + 3.77 \times 10^5)]$ ·	$[s/(s + 3.7)]$ or 1.2 ·	$[1/(s + 2)]$	(22)
Vest senses the field derivative	Input amplifier high-frequency cut-off changes with gain. Shown for Figure 7 data	Inter-stage low-frequency cutoff	Postdetection filter high-frequency cutoff	

This is the transfer function of the electric-field intensity derivative normalized to 60 Hz in V/m. The output is a smoothed dc voltage analog of the derivative magnitude, d(V/m)/dt. An alternative selectable factor is the addition of an integrator which transfers the output to the same dimensions as the field intensity. The selectable integrator transfer function is $377/(s + 100)$.

The current, representing the time derivative of the electric field, and its integral, representing the field itself, were also displayed on an oscilloscope.

Figure 6 shows the recorded induced electric current. Most of the low-to-medium levels come from body-motion clothing static. For example, when getting into an automobile at 4:33 p.m., all current resulted from static induction. The low levels from 4:45 p.m. to 4:55 p.m. reflected small body motions; other fields were shielded by the metal automobile. Between 4:52 p.m. and 4:53 p.m., overhead distribution lines coupled a small electric field through the car window. The much larger induced current from 4:57 to 4:59 was from body motion when leaving and re-entering an automobile. In the house, the largest induced currents were in the kitchen area, particularly near the refrigerator. The induced currents were zero for much of the time around 5:10 p.m., while feeding bread to pet fish; the peaks were from arm motion in throwing the bread. The high humidity over the water gradually reduced the body-motion static currents from clothing at 5:11 and 5:12 p.m. A close study of Figure 6 provides a perspective of the electric-field induction that people actually encounter in noncontrived situations.

The magnetic-field recording shown in Figure 7 was made using a coil worn under the belt, with its sensitive axis pointed ahead of the person; the coil axis tilted slightly upward and to the side. This current represents the time derivative of the magnetic-field component along the axis. The sensed current was processed according to the transfer function described in equation (23).

Detected Signal		Postdetection		
$\{s \cdot s/(s+2.5)$	$\cdot\ [3.77 \times 10^4/(s+3.77 \times 10^4)]$	$\cdot\ [s/(s+3.7)]\}$ or 1.2	$\cdot\ [1/(s+2)]$	(23)
Coil senses field derivative with coupling low-frequency cut-off	Input amplifier high-frequency cut-off changes with gain. Shown for Figure 8	Inter-stage low-frequency cut-off	Postdetection filter high-frequency cut-off	

This is the transfer function of the magnetic-field intensity derivative normalized to 60 Hz in A/m. It is a smoothed dc voltage analog of the derivative magnitude dH/dt normalized to 60 Hz scaled in A/m. An alternative selectable factor is the addition of an integrator which transfers the output to the true dimensions of the field intensity magnitude. In addition to recording the average magnitude, this current, representing the time-derivative of the magnetic field, and its integral, representing the field itself, could be viewed on an oscilloscope.

Figure 7 shows the recorded induced magnetic current. Most of the low-to-medium levels came from body motion in the earth's magnetic field, as during the 7:55 a.m. period. While driving an automobile a person is relatively motionless, with little magnetic-field induction, as indicated at the 8:00 a.m. recording. During that period, the recording shows 60-Hz magnetic peaks from overhead distribution (for example, 8:02 a.m.) and underground distribution (for example, 8:05 a.m.). The highest peak was under a 115-kV line, as shown at the 8:14 a.m. recording. Since the peak saturated the recorder, to make the data more interpretable, the same section of the road was again traversed, at low speed, and recorded using a less sensitive scale. The peak magnetic field intensity was 1.5 A/m. The sensitive axis of the coil was skewed approximately 20° above the horizontal, which accounts for the nonsymmetrical double-peak pattern. At other times, when body motion was substantial, levels were close to the high levels near appliances such as a coffee pot. While sitting relatively motionless at a desk (8:32 a.m. to 8:42 a.m.), the background power-frequency field induction was relatively stable. At approximately 8:33 a.m., loads were being switched, as indicated by the square-shaped recordings. The recording shown in Figure 7 provides a perspective of the magnetic-field induction that people actually encounter in noncontrived situations.

The transfer functions (22) and (23) used in processing the data in Figures 6 and 7 are the standard field-meter signal-processing functions. They were selected for convenient operation of a field meter in normal circumstances. In the strip-chart recordings of Figures 6 and 7, body motion proved to be a large part of the electric- and magnetic-field-induced current. At common body motions of 1 radian/sec or less, these induced currents were attenuated by the three low-frequency poles. To be more accurate, measurements were also made with the lower-frequency cutoffs. The pole cutoff of 0.1 radians/sec has a transient recovery time constant of 10 sec. Three poles with 10-sec time constants in series result in an inconvenient recovery from transients. Therefore, some equipment performance compromises must be made. In any research, documentation of the selected transfer functions is important for replication and future interpretation of the data.

CHARACTERIZING FIELD ENVIRONMENT IN HOMES

Research has supported the concept of induced current as a significant biological influence. For example, the magnetic-field waveform used with bone healing has often been presented as a field-intensity square pulse. Since a square-field-intensity shape is not physical, the rate of rise and fall which induces voltage and current must then be the important property. These properties can only be specified by the field intensity with its derivative, as shown in Figure 8. Figure 9 shows a magnetic field and its time-derivative magnitude measurement normalized to 60 Hz. It was recorded by a coil placed on the table illustrated in Figure 2. Harmonic content measurement is relevant for steady-state, alternating fields. The field intensity, and its derivative in the time domain, is a relevant description of a transient phenomenon such as body motion.

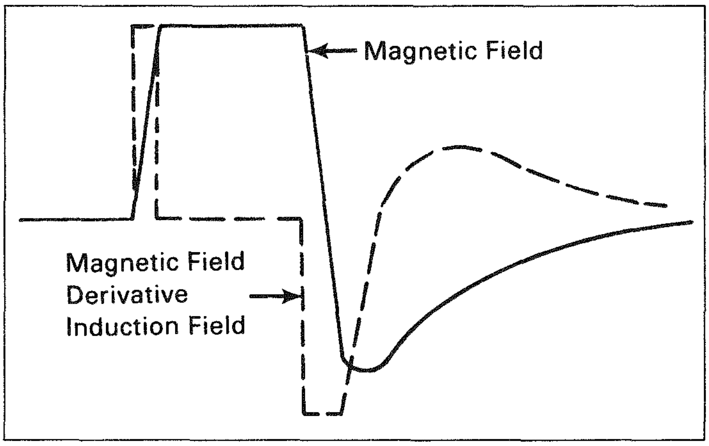


Figure 8. Magnetic-Field Intensity used in Bone-Healing Experiments.

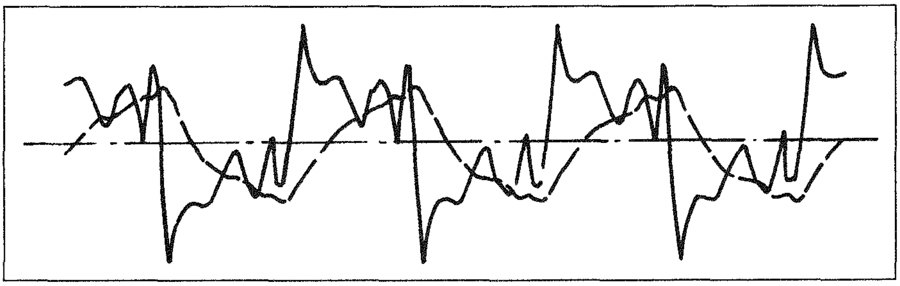


Figure 9. Magnetic Field Measured, from the Data shown in Table 1 and in Figure 2. H_{rms} = 0.1 A/m. The derivative normalized to 60 Hz equivalent was approximately the same average and rms.

Characterization of a home environment field is much more complicated than that for a power transmission line, because a power line has well-controlled boundary conditions and dielectrics, and current paths are well defined. Home environments have very complicated distributed potential boundary conditions with unstable distributed dielectrics. Unbalanced currents in difficult-to-characterize ground loops may cause much of the magnetic field; therefore a complete characterization of the field would have to include overwhelming detail.

Electric potential maps, as shown in Figure 2, are useful (if not mandatory) to interpret field-intensity measurements in the home. Oscilloscope photographs of the field and its time derivative would contribute to understanding the 60-Hz field, its harmonics and the sources of the field.

Magnetic-field intensity mapping is useful to interpret the magnetic field environment in the home. Like the electric field, the magnetic field and its time derivative should be observed on an oscilloscope and photographed.

Measuring, monitoring and reporting of three-dimensional fields require deciding between many possible signal-processing techniques. For example, should the maximum value of the vector be used to characterize the field? Since instantaneous data are too extensive to comprehend, let alone store, what averaging process should be used to condense the data to manageable and comprehensible amounts? Is it desirable to add the three vector components of the field strength? If so, should they be added as average, root-mean-square, peak, or quasi-peak; and what time constant should be used in the continuous averaging of the data acquisition process? Without an explicit mathematical model for the effect of concern, the selection of a process to characterize electric- or magnetic-field exposure remains arbitrary.

Table 1 shows a summary of the typical fields to which humans are exposed, as we have discussed. Clearly, sunlight has the highest energy and induction levels, although it penetrates only the skin. The highest electric fields that we are exposed to are those from clothing static at breakdown field intensities. The highest magnetic field that we are exposed to is the earth's field, at 44 A/m. The highest induced power levels come from sunlight at a nominal 400 W/m, yielding 400-V/m and 1-A/m field intensities. Table 1 lists radio waves at 0.1 mV/m. There are cases where radio field intensities have been as high as 1 V/m, which is ten thousand times greater than the value listed in Table 1. In such a case, the equivalent 60-Hz-field-induced currents would be 16 kV/m instead of 1.6 V/m, and 44 A/m instead of 0.0044 A/m. Radio waves should be interpreted as distributing currents and voltage in a human similar to those from 60-Hz fields. Clearly, 60-Hz power frequency fields are not the greatest that humans experience.

RECOMMENDED MEASUREMENT PROGRAM TO CHARACTERIZE ELECTRIC AND MAGNETIC FIELDS IN THE HOME

A time history (strip-chart-type recording) of real exposure provides a lucid perspective of how people are exposed to fields — a perspective that is not acquired by looking at tables of field-intensity-measurement data. In addition, the derivatives of the fields should be recorded, since research has shown that the induced currents and voltages which they produce may have some biological significance. If other factors are suspected of being relevant, their inclusion in the data base should be accompanied by an explanation of the reason for selecting that factor and the method to be used in interpreting the additional data.

Procedures for obtaining data should include maps of the space potentials and magnetic fields in various rooms. In selected places, electric-field measurements and details of the three-dimensional structure of the magnetic field should be obtained with oscilloscope pictures and time derivatives. When making dosimetric measurements, a number of simplifying assumptions must be made; they should be discussed candidly so that others can quantitatively interpret and review the data. Examples of such assumptions are:

- Sensitive axis or axes and spectrum transfer function measurement process;
- Detector processes, such as peak, quasi-peak, rms, averages, and their filter transfer function;
- Processing of any axis data combination and filter transfer function.

Finally, all work must be sufficiently well reported to be replicable.

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EFFECTS OF AN 1100-kV PROTOTYPE TRANSMISSION LINE ON TREE GROWTH

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ABSTRACT

This report describes results from a continuing study of possible effects on tree growth from a prototype 1100-kV test line located near Lyons, Oregon. Measurement of the growth of Douglas-fir trees located along a natural transect that extends away from the test line was repeated for the eighth year. Trees growing very near the line displayed changes in growth form. Trees within 15 m of the line displayed damage to branches and buds in the upper canopy. Trees 15 to 30 m from the line displayed damaged needles. Trees more than 30 m from this line were not visibly affected. Measurements of increase in trunk diameter and proximity to the test line revealed no detectable relationship between Douglas-fir tree productivity and exposure to the electrical field. Healthy Douglas-fir trees transplanted to locations beneath the test line received damage to their upper branches from the electric field; transplanted alder trees, however, were not visibly damaged.

The Bonneville Power Administration (BPA), which is responsible for marketing power from the Northwest Federal Hydroelectric projects, constructed a prototype 1100-kV transmission system near Lyons, Oregon in 1976. This line is 1.1 mile (2.1 km) in length and traverses an area representative of the types of habitats commonly found west of the Cascade Mountain Range, including forests dominated by Oregon White Oak (*Quercus garryana*) and Douglas fir (*Pseudotsuga menziesii*), meadows, and agricultural lands. Several studies have been conducted at this site to assess the effects of such a power line on the various environmental components occurring there (Rogers et al., 1979).

The study reported here was designed to assess effects from the 1100-kV test line on native trees growing within and adjacent to right-of-way areas. Damage to trees growing close to transmission lines has been reported by Zaffanella and Deno (1978) and Miller and Kaufman (1978). In those cases, damage was associated with leaf-tip corona resulting from the trees growing into the intense electric fields near the conductors. The occurrence of corona on plant parts has been well documented (McKee et al., 1978). However, there has been no assessment of the possible long-term effects of corona damage on trees growing near power transmission facilities.

METHODS

We have conducted two tasks at the Lyons test site designed to determine how electric fields influence the growth of trees located near electric-power transmission lines. The first was initiated in 1976 and has continued through this year (1984). This effort involved measuring the current year's incremental growth in the upper canopies of trees located along a transect extending from near the test line (<10 m) to some 140 m away.

A new effort, initiated in 1982, involved planting mature alder and Douglas-fir trees beneath the line and remote from the line. The remote area was located in an open area about 60 m south of the test line. Soil type, soil depth, exposure, landscape configuration and proximity between exposed trees and controls was considered in designating study locations. A tree-moving company was used to help select and place the locally obtained trees within particular study locations. A total of 30 Douglas-fir and 30 alder trees were moved to designated study locations between September 14 and September 24, 1982.

Prior to moving, we paired similar trees according to height and growth form. Each member of the pair was moved to an identical position within either the exposed or control area. The position of particular pairs within the plot was determined by random selection. A hydraulic spade capable of transporting an 8,000-lb root ball was used to move the trees after they had been sprayed with a foliage sealant to retard transpiration prior to moving. The trees were planted on 12-ft (3.7 m) centers to provide a closed-canopy effect.

Growth measurements were made directly by personnel using a manlift vehicle, during September of each year, when most growth was complete and the buds for the following year were set. Branch growth was measured for each tree; orientation of the branch within the trees and with respect to the test line was recorded.

Qualitative estimates of damage were made to further evaluate electric-field effects on growth. The following categories were used:

0 = no visible damage
1 = needle burn
2 = terminal bud dead or stunted by burning; lateral buds healthy
3 = both terminal and lateral buds dead or stunted by burning; lower lateral becoming dominant
4 = All terminal, lateral and secondary lateral buds dead
5 = Other damage (insect, wind, etc.).

Additional details concerning methods employed are provided in our earlier reports (Rogers et al., 1980; Warren et al., 1981; Rogers et al., 1982).

RESULTS AND DISCUSSION

Native Trees in the Transect

We investigated the relationship between the proximity of particular study trees to the test line and tree growth by regressing the growth of apical terminals during specific study years or combinations of years against distance (or transformations of distance) from the line. Results of those analyses are shown in Table 1.

Results of the first regression (Table 1) indicate a very low r^2 value of 0.076 for the regression of 1983 apical terminal growth versus distance from the line. This indicates that only approximately 7.6% of the variability in apical terminal growth for 1983 was associated with distance from the line. The next three regressions utilize, as the independent variable, the sum of the apical terminal lengths for 1980-83 regressed against distance, natural logarithm of distance and reciprocal of distance from the line.

The log and reciprocal transformations were applied to linearize the apparently curvilinear relationship between apical terminal length and distance. Only those trees included in the analysis were measured each year from 1980 to 1983; all were less than 140 m from the line. Trees located 140 m or more from the line had a different orientation with respect to the border of the forest. Only apical terminal growth was used for independent variables, since we suspected that the most profound influence from the test line, if any, would be experienced first at the apical terminals As indicated in Table 1, a moderately strong association between the sum of the 1980-1983 apical terminal lengths and the reciprocal of distance from the transmission line ($r^2 = 0.88$) was observed.

TABLE 1 Summary of Regression Analyses for the Douglas-Fir Trees Growing Along a Transect away from the Test Line. Degrees of freedom for all regressions were 1, 10

Regression	Coefficient of Determination (r^2)	Level of Significance (α)
1983 apical growth versus distance from line (only original study trees included)	0.076	0.197
Sum of 1980-1983 apical growth versus distance from line	0.643	0.001
Sum of 1980-1983 apical growth versus natural log of the distant from line	0.808	< 0.0001
Sum of 1980-1983 apical growth versus reciprocal of distance from line	0.881	< 0.0001
Sum of 1980-1982 apical growth versus 1976 apical growth	-0.092[a]	0.783
1976 apical terminal growth versus distance from line	0.090	0.319
1976 apical terminal growth versus natural log of distance from line	-0.015	0.381
1976 apical terminal growth versus reciprocal of distance from line	-0.061	0.556
1983 apical growth versus distance from line (31 trees include new trees measured in 1983)	0.081	0.066
Sum of 1981-1983 apical terminal growth versus distance from line	0.707	< 0.0001
Sum of 1981-1983 apical terminal growth versus natural log of distance from line	0.788	< 0.0001
Sum or 1981-1983 apical terminal growth versus reciprocal of distance from line	0.815	< 0.0001

[a] Values of r^2 adjusted for degrees of freedom, resulting in a negative value

The relationships defined above suggest the possibility of some positive association between cumulative apical terminal growth and distance from the line. However, inherent growth patterns of the trees used in this analysis could have contributed, wholly or in part, to the growth responses observed in relation to distance from the test line. We explored the association between growth prior to energization of the line and distance from the line as an indication of inherent growth patterns by regressing apical terminal growth for 1976 (the only year in which pre-energization measurements were available) against distance from the line. A scatter plot of these data is shown in Figure 1. The r^2 value for this regression (no. 6 in Table 1) was 0.09. In addition, regressions of 1976 apical terminal length versus natural log and reciprocal of distance yielded adjusted r^2 values of -0.015 and -0.061, respectively. To further explore the possibility of inherently greater growth of trees at increasing distances from the line we regressed the sum of apical terminal growth of the study trees for 1980-1982 versus the 1976 terminal growth for those same trees. A scatter plot of these data is shown in Figure 2. An adjusted r^2 value of -0.092 indicated a very weak association between the 1980-1982 data and the 1976 data (regression no. 5 in Table 1).

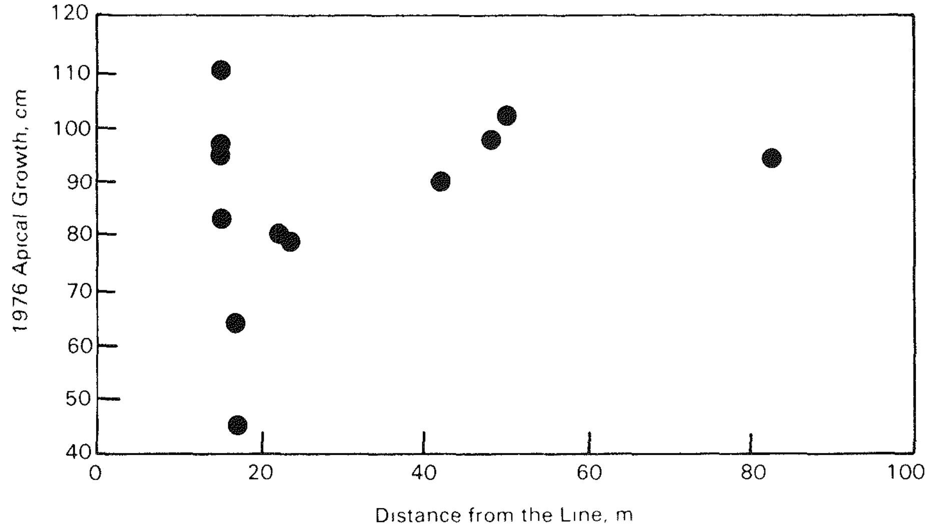

Figure 1. A Scatter Plot of Apical Growth Prior to Energization (1976) Versus Distance from Line.

We measured other trees along the transect in 1983 to further examine the existence of a growth response in relation to distance from the line. This provided a total of 31 trees for the regression of 1983 apical terminal growth versus distance. The r^2 for this regression (no. 9 in Table 1) was 0.081, a slight increase from the regression based on the original 12 trees (no. 1, Table 1).

The sample size used to explore the relationship between growth and proximity to the test line is relatively small. In addition, a high value for r^2 does not necessarily imply cause and effect; regression techniques cannot prove cause and effect. Rather, they may be used to define the strength and shape of association between two variables. Trees located near the line (i.e., 0 to 15 m), where reduced growth would be expected, may have influenced the analysis in that a relationship of reduced growth in relation to distance from the line was shown where none exists.

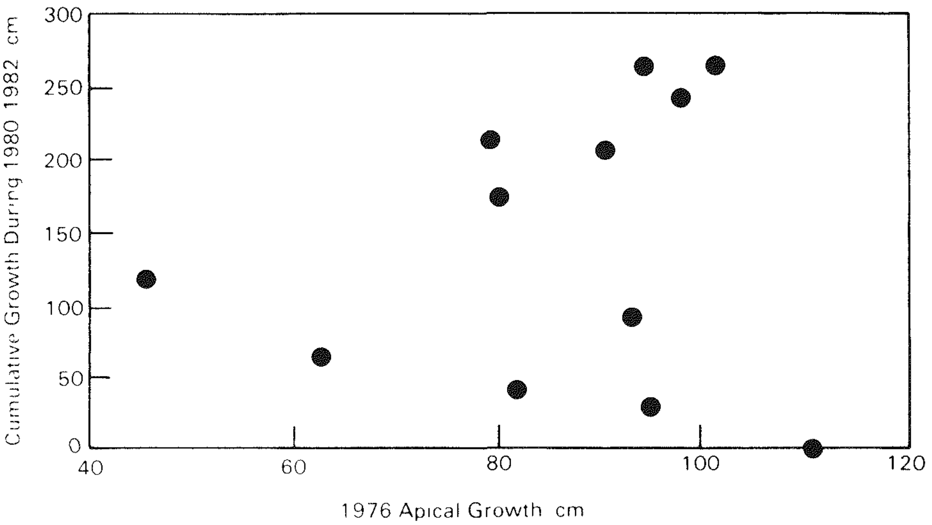

Figure 2. A Scatter Plot of the Cumulative Growth of Apical Terminals during 1980-1982 with the Test Line Energized Versus the 1976 Pre-Energization Period.

We attempted to quantify the effect of the electric field on growth form by examining the types or kinds of damage experienced within the upper tree canopies that were located close to the test line. A test of monotonic trend for the damage classes was conducted using Kendall's tau as the test statistic. This is a nonparametric test similar to a contingency table analysis for correlation. The test is based on the number of trees that fall into categories with various combinations of damage and distance. The analysis was intended to ascertain the strength of any relationship between damage and distance from the line.

Analyzing the frequency of occurrence for damage classes at three distance intervals resulted in detection of a significant ($\alpha \leq 0.0005$) negative correlation between damage category and distance from the line. Trees within 15 m of the line experienced damage sufficient to alter the growth form of the trees (i.e., death of the apical bud or apical whorl). Trees between 15 and 30 m received relatively minor damage which would not be likely to affect growth form (i.e., needle burn). Trees beyond 30 m did not display discernible damage.

The possibility that the test line might in some way influence long-term tree productivity was examined by comparing the increases in trunk diameters during the period from 1976-1983. If there was an influence, trunk growth might have a negative association with increasing proximity to the test line. A scatter plot of stem diameters at breast height (DBH) versus distance from the line is shown in Figure 3. No such relationship was discernible.

The lack of any discernible relationship between distance to the test line and changes in growth of tree diameters suggests that the test line has no apparent effects on the productivity of Douglas-fir trees as measured by trunk diameters. Although the electric field affects the growth form of nearby trees, the line apparently does not adversely affect tree productivity. Electric-field effects may be similar to pruning a hedge row.

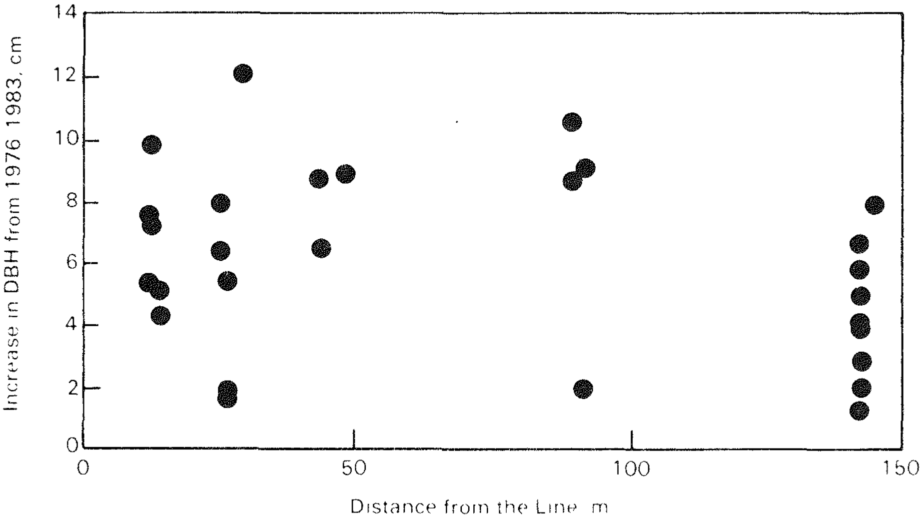

Figure 3. A Scatter Plot Showing the Relationship between Increase in Tree Diameter at Breast Height (DBH) Values and Distance from the Line Following Energization in 1976.

Transplanted Trees

The experimental design of the transplant study is termed control-treatment pairing (Skalski and McKenzie, 1982). This design uses years as replicates; as a result, at least 2 yr of data prior to a potential effect and 2 yr after a potential effect are needed for analysis. Consequently, tests of hypotheses for differences between controls and treatments cannot be made until growth data for the 1984 season are collected and analyzed.

The control-treatment pairing design compares the ratio of tree-growth measurements for paired, control and exposed trees prior to transplanting with those after transplanting. Tests are then performed to determine the significance level of any changes in growth ratios.

Average apical growth in the fir trees showed little change as a result of transplanting (Figure 4). The reduced fir growth in 1983 for the exposed trees can probably be attributed to their close proximity to the test line. The alder trees displayed reduced growth in 1982, and a further reduction in 1983, within both exposed and control locations. Alder, unlike fir, continues to grow until leaf fall. As a consequence, transplanting probably had a greater influence on the growth of these trees. The exposed alder trees generally displayed less growth than the control trees in all years, suggesting some inherent differences between trees since they were not transplanted until 1982.

The exposed fir trees apparently experienced some damage from the electric field during 1982. Table 2 shows the distribution of damage (%) for the transplanted trees located near and remote from the test line. All of the exposed fir trees experienced damage to whorl 1 branches, but only 15% of the control trees showed any damage; damage was less for whorl 2 and 3 branches. Damage to the alder trees was negligible.

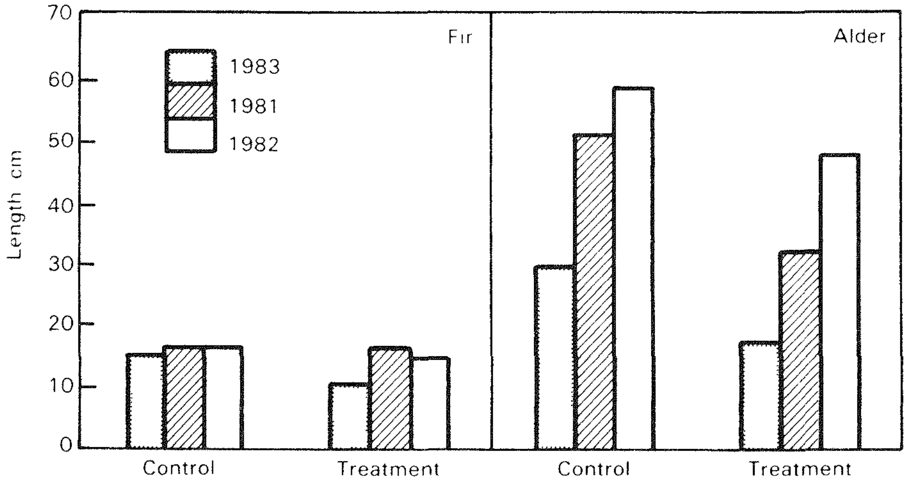

Figure 4. Average Apical Growth in Transplanted Study Trees for the Years 1981-1983.

TABLE 2. Percentage of Transplanted Trees with Visible Damage in the Uppermost Canopy (1983)

Tree	Whorl	Exposed	Control
Douglas Fir	1	100	15
	2	69	0
	3	25	7
Alder	1	0	6
	2	0	0
	3	0	0

Descriptive measurements of the trees and their positions relative to the line were made in conjunction with transplanting (Table 3). The exposed fir trees showed little increase in height compared to the control trees; this, too, was probably in response to the electric field. Some stunting apparently occurred in the upper parts of some exposed trees, although it is too early to tell if this "pruning effect" will prevent trees from growing close to the conductors.

TABLE 3. Basic Data for Transplanted Study Trees and Their Locations

	Study Tree Location	Height (m)[a]		DBH[b] (cm)	Electric Field (kV/m)[c]	Distance to Conductor (m)[d]
		1982	1983			
Exposed Douglas Fir	1-1	9.4	9.5	66.0	4.7	14.0
	2-1	9.6	9.6	78.3	5.0	15.0
	3-1	9.5	9.5	71.1	6.0	16.1
	4-1	12.3	dead top	75.0	6.2	15.1
	5-1	10.9	dead top	66.4	6.5	15.1
	1-2	8.5	8.8	56.9	6.0	15.9
	2-2	10.1	dead tree	62.3	6.5	13.8
	3-2	10.5	10.6	65.8	7.2	13.9
	4-2	9.9	10.0	65.0	7.1	14.6
	5-2	10.2	dead top	52.9	7.2	14.4
	1-3	10.5	dead top	85.2	6.5	14.7
	2-3	10.0	10.1	76.1	7.0	14.9
	3-3	8.9	9.4	61.8	7.0	14.6
	4-3	10.1	10.1	76.1	7.5	12.1
	5-3	10.4	10.4	70.1	7.5	13.8
Exposed Alders	1-1	9.1	9.3	25.2	5.2	16.7
	2-1	8.9	9.1	26.8	4.0	18.7
	3-1	10.0	10.1	30.2/16.5[e]	4.4	17.2
	4-1	9.5	9.6	33.0	4.0	18.2
	5-1	9.7	9.9	26.5	4.4	18.1
	1-2	9.0	9.1	29.0	5.4	16.9
	2-2	10.3	10.3	26.5	6.5	16.1
	3-2	9.7	10.1	33.0	6.0	16.3
	4-2	8.4	8.8	22.9	5.5	18.3
	5-2	10.5	10.6	38.2	5.7	16.6
	1-3	9.4/9.2[e]	9.5/9.4[e]	32.2/28.6[e]	6.2	16.6
	2-3	8.7	8.8	25.2	6.2	17.1
	3-3	10.2/9.4[e]	10.2/9.4[e]	28.0/22.1[e]	6.2	16.4
	4-3	9.3	9.4	34.9	5.8	17.2
	5-3	10.0	10.1	35.2	4.7	17.4

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[a] Height in m at time of transplanting (September 1982)

[b] Diameter at breast height, measured September 15, 1983

[c] Electric field prior to tree planting; measured at 1 m above ground

[d] Distance to conductor (September 1982), measured with a 50-m tape for exposed trees from tree top to center of conductor. Distances approximated with a rangefinder for control trees.

[e] Two trunks

TABLE 3. Continued

	Study Tree Location	Height (m)[a] 1982	Height (m)[a] 1983	DBH[b] (cm)	Electric Field (kV/m)[c]	Distance to Conductor (m)[d]
Control Conifers	1-1	9.5	9.8	54.0	0.5	68.0
	2-1	8.2	8.3	71.5	0.5	68.0
	3-1	9.5	9.9	60.5	0.6	68.0
	4-1	11.0	11.1	73.2	0.6	68.0
	5-1	9.3	9.5	65.8	0.6	68.0
	1-2	8.9	9.2	55.5	0.4	64.0
	2-2	11.2	11.8	62.4	0.4	64.0
	3-2	10.8	10.8	85.3	0.5	64.0
	4-2	10.3	10.5	85.3	0.5	64.0
	5-2	12.7	13.4	61.3	0.5	64.0
	1-3	11.3	11.4	69.5	0.4	60.0
	2-3	11.1	11.3	83.5	0.4	60.0
	3-3	7.9	8.1	48.6	0.4	60.0
	4-3	10.6	10.8	62.6	0.4	60.0
	5-3	9.4	9.6	60.8	0.4	60.0
Control Alders	1-1	8.4	8.8	23.5	0.6	68.0
	2-1	8.8	9.2	26.2	0.6	68.0
	3-1	9.3	9.4	32.8	0.6	68.0
	4-1	9.3	9.6	28.5	0.6	68.0
	5-1	10.1	10.7	25.8	0.6	68.0
	1-2	8.7	8.9	30.6	0.4	64.0
	2-2	9.0	9.2	30.9	0.4	64.0
	3-2	8.7	8.8	29.3	0.5	64.0
	4-2	8.3	9.0	25.4	0.5	64.0
	5-2	10.7	10.9	36.2	0.5	64.0
	1-3	10.4	10.7	30.8	0.4	60.0
	2-3	8.9	9.2	28.2	0.4	60.0
	3-3	9.9/9.6[e]	10.1/9.7[e]	25.6/29.0[e]	0.4	60.0
	4-3	10.1	10.2	34.1	0.4	60.0
	5-3	9.7/9.7[e]	9.9/9.9[e]	33.2	0.4	60.0

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[a] Height in m at time of transplanting (September 1982)

[b] Diameter at breast height, measured September 15, 1983

[c] Electric field prior to tree planting; measured at 1 m above ground

[d] Distance to conductor (September 1982), measured with a 50-m tape for exposed trees from tree top to center of conductor. Distances approximated with a rangefinder for control trees.

[e] Two trunks

SUMMARY

Measurements of the Douglas-fir study trees located along a natural transect that extends from near the test line to over 100 m away were repeated in 1983. Some of the results are summarized below:

- Within any given year, no evidence of any correlation between incremental branch growth in the upper canopy and distance from the test line was found. Over a number of years, however, a negative relationship between growth and proximity to the test line has become evident.

- No correlation between tree growth in the year prior to line energization (1976) and proximity to the test line has been observed.

- Growth during the pre-energization period was not highly correlated with that following line energization; however, data from only one year of pre-energization growth were available for comparison.

- A revised system of classifying visible damage to upper tree parts and inclusion of additional study trees during 1983 resulted in detection of a significant correlation between damage categories and proximity to the line. Trees within 15 m of the line were subjected to changes in growth form due to damage of the uppermost branches and buds; trees within 15 to 30 m were subjected to visible needle burn; trees beyond 30 m were not visibly altered.

- No detectable relationship was observed between productivity of Douglas-fir trees as measured by increase in trunk diameter and proximity to the line.

Although it will not be possible to conduct rigorous statistical testing of growth for the transplanted trees until after the 1984 season, the following observations were noted:

- Transplanting the Douglas-fir trees appeared to have little effect on their growth during the following year. The alder trees, however, were affected following transplanting: both exposed and control alders responded with less growth during 1983.

- The Douglas-fir trees transplanted to locations beneath the test line appeared to experience some damage from the electric field; the alder trees appeared damage-free.

ACKNOWLEDGMENTS

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BIOLOGICAL MODELS OF ELECTROMAGNETIC FIELD INTERACTIONS WITH TISSUES: A REVIEW AND SYNTHESIS OF RECENT FINDINGS

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ABSTRACT

Recent research has confirmed that there is a sequence of events initiated at cell membrane surfaces by humoral stimuli, including hormones, antibodies and neurotransmitters, by which information from these stimuli is communicated to the cell interior Manipulation of this sequence with imposed electromagnetic (EM) fields has disclosed nonlinear and nonequilibrium characteristics A three-stage model of transductive coupling is proposed The first stage involves cooperative modification of calcium binding to membrane surface glycoproteins with "amplification" of energy released Interaction with EM fields at this stage modifies calcium binding and the mosaic of receptor sites The second stage involves transmembrane signaling along proteinaceous molecules that span the lipid bilayer In the third stage, intracellular enzyme systems are activated, releasing metabolic energy, and also carrying signals to intracellular organelles In stage one, modification of calcium binding by extremely low-frequency (ELF) fields and ELF-modulated radiofrequency (RF) fields has been widely reported, with evidence that this occurs primarily at extracellular sites Modified cytolytic capacity of allogeneic T-lymphocytes in ELF-modulated RF fields also indicates action at cell surfaces In stage two, interference with transmembrane coupling proteins has been hitherto inferred from actions of ELF magnetic fields that modulate adenylate cyclase at inner membrane surfaces but do not interfere with binding of stimulating parathyroid hormone molecules to surface receptor sites New evidence from fetal bone exposed to sinusoidal ELF electric fields has shown increased release of a membrane coupling protein, skeletal growth factor, and decreased ${}^{45}Ca^{2+}$ efflux In stage three, conversion of ATP to cAMP by membrane-bound adenylate cyclase follows transmembrane signaling Intracellular messenger enzymes, cAMP-independent protein kinases, sharply decrease activity in human lymphocytes exposed to ELF-modulated RF fields "Windowed" responses to ELF field frequencies or to ELF modulation frequencies were seen in calcium binding, cytolytic response and protein kinase inactivation The major sequence of events in coupling of extracellular stimuli to the cell interior has been clarified by these EM field manipulations Transmembrane coupling of humoral stimuli is sensitive to ELF fields and ELF modulation components On the other hand, we speculate that millimetric microwave/far infrared field may play a physiological role within the cell, where they may provide highly specific communication over short distances

Major research in cellular and molecular biology over the past decade has confirmed the role of cell membranes in communicating to the cell interior events initiated by surface stimuli, including those from hormone, antibody and neurotransmitter molecules. Relatively little attention has been directed to details of the sequence of events in this transductive coupling, nor to the energetics of each step in the coupling sequence. In considerable measure, this hiatus relates to an absence of an interdisciplinary approach combining skills in cellular and molecular biology with biophysical manipulations. Rather, attention has been directed primarily to the steps that occur after initial transductive events, which involve major perturbations in the equilibria of ionic and molecular systems. These events occur at energy levels substantially higher than those characterizing most initial transductive events; e.g., major ionic fluxes in excitable membranes, as in the Hodgkin-Huxley model.

Manipulation of transductive coupling by the imposition of electromagnetic (EM) fields has provided new knowledge on several important aspects of this problem. Previously unsuspected sensitivities in the energetics of initial cellular responses have been revealed to a wide range of natural molecular stimuli at the cell surface. In addition, we can now evaluate details of the sequence of certain key events in initial stimulus detection at the membrane and subsequent intracellular steps in the cell's response (Adey, 1983). In separate studies investigators have detected resonant interactions of certain microwave fields with intracellular macromolecules, specifically DNA (Kohli et al., 1981; Edwards et al., 1983).

As we predicted a decade ago (Adey, 1975a), imposed EM fields have emerged as a powerful tool in studies of cellular mechanisms. Many such interactions occur at "athermal" field levels and relate to specific low-frequency characteristics, either with respect to the field frequency or to low-frequency modulation of radiofrequency (RF) and microwave fields (Adey, 1981a). In view of similar "windowing" sensitivities in the amplitude domain, conclusions from these studies strongly indicate nonlinear and nonequilibrium processes in the cell membrane transductive coupling sequence. Available experimental data now permit a first approach to modeling major functional and structural steps in this sequence.

CELL MEMBRANES AS PRIME SITES OF EM FIELD INTERACTIONS: MANIPULATION OF SEQUENTIAL STEPS IN TRANSMEMBRANE SIGNALING

We have proposed a calcium-dependent, three-step model (Adey, 1984) of signaling from cell membrane surface receptors to intracellular systems:

1) Cell surface glycoproteins protruding outward from lipoprotein particles (intramembranous proteins [IMP]) lying in the main membrane fat layer (plasma membrane) sense the first weak electrochemical events associated with binding of neurohumoral molecules, hormones and antibodies.

2) Transmembrane portions of IMP signal these surface events to the cell interior.

3) Internally, this signal couples to intracellular enzyme systems and, probably, to the cytoskeleton, a system of microtubules and microfilaments with numerous cell membrane connections. The transmembrane signal thus reaches the nucleus and other intracellular organelles.

Experimental findings are consistent with the "fluid mosaic" model of cell membranes (Singer and Nicolson, 1972). External protrusions of IMP "floating" in the lipid bilayer have polyanionic terminals forming a huge negatively charged sheet that attracts hydrogen and calcium ions in a "counter-ion" layer (Figure 1). The mosaic of the IMP is extensively rearranged when they participate in chemical interactions; thus the membrane surface is coded longitudinally in the plane of the membrane surface (Yahara and Edelman, 1972). Tiny channels between cells form preferred conduction pathways for pericellular fields, directing induced currents along cell surfaces rather than through higher-impedance paths across cell membranes. These surfaces, the site of the initial transductive step, involve calcium ions in a highly cooperative interaction (Adey, 1975b). As discussed below, these are also the sites of certain interactions between adjacent enzyme molecules in which they, too, appear to exhibit a calcium-dependent spread of activation over the whole cell membrane from activation of a single molecule (Kikkawa et al., 1983).

Evidence supporting the minimal sequence of three steps in transductive coupling is presented in this review.

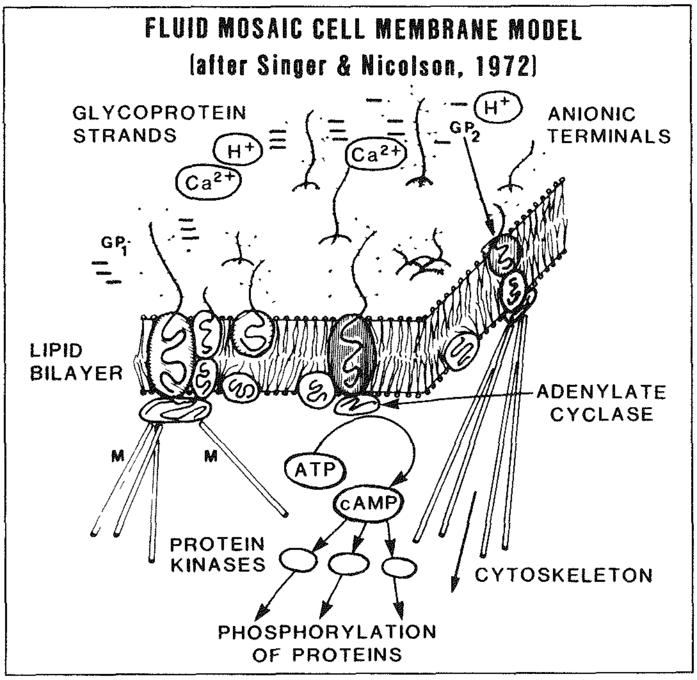

Figure 1. The Fluid Mosaic Model of the Cell Membrane Describes the Structural Substrates of Major Tissue Interactions with Imposed Electromagnetic Fields. Intramembranous protein particles (IMP) in the lipid bilayer have protruding external glycoprotein strands with high negatively charges on their amino sugar terminals. The IMP form receptor sites for antibodies, hormones and neurotransmitters and attract calcium ions. Stimulating molecules and electromagnetic fields alter surface calcium binding in the first step of transmembrane signal coupling, the "amplifying" stage. In the second stage, transmembrane signals may pass along the IMP, which act as coupling proteins to the interior. The third stage involves modulation of intracellular enzyme activity, including adenylate cyclase and the protein kinases of the great intracellular messenger systems (Modified from Singer and Nicolson, 1972).

STAGE 1: AMPLIFICATION OF INITIAL SIGNAL BY COOPERATIVE MODIFICATION OF CALCIUM BINDING

Initial cell surface events appear to involve modulation of calcium binding to the numerous negative charges on the surface glycoprotein sheet, a step presumed to occur along the plane of the membrane surface. For brain tissue, two distinct and contrasting patterns of calcium efflux from cell surface sites were observed in response to differing types of imposed fields.

RF fields at intensities around 1.0 mW/cm^2 and with sinusoidal amplitude modulation from 3 to 35 Hz produced a "tuning curve" of increased calcium efflux, with a maximum increase at 16 Hz and smaller increments at higher and lower frequencies (Bawin, Kacmarek, and Adey, 1975). Unmodulated fields had no effect. These results, in isolated cerebral tissue, have been confirmed in awake cats at tissue field gradients around 0.1 V/cm (Adey, Bawin, and Lawrence, 1982). Far weaker sinusoidal electric fields in the same low-frequency range (calculated levels in isolated cerebral tissue were six orders of magnitude lower) also produced a "tuning curve" of modified calcium efflux, essentially a mirror image of that from the stronger RF fields, but with a decrease rather than an increase (Bawin and Adey, 1976).

These responses thus have windowed characteristics, and they display similar windowing with manipulation of field intensities (Bawin, Sheppard, and Adey, 1978; Blackman et al., 1979). This windowing is the strongest single line of evidence about the essential nonlinearity of these bioeffects.

Recent studies have combined 16-Hz electric fields in the same intensity range as in the studies above (6 to 40 V/m) with a magnetic field component. The combined fields increased calcium efflux from isolated cerebral cortex, and removal of the magnetic component blocked the response (Blackman et al., 1984). In this study, electric fields alone did not reduce calcium efflux as noted in the studies cited above. Reasons for the discrepancy are not known but have focused attention on possible bioeffects of weak magnetic fields, both oscillating and static. Significantly altered effects of these low-frequency electric fields on cerebral calcium efflux (Blackman, 1984) may be explained by possible interactions between the earth's magnetic field and an artificial field in the same intensity range. The most effective electric-field frequencies were also shifted in the imposed magnetic field. Altered firing of nerve cells in the pineal gland and associated alterations in pineal enzyme activity have been reported as a function of orientation in the earth's magnetic field, but the mechanisms are unknown (Semm, 1983).

These are highly cooperative (dissipative) interactions, for which we have proposed the following model (Adey, 1981b). From intracellular sources, fixed charge sites on protruding glycoprotein strands are raised to energy levels substantially above ground state, forming "patches" or domains, with coherent states between neighboring charge sites. Weak triggers at the boundaries of these coherent domains, such as oscillating electromagnetic fields or proton tunneling, may initiate a domino effect, with release of much more energy than in the initial triggering events. Modulation of membrane surface calcium binding is thus an amplifying step in the transductive sequence and is extremely sensitive to imposed electromagnetic fields.

STAGE 2. TRANSMEMBRANE SIGNALING ALONG PROTEINACEOUS MOLECULES THAT SPAN THE DOUBLE FATTY LAYER (PLASMA MEMBRANE)

We have considered the "avalanche" effect of weak fields on calcium binding to the cell membrane surface the first step in cell membrane signal processing.

Are there, in consequence, measurable effects on cell membrane functions, for example, in the direct action of one cell membrane on another; in the cell's internal responses to hormones and antibodies; in the secretion of hormones; or in the synthesis of cement substances or supporting tissue? There are affirmative answers to all these questions in studies of this second step in transmembrane signal coupling. Signals may pass both inward and outward across the cell membrane, and aspects of their energetics in both directions have been evaluated with imposed EM fields.

Imposed fields modify secretion of substances from cell membranes. Release of noradrenalin (Dixey and Rein, 1982) is sharply increased from cultured nerve cells by a 500-Hz magnetic field at an 8-G peak intensity that produces a gradient of only 0.1 mV/cm in the surrounding fluid. This response depends on calcium levels in the fluid and on the calcium/magnesium ratio. Currently accepted models based on equilibrium considerations, as in the Hodgkin-Huxley model, do not account for these sensitivities to fields far weaker than the membrane potential (10^5 V/cm). Cultured pancreatic islets, stimulated by glucose to produce insulin, reduced secretion 35% in the presence of a low-frequency pulsed magnetic field that induced a current density of around 1.0 $\mu A/cm^2$ (Jolley et al., 1983). In bone and cultured bone cells, the first step in formation of new bone is the secretion by the cells of a matrix of fibers or connective tissue. This formation is inhibited by the peptide parathyroid hormone (PTH), which binds to receptor glycoproteins on the cell surface. A 72-Hz pulsed magnetic field at the same intensity as used in the insulin experiments blocked this inhibitory action of PTH (Luben et al., 1982), even though other experiments indicated that the field in no way modified binding of PTH at the receptor site. This result led to the conclusion that the field action is on coupling proteins carrying signals across the cell membrane. This point is further discussed below.

Direct membrane-to-membrane interactions have been assayed in studies of the cytolytic capacity of allogeneic T-lymphocytes targeted against human tumor (lymphoma) cells (Lyle et al., 1983). This cytolytic capacity was reduced more than 20% in vitro with a 450-MHz field at a peak energy of 1.5 mW/cm^2, sinusoidally amplitude-modulated at 60 Hz (Figure 2). This sensitivity was observed with respect to a modulation frequency ranging from 3 to 100 Hz. Unmodulated fields were without effect. Maximum effects occurred at 60 Hz and declined at higher and lower frequencies. Moreover, this altered lymphocyte membrane status persisted after termination of field exposure, with discernible changes persisting for as long as 12 hr. These fields thus modify some forms of direct cell-to-cell communication that depends on the precise pattern of the cell surface antigen-antibody mosaic.

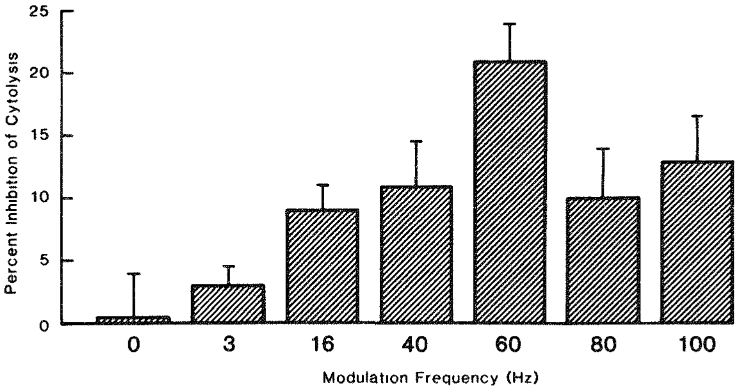

Figure 2. Inhibition of Cytolysis of Allogeneic T-Lymphocytes by Exposure to a 450-MHz, 1.5-mW/cm^2 Field as Sinusoidal Modulation Was Varied Between 0 and 100 Hz (From Lyle et al., 1982).

STAGE 3. COUPLING OF SIGNALS FROM CELL MEMBRANES TO INTRACELLULAR SYSTEMS

The third transductive step couples signals from cell membranes to intracellular systems. There is good evidence that transmembrane signaling occurs along stranded IMP. Their stranded inner ends may interact directly with enzyme molecules lying close to the inner membrane, as in the case of adenylate cyclase. Within the cell, however, a tertiary communication system distributes these signals more widely. The full extent of this system is not known, but it clearly involves the messenger system of the protein kinase enzymes. Its pathways probably also involve the tiny tubules and filaments of the cytoskeleton.

In bone cells and cultured embryonic bones, binding of the PTH to cell surface ceptors activates membrane-bound adenylate cyclase, initiating conversion of adenosine triphosphate (ATP) to cyclic adenosine monophosphate (cAMP), with release of metabolic energy and activation of some protein kinases. This sequence is inhibited by a 70-Hz pulsed magnetic field at 20- to 30-G peak intensity (Luben et al., 1982). Activation of adenylate cyclase bound to the inside of the membrane is inhibited even though PTH is still bound to surface receptors, and the bone cells resume synthesis of connective tissue fibers (collagen). The field appears to "jam" signals that would otherwise pass across the membrane to the cell interior and activate adenylate cyclase.

Protein kinase activity in human lymphocytes is sharply reduced by a 450-MHz field (peak envelope intensity, 1.0 mW/cm^2) sinusoidally modulated at frequencies between 16 and 60 Hz but not at higher or lower frequencies (Figure 3), nor with unmodulated fields. These fields reduce protein kinase activity for only the first 15 to 30 min after onset of exposure (Byus et al., 1984). Thus, in addition to the windows in frequency and amplitude discussed above, there is a window in time for field action (Figure 4). It is not known whether a significant immune insult is associated with such a major but transient response; nor whether its transient nature implies that repeated intermittent exposures may each have separate effects.

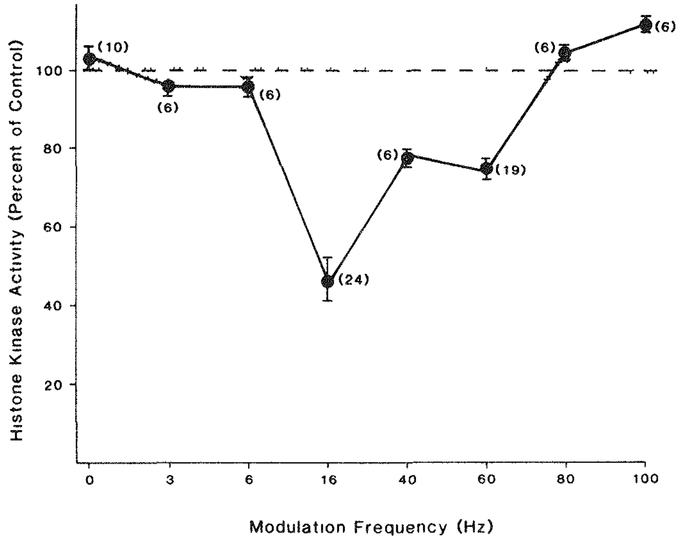

Figure 3. Activity of cAMP-Independent Protein Kinase Activity of Human Lymphocytes is Sharply Reduced by a 450-MHz Field (1.0 mW/cm^2 Peak-Envelope-Power) Amplitude-Modulated at Frequencies Between 16 and 60 Hz, but not at Higher or Lower Frequencies, nor with Unmodulated Fields (From Byus et al., 1984).

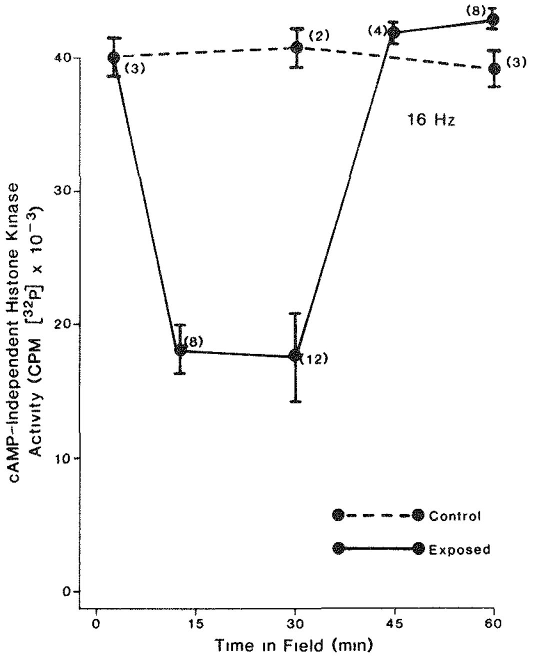

Figure 4. In the Fields Shown in Figure 3, Protein Kinase Activity was Reduced Only for the First 15 to 30 Min after Onset of Exposure, thus Establishing a Window in Time for Field Action (From Byus et al., 1984).

NONLINEAR ELECTRODYNAMICS IN CELL MEMBRANES: BIOPHYSICAL CONSIDERATIONS

Experimental data reviewed here underline the need for substantive new models of field/tissue interactions. They should take adequate account of those data clearly implying nonequilibrium interactions and relate them appropriately to tissue cellular and molecular substrates. Such models should then have a much needed predictive capability for future research.

Salient features of current research for which adequate predictive models are lacking include mechanisms underlying sensitivities at low field frequencies in both ionic and molecular interactions; the windowed character of many of these interactions; the precise nature of membrane surface macromolecular changes arising in joint interactions with calcium ions and imposed fields; and resonant interactions of millimetric and other microwave fields with biological macromolecules, including DNA. Recent developments in these areas are summarized below.

No known mechanisms explain ELF bioeffects on the basis of direct interactions with component dipoles of molecular systems oscillating at these low frequencies. Therefore, a structural and functional basis must reside in the properties of molecular systems. Grodsky (1976) hypothesized that excitable membranes are energetically equivalent to sheets of giant dipoles bathed in controlled external electric fields. His formulation was based on the fluid-mosaic membrane model (see above) and rested on long-range cooperativity in a latticed mosaic, with an Einstein-Bose phase transition as the basis for sensitivity at very low frequencies. This phase transition model had been suggested earlier by Frohlich, but it is not clear that this would occur in the Grodsky formulation (Adey, 1981a).

A novel model for low-frequency sensitivities based on a cyclotron motion of ions bound at the membrane surface in the counter-ion layer has been proposed by Polk (1984). The model implies that the cyclotron current in the earth's magnetic field will be many orders of magnitude larger than the induced current governed by Faraday's law over the same path at ELF frequencies. Ion motion in the surface-bound counter-ion atmosphere would be coherent.

In addition to modulation of calcium binding by highly cooperative processes in the plane of the membrane surface, as discussed above, there is now striking evidence for a simultaneous calcium-dependent macromolecular activation that spreads over the whole cell membrane surface from a single molecular locus. The calcium-dependent enzyme phosphatidyl serine kinase (kinase C) that occurs in cell membranes, particularly in membranes of brain cells, is the focus of intense research in the cancer field, since it is a receptor of powerful cancer-promoting substances, the phorbol esters. Nishizuka (1984) and his colleagues have shown that one molecule of diacylglycerol, produced in the course of excitation by the breakdown of one molecule of inositol phospholipid in the membrane, can activate every molecule of kinase C in the presence of calcium. In the presence of calcium, phorbol esters irreversibly activate this kinase C mechanism. "These findings provide an entirely new concept of receptor function" (Nishizuka, 1984). The results clearly offer a new avenue for studies of EM field bioeffects.

Rapid progress in development of highly stable generators in the millimetric and far-infrared regions of the spectrum has opened new doors to studies of their bioeffects. Based on a collisional model, Illinger (1981) has concluded that resonant molecular interactions are unlikely to occur at frequencies below about 1000 GHz. Prohofsky and his colleagues (Mei et al., 1981; Kohli et al., 1981; Lu et al., 1977) have proposed direct absorption of energy by DNA polymer molecules, based on excitation of one of the fundamental normal modes of molecular vibration. On a long polymer chain, these normal modes correspond to traveling waves of varying wavelengths and their corresponding frequencies. Large-scale motions of nucleosomes and of fibers made of coils of nucleosomes would certainly oscillate below 1.0 GHz and would probably be overdamped. Using highly purified *E. coli* DNA in aqueous solution, Swicord and his coworkers (Edwards et al., 1983) have shown that at 11.0 GHz, energy absorption by DNA fragments is about 400 times higher than in the surrounding aqueous medium, with evidence for chain-length dependence in the absorption.

At still higher frequencies, around 42 GHz, Grundler et al. (1983) have shown that yeast cells exhibited increased or decreased growth with an 8-MHz periodicity as the field frequency was progressively changed. Related experiments with the same field have correlated this effect with nonlinear vibrational energy exchanges between hydrogen atoms in amide groups that form the spines of helical proteins and DNA (Genzel et al., 1983). All these experiments were conducted with athermal levels of field exposure.

These triple parallel spines are formed of amide groups with the repeating atomic sequence -C-O-H-N. Davydov (1979) has modeled energy exchanges in this system in the formation of "packets" of vibrating elements. The vibrational energy of the hydrogen atom is exchanged nonlinearly with that of the amide group to produce an excited state, and vice versa. When this nonlinear exchange reaches a threshold energy level and involves a sufficient number of elements, the packet behaves as a quasi-particle and moves as an entity along the linear macromolecule as a solitary wave (soliton). Solitons may be extremely long-lived and are relatively uninfluenced by interaction with particles through which they pass. They may be detected by Raman-scattering that occurs when they encounter anisotropies in the molecular chain along which they propagate.

Raman-scattering with millimetric microwave exposure was first reported in bacterial cultures by Webb (1975). Scott (1981) modeled vibrational modes in the Davydov soliton and used his model to calculate Raman-scattering numbers for amide spine sequences. These calculated spectral lines produced an excellent fit with Webb's experimental data for nine consecutive Raman lines in the spectrum between 30 and 200 wave numbers. Taboada and Mrotek (1984) have examined the possibility of solitons in alpha-helical proteins of human nasal and mouse adrenal cancer cells. Anti-Stokes Raman spectra of 514-nm laser light support the existence of harmonics of two fundamental solitons predicted by Scott.

Clearly, these are but the first exciting steps into an entirely new area of biophysics and physical chemistry based on new concepts in the physics of matter. Lawrence and Adey (1982) have modeled the nonlinearities of transmembrane signaling in soliton conduction along helical proteins and intramembranous particles. The precise nature of this second step in the sequence of transmembrane coupling awaits future research.

SUMMARY

The role of cell membranes in transductive coupling of signals from cell surface receptors for hormones, antibodies and neurohumoral agents has been reviewed. Electromagnetic fields are powerful and highly specific tools in manipulation of the sequence of events in membrane transductive coupling. By their use, nonlinear and nonequilibrium aspects of these interactions have been evaluated. A three-step model of transductive coupling is presented. In the first step, there is a highly cooperative modification of calcium binding in the plane of the membrane surface following a focal event at a receptor site. This is an amplifying stage, releasing substantially more energy than in the initial events. The second stage of transmembrane coupling occurs along helical proteins that span the membrane as IMP. This conduction may be mediated by soliton processes. In the third stage, transmembrane signals are coupled to the cytoskeleton and to intracellular enzyme systems, including membrane-bound adenylate cyclase and the system of intracellular messenger enzymes, the protein kinases.

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BIOPHYSICAL ASPECTS OF ELECTRIC FIELD BIOEFFECTS AT THE CELLULAR LEVEL

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ABSTRACT

The objective of this research is to elucidate a mechanism of action, at the cellular level, whereby long-term exposures to 60-Hz electric fields affect the growth and development of a multicellular eukaryotic system Roots of 12 plant species were chronically exposed to a 60-Hz electric field of 360 V/m and analyzed for growth rate Other roots were exposed to vertical electric fields, to horizontal electric fields ranging from 150 to 490 V/m, and to such fields while in media of different electrical conductivities All results to date are consistent with the postulates that 1) the cell membrane is the most probable site of action, and 2) the effective exposure parameter is the magnitude of the applied field and not the associated current density The data presented in this report distinguish between two postulated field-related mechanisms for inducing cellular effects the induced transmembrane potential and the tangential field Results support the postulate that induction of the growth-rate effect is dependent on field-induced transmembrane potentials and independent of the magnitude of the tangential field

Several lines of evidence suggest that the mechanism by which electric fields induce biological perturbations at the cellular level involves changes in the transmembrane potential. Classical studies have recognized the role of transmembrane potentials in neural stimulation A recent series of papers by Tsong and colleagues (Teissie and Tsong, 1980, 1981; Tsong et al., 1976) reported the modulation of sodium/potassium transport in human erythrocytes by fields sufficient to induce a transmembrane potential of about 6 mV At much greater induced transmembrane potentials (e.g., 1 V), membrane rupture occurs; this technique has been used in cell-fusion studies by Zimmerman and others (e.g., Scheurich and Zimmerman, 1980, 1981; Zimmerman and Pilwat, 1981). A series of papers by Miller and associates (Inoue et al., 1984, 1985; Miller et al., 1979, 1983; Robertson, Miller, and Carstensen, 1981, Robertson et al., 1981) reported on roots of seedlings that were exposed to 60-Hz electric fields in culture medium and scored for growth-rate reductions The postulate which guided the research is that to be effective at the cellular level an applied field must induce a significant transmembrane potential When a cell is exposed to an extremely low-frequency (ELF) electric field there will be, simultaneously, (a) an induced ELF transmembrane potential, which will be maximal at the poles of the cell (relative to the direction of the field); and (b) an external tangential ELF electric field, which will be maximal at the equator of the cell. Fröhlich (1977) has suggested, for example, that relatively weak tangential fields may excite cooperative interactions among structures along the cell surface.

The purpose of this paper is to report briefly on the general results observed from this series of experiments and their relevance to understanding a mechanism of action for ELF fields at the cellular level.

MATERIALS AND METHODS

Electric Field Exposure System

The exposure system has been described in detail elsewhere (Miller et al., 1979, 1983). Briefly, it comprises a lucite tank and a reservoir containing 68 L of root growth medium (inorganic salts). The medium is continuously circulated between the tank and the reservoir to effect temperature control and aeration. There are two electrode "sandwiches," made of stainless steel separated by plastic dowels; one set of electrodes is energized (EXPOSED) and the other is electrically shorted (CONTROL). Seedling roots are suspended between the pairs of electrodes. The tank and reservoir are contained in a biological oxygen demand (BOD) incubator, and the temperature of the medium is maintained at 19°C. For some exposures the electric field was horizontal to the earth's surface; for others, the electrodes were placed at the top and bottom to achieve a vertical field. Thus, in the horizontal exposures the applied field was perpendicular to, and in the vertical field, parallel to, the root axis.

Biological Materials and Procedures

Seeds or bulbs were germinated in moistened vermiculite or on moistened paper at 19°C in a BOD incubator until their roots were about 4 to 6 cm long. They were then transferred to one of two lucite tanks: 20 roots in the exposed group and 20 roots in the control group. Each experimental determination involved three replicates.

Root-growth rates were determined by measuring the length of each root at the start of the experiment, then daily thereafter. For all experiments, the rate of growth was measured over a 24- to 48-hr exposure period because previous experiments had indicated that growth rate was generally constant over time, beginning with the second day (Cox et al., 1980). Relative daily growth rates were calculated as the ratio of the average for exposed roots to the average for controls.

For cell-size determination, root tips from specimens grown under conditions identical to those of the root-growth-rate experiments were collected, fixed in Craf III, embedded in paraffin, sectioned (10 μm), mounted on microscope slides and stained with safranin and fast green. Cell diameters of each of 50 procambial, cortical and meristem cells were determined, using a calibrated ocular micrometer in a Zeiss photomicroscope. The 60-Hz induced transmembrane potential was then calculated as the approximate product of cell diameter and applied 60-Hz electric field strength (Miller et al., 1979, 1983).

RESULTS AND DISCUSSION

Growth Rate

Figure 1 shows the normalized average growth rate of pea (*Pisum sativum L.*) roots during the second day of exposure to electric fields ranging from 70 to 490 V/m. The electric-field threshold for growth perturbation was about 300 V/m; at 490 V/m growth had virtually stopped. The conductivity of the exposure medium for this experiment was 0.07 S/m.

The measured diameters of root cells from the area of the root meristem varied between 11 and 25 μm. Thus, the threshold field to produce growth effects corresponded to 60-Hz induced transmembrane potentials of 3 to 8 mV, and the debilitating effects observed at about 500 V/m occurred at induced transmembrane potentials on the order of 6 to 12 mV. These values are within an order of magnitude of the typical resting potentials of a wide range of cell types.

We determined that the growth-rate repression in pea roots was related to the applied field and not to the current density in a series of experiments in which we varied the ratio of field to current density (Figure 2). Growth-rate data are shown for three different media with respective conductivities of 0.07, 0.035 and 0.14 S/m. A field strength of 430 V/m (and an associated current density of 30 A/m^2; medium conductivity, 0.07 S/m) noticeably affected root growth rate. When the conductivity of the exposure medium was changed so that a field strength of 430 V/m yielded a current density of 15 A/m^2, the growth rate reduction persisted. (Under this condition, the field intensity was "high," and the current density "low.") When the medium's conductivity was changed so that a field of 215 V/m produced a current density of 27 A/m (a relatively "low" field but a "high" current density), there was no effect on root growth rate.

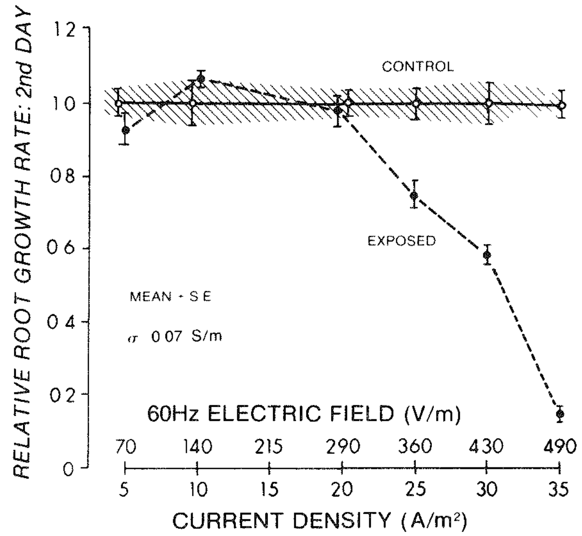

Figure 1. Second-Day Relative Root Growth Rates of *Pisum sativum L.* Roots Exposed or Sham-Exposed to 60-Hz Electric Fields from 70 to 490 V/m in an Aqueous Medium

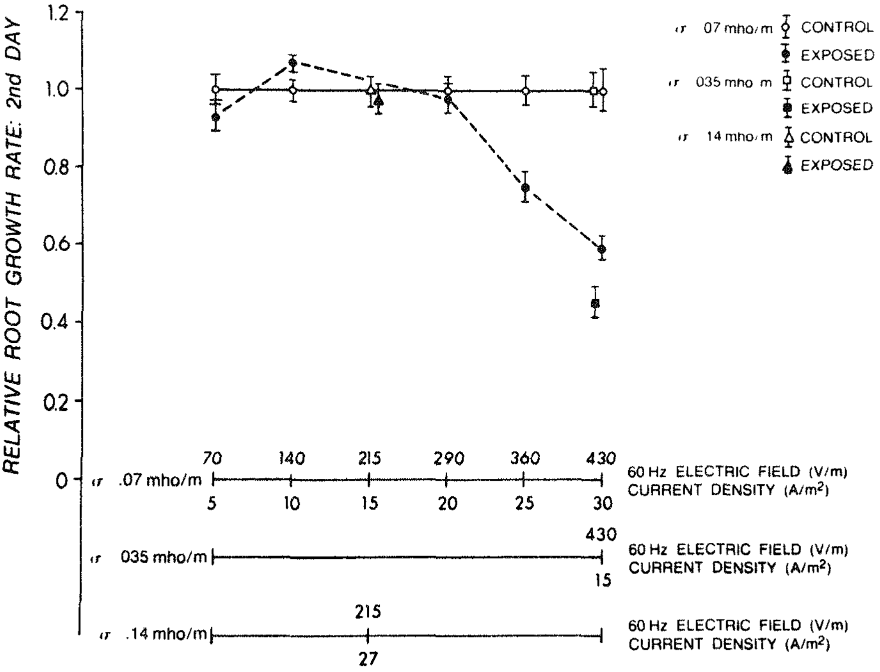

Figure 2. Results of Three Root-Growth-Rate Experiments. Mean of second-day relative growth rate from roots exposed to 60-Hz electric fields ranging from 70 to 430 V/m; current densities ranged from 5 to 30 A/m^2.

When pea roots were exposed to vertical 60-Hz electric fields the growth rate was affected more than when the exposure was to a comparable horizontal electric field. For example, for a field of 290 V/m there was no effect with a horizontal field, but with a vertical field the growth rate of exposed roots was about 30% less than that of controls. At 430 V/m, the horizontal field resulted in a 40% repression in root growth rate, and the vertical field yielded an 80% repression. Perhaps the explanation is that cells in plant roots are much longer than they are broad; thus, if electric-field exposure is parallel to the axis of the root, a correspondingly greater induced membrane potential was induced.

Transmembrane Potential or Tangential Surface Field

An experimental protocol was devised to determine whether the induced transmembrane field (potential) or the external tangential surface electric field is responsible for the observed biological effect. Briefly, the level of the applied electric field was kept constant (360 V/m), but the sizes of the exposed cells were varied (Figure 3). With these conditions, the tangential field, being independent of cell size, was constant for all cells, but the magnitude of the induced transmembrane field, being proportional to cell diameter, varied. The responses to this field of 12 species of plant roots with widely differing cellular diameters were determined. Roots with large cells were more affected than roots with small cells. The degree of growth repression ranged from nearly 100%, compared to that of controls, to nearly 0 The average value for procambial, cortical, and meristematic cell diameters ranged from 13.5 to 31.8 μm (Figure 3). Root growth-rate repressions increased with increasing 60-Hz induced transmembrane potentials. The transmembrane potential threshold for growth repression was about 5 to 6 mV, and the potential for near-complete cessation of growth was about 10 to 11 mV If the dominant mechanism depended on tangential fields, the effects would have been independent of cell size. It is reasonable to postulate that individual species have different sensitivities to transmembrane potentials, but it is extremely unlikely that the progression shown in Figure 3 for 12 species could have resulted from a systematic increase in sensitivity of membranes with increase in cell size ($p < 0.01$).

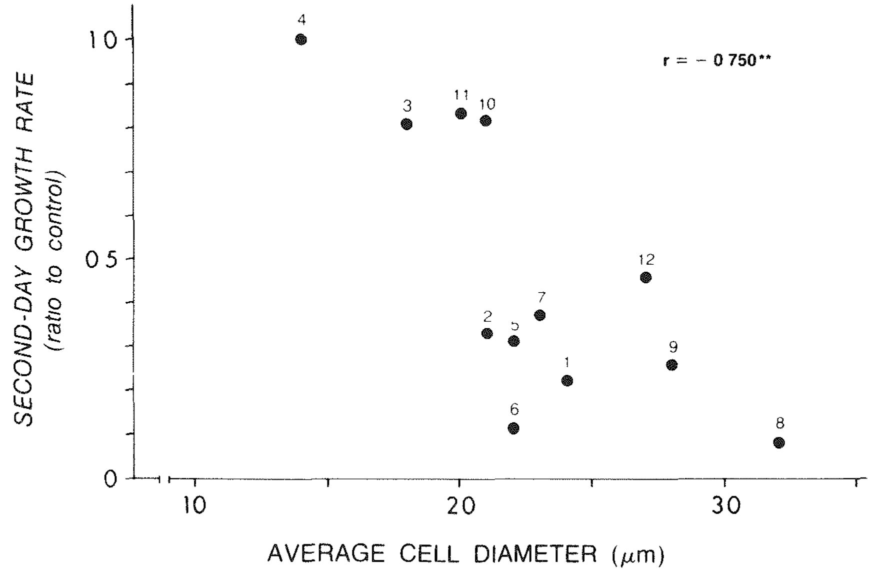

Figure 3 Relationship Between Second-Day Relative Growth Rates and Average Root-Cell Diameters for 12 Species Continuously Exposed to a 60-Hz, 360-V/m Electric Field in Aqueous Growth Medium 1 = pumpkin, 2 = faba bean, 3 = pea, 4 = cucumber, 5 = morning glory, 6 = gladiolus, 7 = hyacinth, 8 = amaryllis, 9 = onion, 10 = corn, 11 = barley and 12 = wheat

CONCLUSION

For effects at the cellular level, the applied field, rather than its associated current density, was the relevant causative factor. Effects may have been mediated through a change in transmembrane potential; however, the electric fields in the root growth medium that affected growth rate were much higher than those normally encountered in air

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VIABILITIES AND MUTATION FREQUENCIES OF CHO-K1 CELLS FOLLOWING EXPOSURE TO 60-Hz ELECTRIC FIELDS

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ABSTRACT

Chinese hamster ovary (CHO) cells were exposed to 60-Hz ac electromagnetic fields at strengths from 0 15 V/m to 10 9 V/m, using an exposure system which magnetically induces an electric field in the culture medium without the use of electrodes Electric-field exposure with this system had no detectable cytotoxic or mutagenic effects Mutation frequencies were not significantly increased at any of the electric-field strengths or exposure durations However, cell viability, as measured by plating efficiency (ability of a cell to produce a colony), was significantly reduced The threshold of detectability for this effect was a 24-hr exposure at 0 7 V/m As a result of these findings, and because of limitations of the exposure system, we designed and tested another exposure system which allowed exposure at higher field strengths This system employs carbon electrodes directly coupled to the culture medium To assure that electrode effects did not perturb the experiment, agar bridges were interposed between the electrodes and the cell suspension The plating efficiency of cells exposed to 3 5 V/m in the agar-bridge graphite-electrode exposure system was not significantly different from those of control cultures Therefore, the decreased cloning efficiency observed with the magnetically induced electric field may be either artifactual or a function of the system itself (i e the greater magnetic component relative to that of the agar-bridge exposure chamber)

INTRODUCTION

Considerable concern exists about the possible health hazards of exposure of the general population to electromagnetic fields (EMF) associated with high-voltage transmission and distribution lines A number of articles have appeared both in the popular press and in scientific journals which link such exposures with increased incidences of cancer (Wertheimer and Leeper, 1979, Wertheimer et al , 1982, Milham 1982, Wright, Peter, and Mack, 1982) and birth defects (Sikov, Phillips, and Buschbom, 1982, Nordstrom et al , 1981) When exposure to a given insult, such as electric fields, appears to be associated with either an increase in cancer incidence or birth defects, it is important to determine whether the suspected agent is capable of directly damaging cellular DNA The least expensive and fastest methods for detecting such potential mutagens/carcinogens involve the use of in vitro studies The purpose of this study was to detect and quantify cytotoxicity, DNA damage and/or specific gene mutations resulting from exposure of cultured mammalian cells to 60-Hz ac electric fields The hypoxanthine-guanine phosphoribosyl transferase (HGPRT) locus, an enzyme from the purine salvage pathway, was selected to measure mutation frequencies because it is not essential for growth of cultured cells under normal conditions As a result, this assay is responsive to various genotoxic mechanisms, including deletions, frameshift mutations and base substitutions, as well as chromosomal breaks and rearrangements All these lesions can cause loss or inactivation of the enzyme Most other genetic markers commonly used to measure mutation frequencies of Chinese hamster ovary (CHO) cells detect only mutations resulting from base substitutions (Gupta and Singh, 1982). The HGPRT locus was also chosen because it has been shown to be sensitive to mutation by physical agents (Hsie et al., 1975; Hsie et al., 1977; Hsie et al., 1978) as well as metals (Hsie et al., 1979) and a wide variety of chemicals (Frazier and Mahlum, 1984; O'Neill et al., 1977b).

METHODS

Cells and Medium

The cell line, CHO-K_1-BH_4 (Hsie et al., 1975), was held as a large stock in ampules frozen in liquid nitrogen. Prior to each treatment, an ampule of cells was thawed and maintained in exponential growth for 2 to 4 days. Cells were grown as a monolayer in Ham's F12 medium (K.C. Biological Co., Lenexa, KS), supplemented with 10% heat-inactivated (56°C, 30 min), fetal calf serum (F12FCS10, K.C. Biological Co.) in plastic culture dishes (Corning) within an incubator humidified to near 100% at 37°C in 5% CO_2/95% air. Cells were removed with 0.05% trypsin for subculture, and cell numbers determined with a Coulter counter (Model S, Coulter Electronics, Hialeah, FL). Checks for mycoplasma (Chen, 1977) on the CHO cell line were negative.

Cytotoxicity and Mutation Assay

Procedures used for cytotoxicity and mutagenicity assays are outlined schematically in Figure 1. A well-characterized assay system for measuring mutation frequency in CHO cells has been described elsewhere (Carver, Adair, and Wandres, 1980; Hsie et al., 1977, 1978, 1980; O'Neill et al., 1977a; O'Neill and Hsie, 1979). The modifications of that assay and procedures necessary to conduct these experiments are shown in Figure 1 and outlined below.

CHO cells were seeded at approximately 3×10^5/dish, each dish representing an initial culture, incubated for 24 hr to reach approximately 1×10^6 cells/dish, then treated in one of the following ways: 1) irradiated with 200 rad ^{60}Co γ-rays; 2) incubated for 4 hr at 37°C in 100 μg/ml ethylmethyl sulfonate (EMS; Sigma, St. Louis, MO) in medium F12 without fetal calf serum; 3) given no mutagen treatment and incubated in medium F12FCM5 for 24 hr at 37°C on top of an agar-culture medium (0.63% ionagar-F12FCM5; incubator control); 4) placed in an electric-field exposure chamber within the exposure system and incubated for the specified time at 37°C in the absence of an electric field (sham control); or 5) placed in an electric-field exposure chamber within the exposure system and incubated at 37°C for the time and field strength specified (electric-field-exposed).

After radiation treatment the cultures were washed and supplied with fresh medium; after EMS treatment the cells were washed twice before replacing the medium. Both cultures were then incubated at 37°C until the remainder of the treatment groups were harvested. At that time they were monodispersed by trypsinization, counted, and viability determined using trypan blue. The incubator controls, sham-exposed and electric-field-exposed cultures were harvested, counted, and viability was determined; they were then washed twice with medium. Following treatment the cells were harvested, counted, split into two samples, and a portion used to measure cytotoxicity as determined by each cell's ability to form a countable colony after 5 days. In this assay a known number of cells (~100) were seeded into each of 48 petri dishes containing

F12FCM5 and grown for 7 days at 37°C. At the end of the incubation period the plates were fixed with 3.7% formalin and stained with a dilute crystal violet solution. More than 50 cells growing within a confined area were considered a colony. Colony counting was conducted using a Biotran III colony counter (New Brunswick Scientific Co., New Brunswick, NJ). The effect of the treatment on cloning efficiency was expressed as percent survival relative to that of untreated controls (relative plating efficiency).

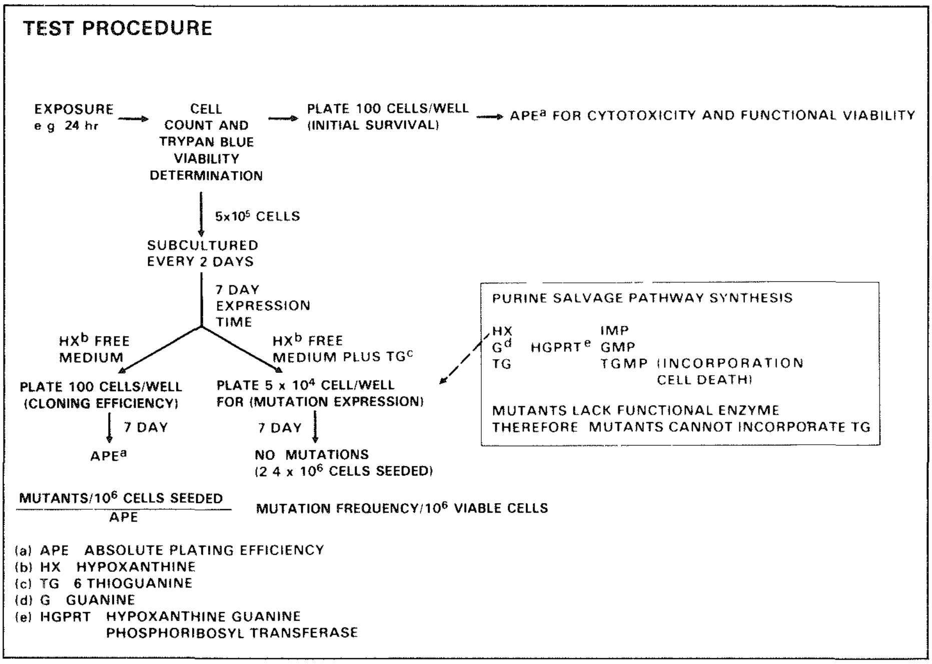

Figure 1. Schematic Diagram of Cytotoxicity and Mutagenicity Assay Procedures.

For determination of mutation induction, the remaining portion of the treated culture was allowed to express the mutant phenotype in F12FCM5 for 7 days. Routine subculture was performed at 2-day intervals during the expression period. After 7 days, cells from each treatment flask were trypsinized, washed and counted. The cloning efficiency and mutation frequencies were then determined.

In order to determine the cloning efficiency of these cells, six 6-cm petri dishes were seeded with ~100 cells each in 4 ml of hypoxanthine-free F12FCM5. The remaining cells from each treatment were reseeded into 48 6-cm dishes at 5 x 10^4 cells/dish. This was a seeding density which did not suppress thioguanine (TG)-resistant clonal growth (O'Neill and Bowman, 1982) in hypoxanthine-free F12FCM5 containing 6 μg/ml of 6-TG (Sigma). The dishes were all incubated at 37°C, and fixed and stained after 7 days. Mutant colonies were counted by hand. Mutation frequency was calculated by dividing the total number of mutant colonies by the number of cells plated to determine cloning efficiency.

Exposure System

The exposure chamber used in these studies has been described and characterized elsewhere in detail (Kaune et al., 1984). Briefly, the cells were exposed in a siliconized glass tube, which was designed to serve as a portion of the toroid-like chamber, which encircled a ferromagnetic core. The electric field was inductively generated by a 60-Hz magnetic field contained within the core.

The exposure system was divided into two sections: the exposure chamber, which actually contained the cells, and the return leg, which was filled with conducting medium and therefore completed the electrical circuit around the core.

The exposure chamber has an agar-medium bed and agar-medium plugs at each end (Figure 2). The technique of assembling this chamber consists of the following steps (steps 2-5, 7 and 8 were performed in a laminar-flow hood):

1. Siliconize and sterilize the glass exposure and control chambers; sterilize the various rubber parts.
2. Premix an agar solution and hold at a temperature (approximately 42°C) above the gelation temperature.
3. Seal, with rubber stoppers, one end of each an exposure and a control chamber. Stand the two chambers on their sealed ends and pour in agar solution to form the agar plugs in these ends. Place the two chambers in a refrigerator (4°C) for about 15 min.
4. Pour the agar plugs in the opposite ends, using the same procedure as in the previous step.
5. Mount the two exposure chambers in the normal position (Figure 2) and pour 7.5 ml of agar into each of them to form agar beds. After these beds have gelled, add 7.5-ml aliquots of medium and cells. Fill the remaining 7.5-ml volume with a 95% air/5% CO_2 mixture and seal the access ports with rubber serum-bottle stoppers.
6. Move the assembly to the exposure system and complete the circuit for the exposure chamber with Tygon tubing filled with 4M NaCL. Place the whole assembly in the water bath (temperature = 37°C).
7. At the conclusion of the experimental run, remove the exposure assembly from the water bath, remove the Tygon-tubing portion of the exposure chamber and seal the ends with rubber stoppers. Transfer the exposure-chamber assembly to a hood.
8. Wash the outside of the chamber with 70% ethyl alcohol. Agitate the chamber (to resuspend the cells), remove the serum-bottle stoppers, and pipette off as much of the medium-cell mixture as possible. Wash the chamber and agar bed twice by adding fresh medium, agitating the chamber, and pipetting off the resulting mixture. Count the cells, and determine viabilities, using trypan blue.

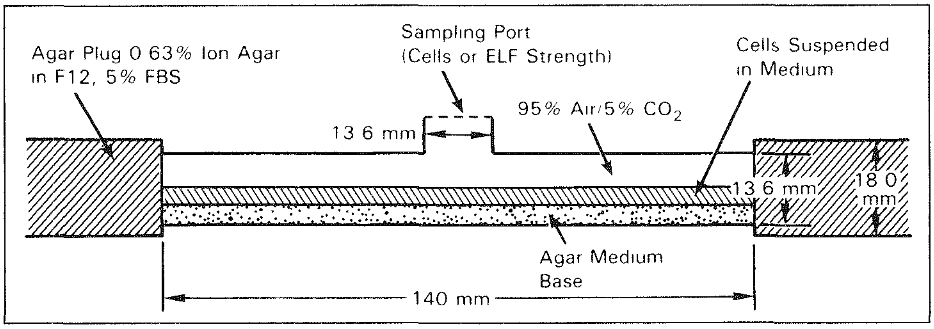

Figure 2. Cell Exposure Chamber, Consisting of a Glass Section (140 mm long x 13 mm diameter) that Contains: a) 7.5 ml of an Agar (0.63%) Medium (F12 FBS) Mixture; b) 7.5 ml of Medium (F12 FBS) with Cells; and c) a 7.5-ml Air Space that Contains a 95% air/5% CO_2 Mixture. The sampling port is closed with a rubber stopper that can be used to remove cells or to insert a probe for measuring electric field strength. Attached to the ends of the cell exposure chamber is the return leg (not shown), which consists of a piece of Tygon tubing filled with conducting medium. This return leg loops around the ferromagnetic core, thus completing the electric circuit.

Cell cultures were sham-exposed in a similar "exposure chamber," with the difference that the conductive path of the sham-exposure chamber was blocked or broken at some point. Additional control cultures were grown in plastic petri dishes in a standard cell-culture incubator on an agar-medium bed.

Following assembly of the exposure and sham-exposure chambers around the ferromagnetic core, they were placed in the water bath (built around the core), which was enclosed by u-metal. Temperature of the water bath was maintained at 37°C ± 0.1°C throughout the exposure by using a remote Haakke water circulator. In addition to the electric-field exposure, the cells received exposure to a magnetic field of up to 0.5 gauss. Sham exposed cultures also received the same magnetic field exposure (Kaune et al., 1984).

The agar-bridge graphite electrode exposure system was prepared by using the chamber assembly shown in Figure 2. However, the electric field was applied directly through carbon electrodes inserted into the agar plugs on each side of the exposure chamber.

Statistics

All experiments were run in a blind fashion. Technicians counting cells and colonies were unaware of field strengths and exposure duration. Cloning efficiencies and mutation frequencies were compared, using a two-tailed unpaired Student's *t*-test. Individual data sets were analyzed, using an analysis of covariance, and "dose-response" relationships were investigated, using standard curve-fitting techniques.

Dosimetric Measurements

The field probe used for making measurements in the conductive medium has been described elsewhere (Kaune et al., 1984). The electric field strengths were determined by inserting the probe into the culture medium and dividing the measured differential voltage by the distance between the probe tips. The electromotive force induced in the exposure toroid was determined by measuring the voltage generated in a wire loop which surrounded the transformer core; this was designated the secondary voltage (V_{sec}; Kaune et al., 1984).

RESULTS AND DISCUSSION

Electric field strengths (60-Hz ac) up to 10.9 V/m were obtained by filling the return leg of the magnetic induction exposure system with 4M NaCl. Actual electric field strengths were measured in the manner described by Kaune et al. (1984); results are presented in Figure 3. The data show that a linear relationship exists between V_{sec} and the actual measured electric field strength in the exposure chamber, with a maximum error of 8 to 10%. In the remainder of the experiment, the field strengths were determined by measuring the V_{sec} and that value was extrapolated to provide the "nominal" field strength.

Cell division was an important criterion for successful exposure in all our experiments since we were attempting to determine the effects of 60-Hz ac electric fields on growing cells. Differences in final cell concentration were used as an indicator of growth rate. Growth ratios (total number of cells at the end of the experiment divided by the initial number of cells seeded) from five series of cells exposed to 3.5-V/m electric fields were not significantly different ($P = 0.4$) from those of sham-exposed cells (Figure 4). Positive controls were included in each experiment to assure that the assay systems were sensitive to known mutagens/toxicants. The agents used were 200 rad of γ-irradiation (from ^{60}Co), a physical agent, and EMS, a radiomimetic drug. The results from five experiments that examined the effect of 3.5-V/m, 60-Hz ac electric fields showed no significant difference ($P = 0.2$) in viability between exposed and sham-exposed cells, as measured using the trypan blue dye exclusion test (Figure 5). A significant ($P > 0.05$) reduction in cloning efficiency was observed for cells exposed to 3.5-V/m, 60-Hz ac electric fields for 24 to 28 hr (Figure 6). Further, the cytotoxic effect of this electric field exposure was greater than that of exposure to either 100 μg/ml of EMS or 200 rad of ^{60}Co.

The mutation frequency of CHO cells exposed to 3.5 V/m was measured using the HGPRT locus. No significant differences ($P = 0.2$) were observed between the exposed (3.5 V/m) and sham-exposed cells (Figure 7). Neither group produced a significant increase ($P = 0.8$ and $P = 0.2$) in mutation frequency compared with that of the incubator controls. The response of the CHO cells to the positive controls (^{60}Co and EMS) indicates that the assay system was capable of detecting direct-acting mutagens.

In an effort to enhance the statistical probability of measuring a relatively small increase in mutation frequency due to electric field exposure, another series of experiments were initiated in which cells were exposed to electric field strengths of 3.5 V/m or 10.9 V/m. Again, no significant differences in mutation frequencies were observed (Table 1).

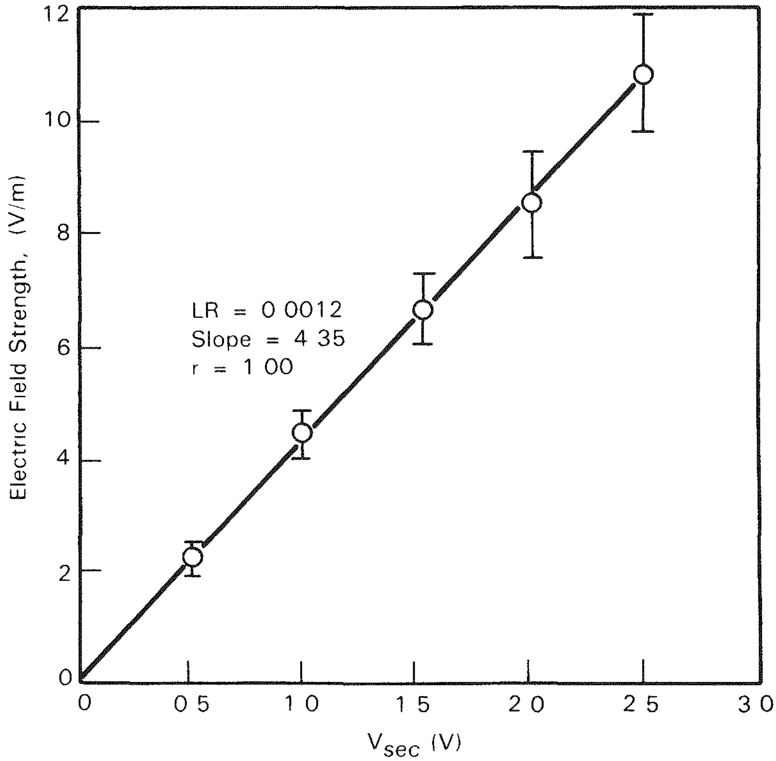

Figure 3. Cell Culture Dosimetry as Determined by Electric-Field-Probe Measurements. The electric field strength for each experiment was determined by measuring the parallel current (V_{sec}) produced in a wire below the cell exposure chamber. This indirect measurement was necessary in order to avoid contaminating the cultured cells with the probe. To validate our dosimetry measurements, a series of experiments was conducted in which the currents produced in cell exposure chambers were measured directly in V/m, using a probe inserted in the cell culture chamber. This electric field strength was designate V_{probe}. The probe measurement (electric fields in V/m) and parallel-wire (V_{sec}) electric field measurements had a linear relationship and direct correlation ($r = 1.0$).

In our experiments, 24-hr exposures were used to allow the cells to undergo at least one cell division during exposure. The initial field strength (3.5 V/m) was selected because it was near the upper limit of the exposure system. After observing that the decreased plating efficiency following electric field exposure was reproducible, we attempted to find a threshold for the effect. Duration of exposure and electric field strength were used as independent variables. First, we varied field strength: cells were exposed to 0, 0.15, 0.7, 1.4, 3.5 or 10.9 V/m in separate experiments. Results were compared to those with sham-exposed cultures, which received no electric field exposure but were exposed to equivalent magnetic fields, as well as to incubator controls (Figure 8). The effect was clearly reproducible at 1.4 V/m and above but not detectable at electric fields of ≤ 0.15 V/m. Four of the five experiments at 0.7 V/m showed significant differences in cloning efficiency. Increasing electric field strengths above 0.7 V/m did not significantly increase the magnitude of the observed effect.

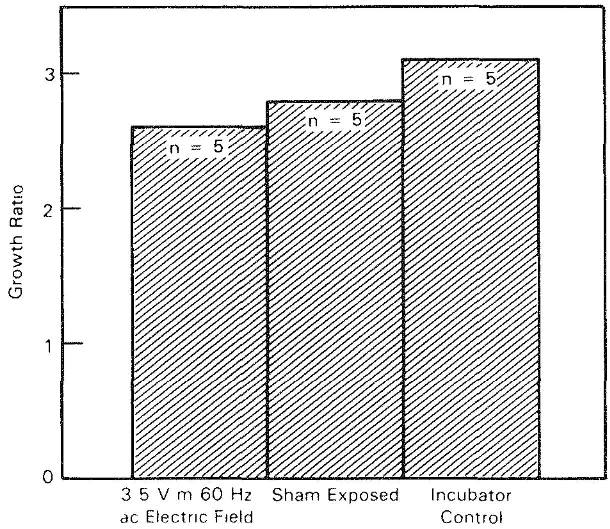

Figure 4. Comparison of Growth Rates of CHO Cells Exposed to 3.5-V/m, 60-Hz ac Electric Fields with Those of Sham-Exposed and Untreated (incubator control) Cells. Values are expressed as growth ratios: total number of cells following exposure divided by the number of cells seeded. The number of initial inocula were between 1 and 3 x 10^5 cells. Values are averages from five experiments.

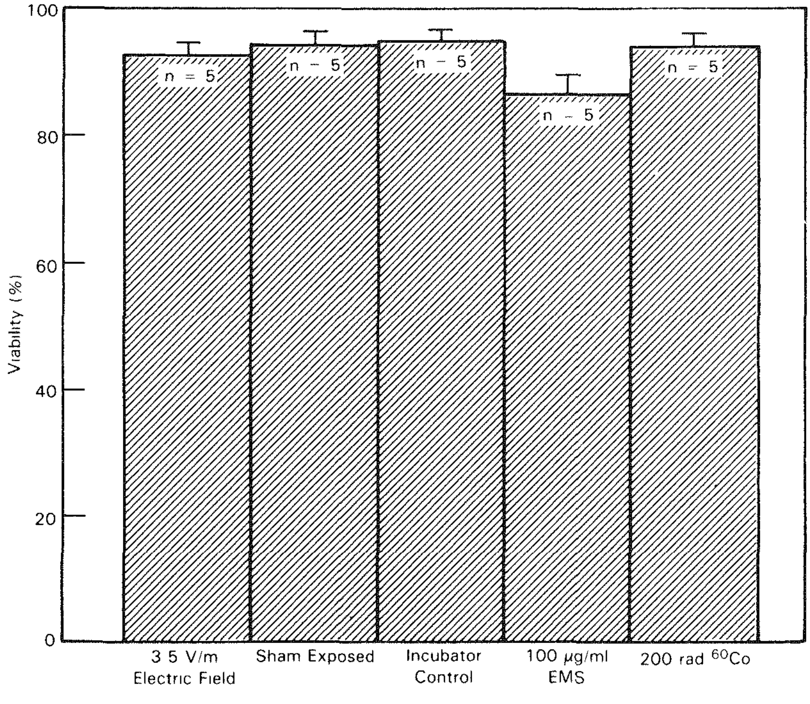

Figure 5. Viability of CHO Cells Following Various Treatments, Determined Using Trypan Blue Exclusion Test. Results of five experiments were averaged. Error bars represent ± 1 SD.

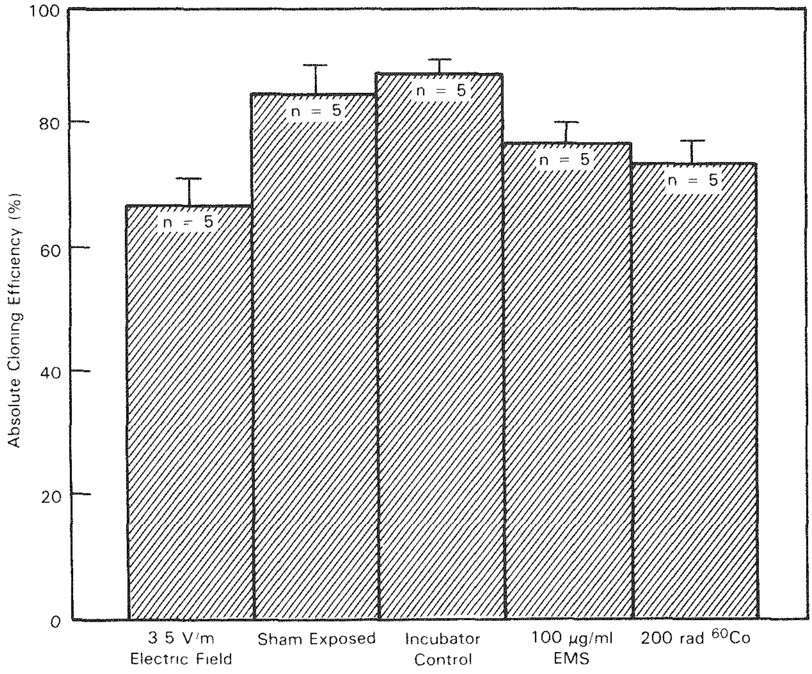

Figure 6. Cloning Efficiencies of CHO Cells Following Treatment with 60-Hz ac Electric Fields, Ethylmethylsulfonate (EMS) or 60Co γ-Irradiation Compared with Those from Sham-Exposed and Untreated Cells. Values are averages of five experiments. Error bars represent ± 1 SD.

In another series of experiments the electric field strength was held constant at 3.5 V/m, and the duration of the exposure was varied. Exposures were for 0, 1, 8, 24 or 48 hr. In these studies at least 1 hr (probably somewhat longer) was necessary to produce the observed cytotoxic effect on CHO cells (Figure 9). Following 8 hr of exposure to 3.5 V/m, a reproducible and significant effect was observed. The effect could not be enhanced by increasing the duration of cell exposure up to 48 hr, even though additional cell division was occurring.

The possibility of a dose-response effect was suggested by the experiments in which electric field strength was varied. Unfortunately, we had reached the upper limit of exposure field strength with that system. Therefore we devised another exposure system, which used graphite electrodes, to allow the direct application of current. The agar plugs served to isolate electrolytic products from the cell culture area. This system had the additional advantage of not having the contaminating magnetic field. A series of four experiments were conducted (Table 1). No effect of a 3.5-V/m, 60-Hz ac electric field on the cloning efficiency of CHO cells was observed in the graphite-electrode agar-bridge exposure system. However, the magnetically induced exposure system still decreased plating efficiency of exposed cells. The only measurable differences between the exposure systems appear to be in the harmonics and the presence of a small (up to 0.5 gauss) contaminating (magnetic) field.

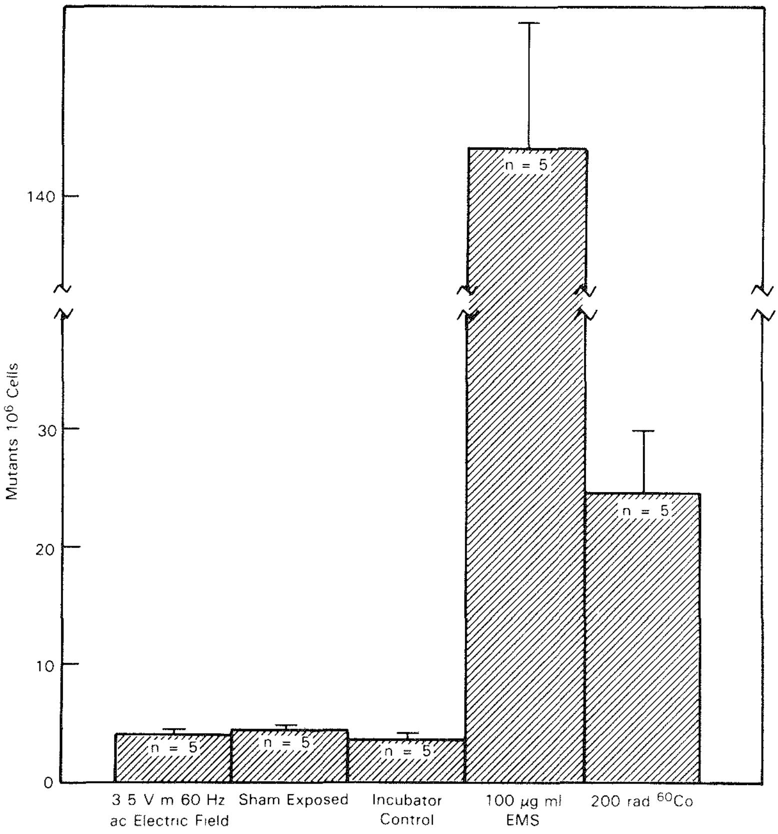

Figure 7. Mutation Frequencies of CHO Cells Following 60-Hz ac Electric-Field Exposure Compared with Those of Cells that Were Sham-Exposed, Untreated, Treated with Ethylmethyl Sulfonate (EMS) or ^{60}Co γ-Irradiation. Values are averages of five experiments. Error bars represent ± 1 SD.

We have recently built and are testing an ac magnetic-field exposure system which can be used for exposures up to 20 gauss. We will use this system in conjunction with the graphite-electrode exposure system to determine if we can replicate the effect on plating efficiency observed with the magnetically induced electric-field exposure system.

Our highest exposure level for cells (~10.9 V/m; Figure 9) was 50 to 100 times the maximum level encountered by humans (Kaune and Phillips, 1980).

TABLE 1 Effects of 60-Hz Electric Fields on Mutation Frequency of CHO-K1 Cells

	Exposure Duration (hr)	Mutation Frequency/ 10^6 Viable Cells Electric-Field-Exposed	 Sham-Exposed	P
3 5 V/m	24	7 8	6 2	NS[a]
	24	2 1	2 3	NS
	24	3 8	3 2	NS
	24	0 87	0 93	NS
	24	10 3	11 3	NS
10 9 V/m	24	2 5	2 3	NS
	24	2 8	3 0	NS
	24	3 5	3 1	NS

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[a] Not significant at 0 05 level using Student's *t*-test, 2 4 x 10^6 cells were assayed for each experimental point

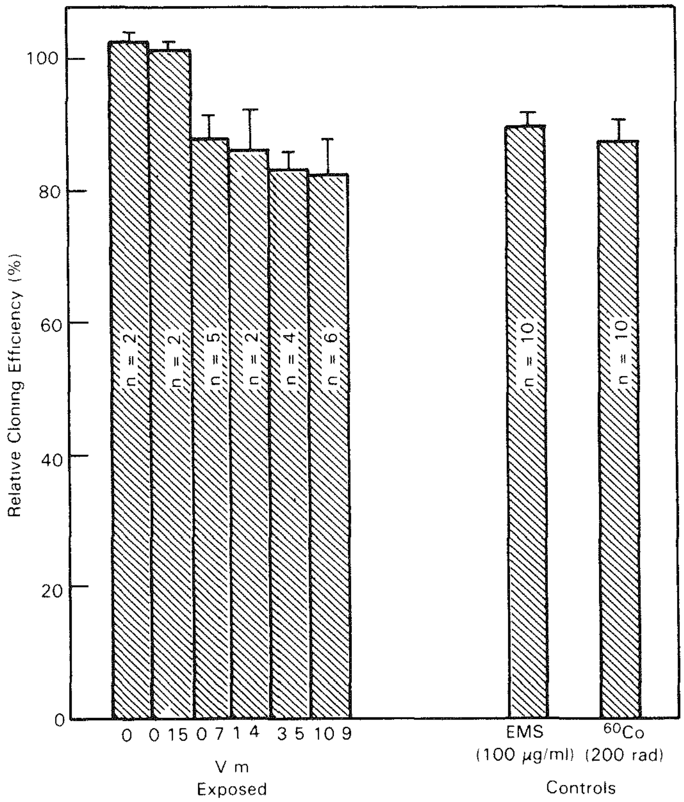

Figure 8 Effect of 60-Hz ac Electric-Field Exposure on the Cloning Efficiency of CHO Cells Values plotted are means ± SD Cells treated with ethylmethylsulfonate (EMS) or ^{60}Co γ-irradiation serve as controls

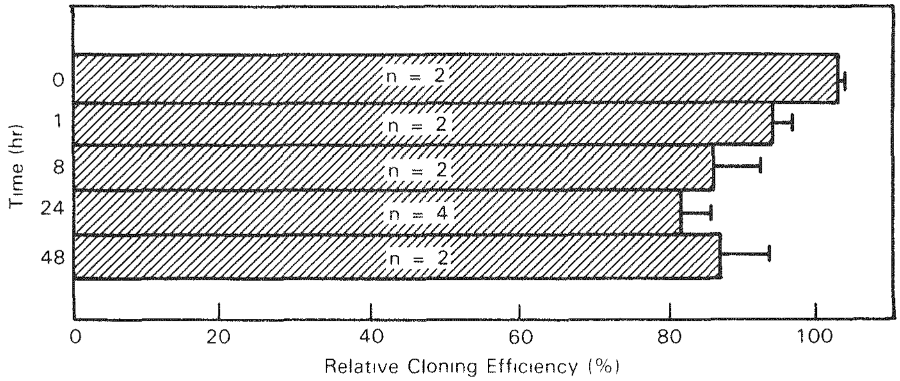

Figure 9 Effect of Exposure Duration on Cloning Efficiencies of CHO Cells Mean cloning efficiencies ± SD Cells were exposed to 3.5-V/m, 60-Hz ac electric fields for varying times.

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PULSED ELECTROMAGNETIC FIELD EFFECTS ON PTH-STIMULATED cAMP ACCUMULATION AND BONE RESORPTION IN MOUSE CALVARIA

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ABSTRACT

Low-frequency electromagnetic fields in a Helmholtz coil configuration are successful in healing non-union bone fractures. A 15-Hz field with a 100-μsec positive pulse and a negative pulse of 2 msec induced a peak field intensity of approximately 8 gauss. The 15-Hz field affected two related responses to parathyroid hormone (PTH) in cultures of mouse cranial bones: the cAMP response, measured 3 to 5 min after PTH treatment, and bone resorption, measured 72 hr after PTH treatment. Exposures for both assays were performed in a humidified incubator at 37°C and 5% CO_2. After a 1-hr exposure to the field, followed by a 30-min incubation with 5 mM theophylline (a phosphodiesterase inhibitor), the biphasic time course of the cAMP response to PTH was affected. Exposed bones responded within 3 min, and unexposed bones responded within 5 min after PTH treatment. The cAMP accumulation in exposed bones decreased within 5 min, as opposed to 7 min for the unexposed bones. Field effects were also observed in the complex cellular differentiation process leading to bone resorption; after 1 to 5 hr exposure, PTH-stimulated $^{45}Ca^{++}$-release from the extracellular matrix was inhibited by 35-40%. Bone resorption in the absence of PTH increased 40%, although basal cAMP levels were not affected after a 1-hr exposure. These data are consistent with the hypothesis that field perturbation occurs at the membrane level.

Although it is clearly established that low-energy electromagnetic fields can profoundly affect the healing functions of bone in animals and humans, there are virtually no data which explain the mechanisms of this phenomenon. The purpose of our study is to elucidate the biochemical mechanisms of electromagnetic influences on bone healing.

Pulsed electromagnetic fields (PEMF) have been clinically successful in treating non-union bone fractures and pseudarthroses (Bassett, Pilla, and Pawluk, 1977; Bassett, Mitchell, and Schink, 1982; Bassett, Mitchell, and Gaston, 1982). In our treatment regimen we attempted to generate in bone, by noninvasive means, currents of approximately 10 $\mu A/cm^2$, similar to those produced by implanted electrodes previously shown to promote healing of non-union bone fractures (Brighton, et al., 1981; Bassett, 1982). We selected extremely low frequency (ELF) PEMF (10 to 100 Hz) because of reports in the literature (Adey, 1981) that weak electromagnetic (ELF) fields affect biological processes.

The clinical success of PEMF treatment for bone healing has inspired in vivo (Cruess, Kan, and Bassett, 1983; Smith and Nagel, 1983) and in vitro models for studying its mechanism of action. On theoretical grounds (Adey, 1981, 1982; Pilla, 1980) and experimental grounds (Bawin and Adey, 1976; Bawin, Adey, and Sabbot, 1978; Luben et al., 1982; Luben and Cain, 1984; and Pilla, 1980), it is probable that the primary site of interaction of PEMF and other ELF nonionizing radiation with biological systems is the cell membrane. For these reasons, the in vivo cranial bone culture used in our studies is an excellent system for observing early and late responses to parathyroid hormone (PTH), a polypeptide hormone that acts by means of receptors at the cell membrane. Adenylate cyclase, a membranous enzyme, produces cyclic adenosine monophosphate (cAMP) as early as 1 min after exposure to PTH. In addition to the early cAMP responses, bone resorption (as determined by release of extracellular Ca^{++} from the bone matrix) is measured 72 hr after hormone treatment. The cAMP experiments have enabled us to study the initial effects of the PEMF, whereas the bone resorption experiments have confirmed the biological significance of these interactions. The adenylate cyclase complex amplifies low-level external signals across the cell membrane and is thus a logical candidate for a potential site of action by PEMF. The data presented here further support our hypothesis that alteration of hormone receptor/adenylate cyclase function is an important component of PEMF effects on bone cells.

MATERIALS AND METHODS

PEMF Exposure System

The PEMF exposure system used is described in Luben et al., 1982. Petri dishes (60 mm) containing 8 ml of minimum essential medium (MEM, Gibco), 10% fetal bovine serum (FBS; Irvine Scientific, Irvine, CA) and 0.1% penicillin/streptomycin solution (Gibco, Grand Island, NY) were placed in a 10 x 10-cm^2 Helmholtz coil of a Bi-Osteogen clinical field generator (furnished by Electro-Biology, Fairfield, NJ). The coils were kept in a humidified incubator at 37°C and 5% CO_2; the generator unit remained outside the incubator at normal room temperature and humidity. Field-exposed and unexposed bones were placed in the same incubator. The unexposed bones were isolated with stainless steel and styrofoam, which decreased the field by 99.9% as measured by induction probes (Luben et al., 1982). The waveform parameters of the field used in these experiments were a positive pulse at 100 μsec and a negative pulse of 2 msec, repeated at a frequency of 15 Hz. The induced magnetic field was approximately 8 G, with an electric field strength of 0.6 mV/cm and a current density of 20 $\mu A/cm^2$ in the medium (Luben et al., 1982).

Bone Resorptions

Bone resorption experiments were carried out as described in Luben and Cohn (1976). Briefly, 2 to 3 μCi of $^{45}Ca^{++}$ (Amersham, Arlington Heights, IL), 0.52 mCi/ mole, were subcutaneously injected in newborn Swiss-Webster mice (Hilltop Farms, Scottsdale, PA). Seventy-two hr later the cranial bones were aseptically removed, split in half at the midline suture, and preincubated in 8.0 ml of MEM, 10% FBS, and 0.1% penicillin/streptomycin solution in 60-mm petri dishes (30 bones/dish). Following incubations of 6 to 24 hr to equilibrate exchangeable Ca^{++}, the bones were placed in PEMF coils for 1 to 5 hr exposure. After removal from the field, the bones were placed in 24-well plates with 1.0 ml of BGJ_b culture medium (Fitton-Jackson modification, Gibco, Grand Island, NY) containing 0.5% BSA, 1% FBS and various concentrations of bPTH (1-34; 2.3, 6.9 or 23 nM; Bachem, Torrance, CA). Hormone treatment was begun within 30 min after the bones were removed from the field. After preincubation and field exposure, some bones were frozen on dry ice, then alternately thawed and frozen three times; they are referred to as "dead" bones. Those that were not frozen are called "live" bones. The bones were then cultured in 24-well plates for 72 hr, with continuous rocking, in a medium maintained at 37°C and 5% CO_2, after which they were decalcified in 1.0 ml of 0.1 N HCl for 1 hr.

The $^{45}Ca^{++}$ radioactivity was measured for both medium and bones, using a liquid scintillation counter. The percentage of bone calcium released during 72 hr of culture was determined by comparing ^{45}Ca radioactivity in the medium versus that remaining in the bones. The percent release for dead bones was subtracted from the percent release of live bones.

cAMP Assays

Cranial bones were prepared and incubated as for the bone-resorption assays but without $^{45}Ca^{++}$ labeling. Bones were removed from the field at the indicated times and incubated in fresh MEM, 10% FBS with 5 mM theophylline (Sigma, St. Louis, MO), a phosphodiesterase inhibitor, at 37°C and 5% CO_2 for 30 min. They were then treated with bPTH for 3 or 5 min, after which the bones were rapidly "killed" by exposure to a microwave oven (Luben et al., 1979). The cAMP accumulation was measured by radioimmunossay, as described in Luben et al. (1979, 1982). Student's *t*-test value was calculated for each experimental group of samples versus the corresponding control group. Probability estimates for rejection of the null hypothesis were calculated using Dunnett's modification of the *t*-test for multiple comparisons against a control (Dunnett, 1964).

RESULTS

BONE RESORPTION STUDIES

The purpose of the bone resorption experiments was to determine whether 1 to 5 hr of exposure to PEMF would affect Ca^{++} release from the bone matrix. The major result observed was that a field exposure of this time course (1 to 5 hr) altered $^{45}Ca^{++}$ release measured 72 hr after hormone treatment and field exposure. At submaximal PTH doses (2.3 nM and 6.9 nM), 1- to 5-hr field exposures inhibited bone resorption (35% and 44%, respectively [Table 1]), but the PEMF did not inhibit at the maximal PTH dose, 23 nM. This inhibition suggests decreased efficiency in activating the molecular cascade and cell differentiation process leading to bone resorption.

We also wished to examine whether basal bone resorption (i.e., in the absence of added PTH) was influenced by PEMF. To increase basal resorption, the serum level was raised to 7% (Table 2), causing basal resorption to rise to 6.17 ± 0.45% in eight pooled experiments. Exposure to the field further increased this basal resorption, by 40% ($P < 0.025$). Field exposure produced an increase in basal resorption as early as 15 min after initiation, it continued throughout the 5 hr of exposure (Figure 1A). The assay is not sensitive enough to ascertain whether the apparent fluctuations in basal resorption are significant, although time "windows" with respect to field exposure have been reported (Luben and Cain, 1984; Goodman, Bassett, and Henderson, 1983; Byus et al., 1984). Figure 1B also shows that the field inhibited PTH-stimulated bone resorption after 30 to 45 min of exposure.

TABLE 1. Pulsed Electromagnetic Field Effect on PTH-Stimulated Bone Resorption. (Each value represents 7 or 8 half-calvaria plus or minus the SEM; exposed and unexposed were compared at the respective doses.)

Solution, nM PTH	Percent $^{45}Ca^{++}$ Released[a]			
	1 Hour Exposure		5 Hour Exposure	
	No Field	Field	No Field	Field
Control	5.27 ± 0.56	6.94 ± 0.67[b]	3.36 ± 0.43	4.95 ± 0.45[b]
2.3	11.73 ± 2.00	7.23 ± 1.03[b]	8.79 ± 0.68	5.26 ± 0.38[d]
6.9	12.40 ± 0.97	8.02 ± 0.46[c]	12.3 ± 0.63	5.84 ± 0.43[d]
23	12.62 ± 1.52	10.62 ± 0.62	8.28 ± 1.11	7.12 ± 0.79

[a] The percent release for dead bones (6.38 ± 0.23 for 1-hour-exposed bones, 6.49 ± 0.12 for 1-hour-unexposed bones, 4.72 ± 0.34 for 5-hour-exposed bones and 4.51 ± 0.13 for 5-hour-sham-exposed bones) was subtracted from percent release of live bones.

[b] $P < 0.1$

[c] $P < 0.005$

[d] $P < 0.001$

TABLE 2. Pulsed Electromagnetic Field Effect on Basal Bone Resorption and cAMP Levels. (Field-exposed and unexposed bones were compared for both assays.)

	Percent $^{45}Ca^{++}$ Released	Amount of cAMP (pmoles/bone)
1-hour field exposure	8.66 ± 0.52[a]	1.02 ± 0.22[b]
No field	6.17 ± 0.45[a]	0.71 ± 0.46[b]

[a] 8 pooled experiments, n = 5.2; $P < 0.025$.

[b] 6 pooled experiments, n = 5

cAMP Studies

The protocol for studying the effects of PEMF on PTH-stimulated cAMP accumulation in calvaria was designed to answer the following question: After a 1-hr exposure to PEMF and 30 min of preincubation with 5 mM theophylline, did PEMF affect PTH-stimulated cAMP accumulation? We reported previously (Luben et al., 1982; Luben and Cain, 1984) that PEMF inhibited the PTH-stimulated cAMP accumulation in calvaria after 14- to 48-hr exposures; we now report a similar inhibition after a 1-hr exposure (Figure 2). However, our observation of this inhibition was complicated by the fact that the PEMF hastens the time course of cAMP accumulation stimulated by PTH (Figure 2). Usually, PTH stimulates adenylate cyclase production, with a peak of activity at approximately 5 min, followed by a gradual return to control levels within 10 min after hormone treatment. This biphasic response was observed in the presence of theophylline, though it was attenuated because theophylline inhibited breakdown of accumulated cAMP. As shown in Figure 2, cAMP production in both exposed and unexposed bones had biphasic time courses, but the response of the exposed bones was quicker, and cAMP levels fell sooner than in the unexposed bones. Thus, when cAMP measurements were made after 5 min of PTH treatment (Figure 3A), the peak of adenylate cyclase activity had passed for the field-exposed bones, and the efficiency of the adenylate cyclase system had apparently decreased. Conversely, when cAMP was measured after 3 min of PTH treatment (Figure 3B), the field apparently enhanced the cAMP response by shifting the dose response curve 1 log unit to the left.

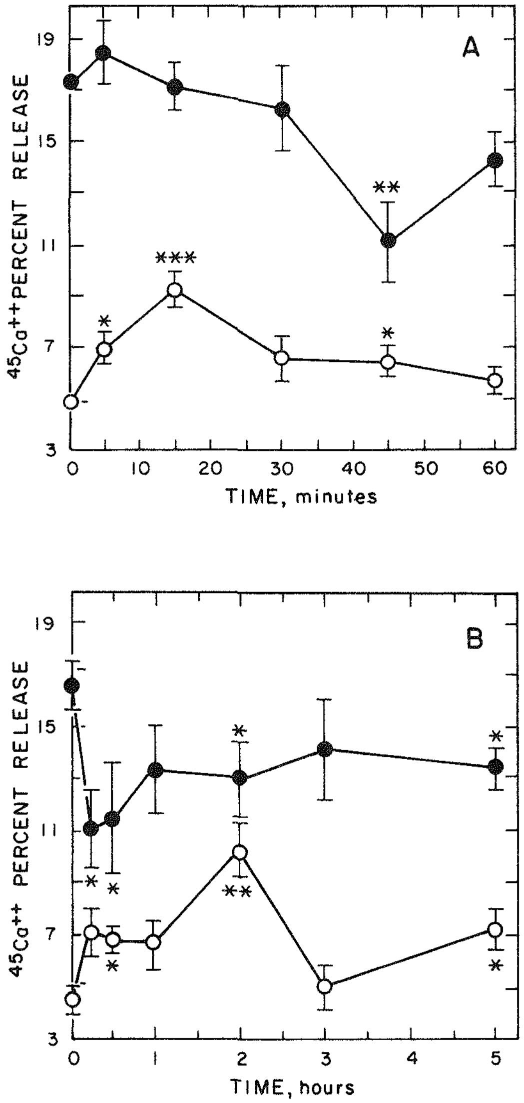

Figure 1. Effect of Pulsed Electromagnetic Field on Basal and PTH-Stimulated Bone Resorption Versus Time Course in the Field. Half-calvaria were prepared as described in Materials and Methods. For the last 5 hr (1A) or the last hour (1B) of the preincubation, calvaria were exposed to the field for the indicated times. After the field exposure, all bones were placed in 1.0 ml of BGJ$_b$ media with 6.9 nM PTH (●) or without (O). Each point represents 7 or 8 half-calvaria; error bars are SEM; * = $P < 0.05$, ** = $P < 0.005$, *** = $P < 0.001$. Field-exposed bones were compared to unexposed bones. The percent dead bone release for both preincubation periods was 4.80 ± 0.33 (A) and 7.30 ± 0.23 (B).

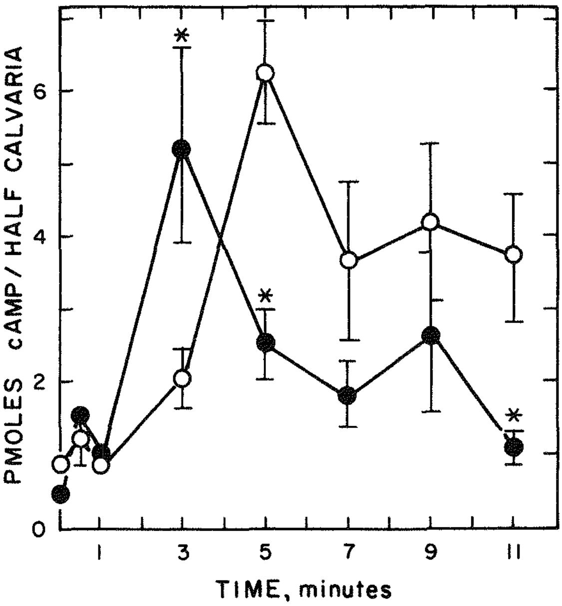

Figure 2. Field Effect on Time Course of PTH Stimulation After 1 hr Pulsed Electromagnetic Field Exposure. Half-calvaria were prepared as described in Materials and Methods. During the preincubation, the bones were exposed to the field for 1 hr, removed from the field, incubated for 30 min in fresh MEM with 10% FBS and 5 mM theophylline, then treated with 2.3 nM bPTH for the indicated time. Each point represents 4 half-calvaria; error bars are SEM; * = $P < 0.05$. Field-exposed bones, ●, were compared to unexposed bones, O, at their respective times. These data are representative of five experiments.

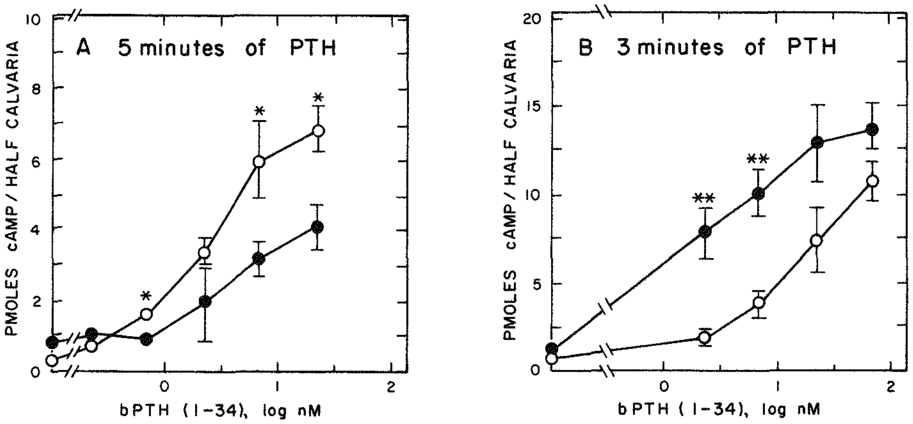

Figure 3. Field Effect on cAMP Dose Response to PTH After 1-hr Pulsed Electromagnetic Field Exposure. Half-calvaria were prepared as described in Materials and Methods. During the preincubation, half the bones were exposed to the field for 1 hr, removed from the field, incubated for 30 min in fresh MEM with 10% FBS and 5 mM theophylline, then treated with bPTH for 5 min (A) or 3 min (B); A and B are separate experiments. Each point represents 5 half-calvaria; error bars are SEM; * = $P < 0.005$, ** = $P < 0.005$. Field-exposed bones, ●, were compared to unexposed bones, O, at their respective PTH doses.

DISCUSSION

Our working hypothesis is that PEMF influence membrane activities in bones maintained in culture. We have previously reported evidence (Luben et al., 1982) that PEMF affect the hormonal action of PTH, whose initial action is at the cell membrane, whereas PEMF do not affect the action of $1,25(OH)_2D_3$, a sterol hormone whose initial action is in the cytoplasm. How the PEMF couple to membrane activities is still unclear, but empirically, both endogenous and exogenous electric fields, current fluxes and magnetic fields can have direct effects on membrane processes in bone. The electric field strength associated with our PEMF, 0.6 mV/cm, is eight orders of magnitude less than the electric potential gradient of a typical cell membrane, 10^5 V/cm. Evidence exists that such low-strength electric fields can profoundly affect membrane activities. For example, DC fields as low as 10 mV/cm affected embryonic fibroblast motility (Erickson and Nuccitelli, 1984), and cell-surface concanavalin A receptors of myoblasts migrated within the lipid bilayer in pulsed electric fields of 300 mV/cm (Lin-Liu and Adey, 1984).

With respect to current densities induced by our PEMF, 20 $\mu A/cm^2$, it has been known for 20 years that surgically implanted electrodes promote bone healing with current densities in the same range. These current densities can now be considered physiologically relevant because Borgens (1984) measured endogenous current densities of 0.5 to 12 $\mu A/cm^2$ at the surface of mouse metatarsals, using ultrasensitive vibrating-probe system; current densities rose to 40-100 $\mu A/cm^2$ after damage to the bone.

It has recently been reported that a variety of biological systems are perturbed by weak ELF electromagnetic fields with field strengths within the range of the earth's geomagnetic field, 0.54 G. These systems range from in vivo bone healing and chicken embryo exposures to *E. coli* and mammalian-cell-culture exposures. For example, ELF magnetic fields from 23 to 65 G decreased phytohemagglutinin-stimulated thymidine incorporation in human lymphocytes (Conti et al., 1983). With 0.5- to 10-G PEMF, Aarholt (1981a, 1981b) perturbed the mean generation time and b-galactosidase activity of *E. coli.* Delgado et al. (1982) and Ubeda et al. (1983), using 0.0012- to 0.12-G PEMF, induced anatomical abnormalities in chicken embryos. With 8.5-G PEMF, Dixey and Rein (1982) increased noradrenaline release from a neuronal cell line (PC 12).

It is still unclear what aspects of the electric field, current densities and/or magnetic field are operative in these biological effects. However, these effects cannot be attributed to heating since the energy introduced to all the systems cited above is far below that of thermal noise. To resolve the question of what the active component of the PEMF that perturbs the membrane may be, our approach has been to study one of the most sensitive biochemical reactions in the membrane, hormone-stimulated cAMP accumulation. Our protocol for field exposure probably precludes any differentiative changes in the membrane components that could account for the cAMP effects; therefore it is more likely that the steric arrangements and/or interactions of the membrane components are affected by PEMF. It should be kept in mind, however, that the bone-resorption experiments suggest that PEMF can also affect a complex differentiation process.

Some of the reported biochemical reactions stimulated by PTH in calvaria are as follows: PTH bound its receptor which, in turn, coupled to the adenylate cyclase system to produce cAMP within 3 min. The PTH also depolarized the osteoblast membrane of calvaria in the same time frame (Jeansonne et al., 1978) and increased $^{45}Ca^{++}$ influx in calvaria within 5 min, regardless of adenylate cyclase activity (Dziak and Stern, 1975a). The Ca^{++} influx, without observed concurrent increase in intracellular cAMP, caused bone resorption, using the Ca^{++} ionophore A23187 (Dziak and Stern, 1975b, 1976). After the initial cAMP increase and Ca^{++} influx, the osteoblast underwent differentiation and sent paracrine factors to osteoclasts. The osteoclasts then increased in number and secreted enzymes to chelate extracellular Ca^{++} from the bone matrix. The Ca^{++} release could be measured as early as 48 hr after hormone treatment.

PEMF experiments have examined PTH binding, Ca^{++} influx, cAMP levels, and extracellular Ca^{++} release in bone cultures. The PEMF did not affect equilibrium hormone binding to calvaria with regard to affinity, number of PTH receptors (Luben and Cain, 1984) or basal cAMP levels (Table 2); however, a 30-min exposure to PEMF increased $^{45}Ca^{++}$ uptake by 16% in chicken tibiae according to Colacicco and Pilla (1983; Colacicco, 1983). Therefore, one can hypothesize that the PEMF-stimulated Ca^{++} influx, which increased basal bone resorption by 40% (Table 2), occurred without stimulating adenylate cyclase. Fitzsimmons et al. (1984) observed a 41% increase in basal bone resorption in mouse calvaria exposed to weak electric fields. In addition, this initially altered Ca^{++} influx may have prevented optimal coupling of the PTH receptor to the adenylate cyclase complex since PTH itself stimulates Ca^{++} influx (Dziak and Stern, 1975a). Since Ca^{++} and cAMP are tightly regulated intracellular second messengers, an imbalance in the "synarchic" relationship between the two (Rasmussen, 1981) could then impair osteoblast differentiation and the subsequent bone-resorption response to PTH (Table 1). The PEMF perturbation on PTH-stimulated bone resorption can be considered subtle in molecular terms because the PEMF inhibition disappears at maximal PTH levels (Table 1).

The PEMF effect on PTH-stimulated cAMP accumulation is more ambiguous because we were observing events closer to the PEMF primary interaction. This interaction with any biological system cannot be considered in classical thermodynamic equilibrium terms because it is time-dependent. If one is not observing a biological response at the appropriate time, no field effect will be observed. For example, Goodman, Bassett and Henderson (1982) observed marked and specific increases in RNA transcription of dipteran salivary gland cells during exposure to PEMF for 45 min, but the effects declined after a 60-min exposure. Similarly, Byus et al. (1984) observed decreased cAMP-independent protein kinase activity of cultured human lymphocytes exposed to modulated microwave fields for 30 min, but the cells showed no effect after a 60-min exposure. We have shown that after a 1-hr PEMF exposure and a 30-min incubation with theophylline, PEMF hastens the time course of PTH-stimulated cAMP accumulation (Figure 2). A difference of only 2 min in the time of measurement determined whether PEMF was observed to enhance (Figure 3A) or to inhibit (Figure 3B) PTH-stimulated cAMP accumulation. This is a very subtle effect to detect in an organ culture system, and we would not be surprised to observe other effects by varying such parameters as duration of field exposure and/or preincubation conditions. Nevertheless, we would expect subtle and time-dependent PEMF effects at the cell membrane, considering the extremely low energy exerted on the system, and the possibly nonequilibrium processes affected by PEMF.

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ELECTROMAGNETIC-FIELD INDUCED BIOEFFECTS IN HUMAN CELLS IN VITRO

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ABSTRACT

Two human colon cancer cell lines, Colo 205 and Colo 320 DM, have been used to study the effects of electromagnetic-field exposure on several cellular structural and functional parameters. Cells in replicate suspensions were concurrently exposed for 24 hr at 37°C to four test conditions: electric field only (E+; 300 mA/m^2 rms); magnetic field only (M+; 1.0 G rms); combined fields at those intensities (E+M+); and to no fields (E-M-, control). Following exposure, proliferative capacity of the cells was determined by cloning in soft agar, and monoclonal antibodies were employed to measure tumor-associated antigen (TAA) levels on the cell surface. Eight replicate experiments using Colo 320 DM cells demonstrated an overall increase in colony formation in soft agar of 3.2 ± 0.84 (mean ± SE) times control for E+M+ cells; 1.73 ± 0.57 times control for E+ cells; and 5.3 ± 0.98 times controls for M+ cells. Colo 205 cells, in five replicate experiments, responded with growth increases of 6.62 ± 4.46 times control for E+M+; 1.44 ± 0.25 times control for E+; and 4.16 ± 2.46 times control for M+ cells. Additionally, TAA expression was also increased in exposed cells. Colo 205 cells exposed to each of the four conditions in several different experiments have been established in long-term culture, thus permitting continuous study of the changes produced. Results of various assays for one of these long-term lines indicate the following (for cells exposed to E+M+ and M+): maintenance of their initially observed increased clonogenic capacity, even after several months in culture; continued increased expression of TAA; increased numbers of transferrin receptors (and index of proliferation); and decreased lysis by natural killer (NK) cells. Therefore, it appears that exposure of human colon cancer cells to electromagnetic (EM) fields produced permanent changes in these cells consistent with an increase in both reproductive and survival potentials.

In vitro studies of established human cell lines have been of fundamental importance in virology, biochemistry, immunology, and cell biology, although the extent to which these cultured cells represent human cells in vivo is not fully understood. Recognizing the limitations involved, we have used normal and tumor cells of well-characterized lineage to study the effects of EM field exposure on certain structural and functional cellular parameters. A twofold approach has been used: 1) to study EM-field-induced changes in the reproductive capacity of the cells as determined by colony formation after cloning cells in soft agar; and 2) to study EM-field-induced changes in surface membrane properties (i.e., tumor-associated antigen [TAA] expression, transferrin receptor number and affinity for transferrin, and cell lysis by NK cells). There is ample evidence in the literature to suggest that the surface membrane of cells is a major target of EM-field irradiation (see, for example, Colacicco and Pilla, 1983 and Conti et al., 1983). Our approach has been to follow EM-field-induced effects as a function of time after exposure to determine, where possible, both the onset and the permanence of change. This report describes results of studies performed with two human colon adenocarcinoma cell lines, Colo 205 and Colo 320 DM.

MATERIALS AND METHODS

The Colo 205 and Colo 320 DM cell lines used in these studies were obtained from the American Type Culture Collection, and were grown in RPMI-1640 tissue culture medium as recommended by the supplier. The apparatus and equipment of the EM-field exposure system have been described in detail elsewhere (Lucas and Johnson, 1984). The EM exposure system provides identical cell exposure chambers containing suspensions of target cells to be exposed concurrently to no fields (E-M-; control), electric field alone (E+), magnetic field alone (M+), and electric plus magnetic fields (E+M+), thus allowing full, controlled experimentation with any given population of cells.

In a typical experiment, approximately 20 x 10^6 cells were placed in each of four chambers in a final volume of about 50 ml tissue culture medium and were exposed as follows: one chamber (E+) to an electric field of 300 mA/m^2 rms; one chamber (M+) to a magnetic field of 1.0 G rms; one chamber (E+M+) to the combined electric and magnetic fields at the intensities given; and one chamber to neither the electric nor magnetic fields (E-M-). All chambers were maintained at 37°C, and exposure was continuous for 24 hr. Following exposures, cells were removed from the chambers, centrifuged, resuspended in fresh tissue culture medium, and counted in a hemacytometer. Viabilities were determined by exclusion of trypan blue. Cells were then diluted with fresh medium to cell densities appropriate for conducting subsequent bioassays.

Cloning in soft agar was performed according to the procedure of Hamburger and Salmon (1977) except that RPMI-1640 medium was used in the upper agar layer. To assure the most reliable data, cells were cloned at three different cell concentrations, and each data point comprised six replicate agar plates. All plates were incubated for 7-21 days at 37°C in a humidified atmosphere of 5% CO_2 in air. Colony formation was assessed with a Bausch and Lomb FAS II image analyzer.

Assessment of TAA expression on control and EM-exposed cells was accomplished by incubating equal numbers of cells from each chamber with selected monoclonal antibodies, washing the cells, then incubating with an appropriate ^{125}I-labeled anti-species antibody with subsequent measurement of antibody binding by standard RIA methods. The monoclonal antibody used in these studies was derived by standard methods as a result of fusion of SP02 myeloma cells with spleen cells from animals injected with Colo 320 DM cells. Fluorescence and radioimmunoassays were used to screen and select hybrid cells producing antibody specifically reactive with epitopes of the Colo 320 DM and Colo 205 cells, but not reactive with normal human cells or with other malignant cells.

Transferrin receptors were quantitated by incubating cells with ^{125}I-labeled transferrin (0.125 to 2.0 μg) for 4 hr at 4°C. After washing, cells were collected on glass fiber filters, and the radioactivity assessed by gamma counting. Data were analyzed to determine receptor number and an association constant by the method of Scatchard (1949).

Lysis of tumor cells was measured by a standard ^{51}Cr-release assay (Mangan et al., 1984). Briefly, control and exposed tumor cells, i.e., target cells, were loaded with ^{51}Cr for 1 hr at 37°C. After washing and resuspension in fresh medium (RPMI-1640 containing 10% fetal calf serum), the labeled target cells (10^4 cells in 0.1 ml) and freshly isolated human lymphocytes (5 x 10^5 cells in 0.1 ml) were incubated for 4 hr or for 20 hr at 37°C in a humidified atmosphere of 5% CO_2 in air. After incubation, cells were centrifuged, and ^{51}Cr in the supernatant was measured by gamma counting. Control cultures were also run to assess spontaneous and maximum release of isotope. All assays were performed in triplicate.

RESULTS

Tables 1 and 2 present the results of cloning experiments following EM-field exposure for Colo 205 and Colo 320 DM cells, respectively. In all cases, the data have been normalized to 1.00, which represents the mean number of colonies for the six E-M-(control) plates. In general, exposure of these two cell lines to EM fields resulted in increased reproductive capacity, as judged by increased colony formation in soft agar compared to concurrently assayed control cells. Furthermore, certain trends are indicated: 1) for Colo 205 cells, the greatest increase in reproductive capacity was generally observed for cells exposed to combined electric and magnetic fields (E+ M+), followed by M+ cells, then E+ cells; 2) for Colo 320 DM cells, the greatest increase in reproductive capacity was generally observed in M+ cells, followed by E+ M+, then E+ cells. These trends have been confirmed in recent studies from this laboratory (Phillips, Winters and Rutledge, 1986) and indicate the importance of the magnetic field in eliciting a change in cellular function.

TABLE 1. Effect of Electromagnetic-Field Exposure on Colony Formation in Soft Agar by Colo 205 Cells

Experiment Number	Normalized Colony Counts[a]			
	E+M+	E+	M+	E-M-
1	24.4	1.7	13.9	1.0
2	1.5	1.3	0.9	1.0
3	2.9	0.7	2.8	1.0
4	2.8	2.2	2.3	1.0
5	1.5	1.3	0.9	1.0

[a]Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ exposed to magnetic field; E-M- = unexposed (controls)

Table 3 presents the results of experiments to measure the level of TAA on the cell surfaces of control and EM-field-exposed Colo 205 and Colo 320 DM cells, using three different monoclonal antibodies specifically reactive with antigens of these cell types. In agreement with the results of the cloning studies described above, it is seen that exposure of cells to E+ M+ and to M+ consistently resulted in increased expression of cell surface antigens compared to levels of these antigens detected on non-EM-exposed control cells.

TABLE 2. Effect of Electromagnetic-Field Exposure on Colony Formation in Soft Agar by Colo 320 DM Cells

Experiment Number	Normalized Colony Counts[a]			
	E+M+	E+	M+	E-M-
1	6.9	2.7	3.0	1.0
2	5.0	5.3	7.5	1.0
3	1.7	1.0	5.3	1.0
4	1.3	0.6	11.0	1.0
5	6.0	0.4	3.5	1.0
6	1.0	1.0	5.4	1.0
7	1.9	1.2	2.9	1.0
8	1.8	1.6	3.9	1.0

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[a] Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ exposed to magnetic field; E-M- = unexposed (controls)

TABLE 3. Monoclonal Antibody Binding to Electromagnetic-Field-Exposed Human Colon Cancer Cells[a]

Cell Type/Exposure Group	%Change from Control (E-M-)		
	Antibody 10	Antibody14	Antibody 19
Colo 205/E+M+	+56	+32	+38
E+	ND	0	+24
M+	+23	+8	+47
Colo 320 DM/E+M+	+24	+35	+11
E+	ND	+33	+16
M+	+33	+24	+15

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[a] Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ exposed to magnetic field; E-M- = unexposed (controls); ND = not determined

A series of additional experiments have been performed using Colo 205 cells from control, E+, M+ and E+M+-field-exposed cultures. These cells were obtained by removing the cells from the respective soft agar dishes after evaluating the first cloning assay, placing the cells in fresh tissue-culture medium, then maintaining them in long-term culture. The four groups of cells obtained for study (E+M+, E+, M+, and E-M-) have been designated Colo 205LT.

Table 4 compares the results of repetitive cloning experiments with the Colo 205LT cells with those obtained in the original cloning experiment. These cells maintained their increased reproductive capacity during the several months of study following the original (and only) exposure to electric and magnetic fields. Table 5 presents the number of transferrin receptors quantitated in cells from each of the four 205LT exposure groups at 4 mo after the original EM-field exposure. Increased numbers of receptors are present on E+ M+ and on M+ cells; decreased numbers are present on E+ cells. The E-M-cells displayed virtually the same number of transferrin receptors as other Colo 205 cells grown in stock cultures of similar cell density (Phillips, Rutledge, and Winters, 1986). Furthermore, the number of transferrin receptors observed in E+ M+ and on M+ cells is very close to the maximum theoretical number of receptors calculated for this cell line (Phillips, Rutledge, and Winters, 1986). Also presented in Table 5 are the association constants calculated for each of the exposure groups. Values determined for E+ M+, M+, and E-M- are virtually the same as values obtained with other Colo 205 cells from reference cultures, but the value obtained for E+ cells is nearly three times greater. Finally, Table 6 presents a summary of the results of six separate experiments to determine the susceptibility of the four sets of 205LT cells to lysis by human NK cells at 5.5 mo after the original EM-field exposure. The NK cell susceptibility, described as percent cytotoxicity, was significantly altered in all three exposure groups compared to that of the control cells. Lysis was decreased approximately 70% for both E+ M+ and M+ cells but was increased about 53% for E+ cells.

TABLE 4. Colony Formation in Soft Agar by Colo 205 LT Cells During Long-Term Culture after Electromagnetic Field Exposure

		Normalized Colony Counts[a]			
Date	Cloning Interval	E+M+	E+	M+	E-M-
December, 1983	After Original EM Exposure	2.4	1.7	13.9	1.0
February, 1984	Repeated at 2 months	23.7	1.7	7.3	1.0
March, 1984	Repeated at 3 months	14.5	2.4	8.5	1.0
April, 1984	Repeated at 4.5 months	18.8	2.1	10.1	1.0

[a] Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ = exposed to magnetic field; E-M- = unexposed (controls)

TABLE 5. Transferrin Receptors on Colo 205LT Cells at 4 Months after Electromagnetic Field Exposure

Exposure Group[a]	Receptors Thousands/Cell	Association Constant [$K_a(M^{-1}) \times 10^8$]
E+M+	127	10
E+	17	27
M+	135	8
E-M-	64	9

[a] Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ = exposed to magnetic field; E-M- = unexposed (controls)

TABLE 6. Effect of Human Natural Killer Cells on Lysis of Colo 205LT Cells at 5.5 Months after Electromagnetic-Field Exposure

Exposure Group[a]	% Cytotoxicity, mean SD (range)
E+M+	9.58 ± 4.42 (4.5 - 16.5)
E+	52.25 ± 9.72 (36.9 - 63.1)
M+	10.10 ± 2.40 (5.9 - 12.2)
E-M-	34.13 ± 5.85 (24.1 - 38.7)

[a] Abbreviations: E+M+ = exposed to combined electric and magnetic fields; E+ = exposed to electric field; M+ = exposed to magnetic field; E-M- = unexposed (controls)

SUMMARY AND CONCLUSIONS

A series of experiments were performed with two human colon cancer cell lines to determine the effect of EM-field exposure on the reproductive capacity and surface properties of these cells. Furthermore, EM-field-exposed Colo 205 cells were established in long-term culture to allow continuous and repetitive assessment of changes in cell structure and function. Our data indicate that exposure of these cells to EM fields resulted in increased reproductive capacity, as judged by increased colony formation in soft agar. The increase was of greater magnitude for cells exposed to combined electric and magnetic fields or to the magnetic field alone than for cells exposed only to the electric field. In addition, this increased proliferative response was maintained for at least several months and for many cell divisions, as evaluated by repetitive cloning experiments. Additionally, the increase in reproductive capacity was correlated with the increase in the number of transferrin receptors determined for the E+M+ and M+ Colo 205LT cultures. This result is in agreement with previously reported direct correlations between the number of transferrin receptors and a cell's state of proliferation (Larrick and Cresswell, 1979). Indeed, there is a reported inverse relationship between the number of transferrin receptors and the clinical outcome in lymphoma (Kvaloy et al., 1984).

Since the cell surface membrane has been reported to be a major target for EM-field irradiation (Colacicco and Pilla, 1983; Conti et al., 1983), we have studied several parameters that indicate directly the state of that membrane, including TAA expression, number of transferrin receptors, and susceptibility to lysis by NK cells. Our results demonstrate changes in the properties of the cell surface, especially in cells exposed to E+M+ and M+ fields, that we consider consistent with a long-term increase in the proliferative capacity and survival potential of those cells.

The purpose of these studies has been to determine if there are consistent effects on cellular function following in vitro exposure of human cells to 60-Hz-generated EM fields. The data presented indicate, in part, a consistent increase in clonogenic capacity in cells exposed to E+M+ and to M+ fields. There is, however, variability in the magnitude of that response, which we do not find surprising. It is not yet known what determines the sensitivity of a target cell to EM field radiation. Such variables as the state of the cell, the cell type, and the orientation of the cell in the EM field are among the factors recognized as potential contributors to response variability; they are being investigated in various laboratories (Pereira et al., 1967, Delgado et al., 1982; Toroptsev and Taranov, 1982).

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CENTRAL NEURAL REGULATION IN RATS EXPOSED TO 60-Hz ELECTRIC FIELDS

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ABSTRACT

Male Long-Evans rats were evaluated for an early stress response (corticosterone increase) after exposure to an 80-kV/m, 60-Hz electric field. Blood samples were collected for a 1-hr period (1200 to 1300) at 14-sec intervals, via a carotid-implanted cannula. Additional rats were subjected to sham or electric-field exposure, followed by field- or sham-exposure conditions, respectively. These treatments occurred between 1200 and 1600 hr at 72-hr intervals to assess the cumulative effect of protracted 80-kV/m exposure. No statistically significant ($P > 0.05$) differences in corticosterone levels were noted in rats subjected to 14-sec blood sampling for 1 hr when exposed to 80 kV/m. Attenuation of the corticosterone response, the relaxed attitude of the rat, and little or no change in prolactin during protracted (4-hr) 80-kV/m exposure suggest that endogenous opiates may participate in the response of rats to electric-field exposure. Further studies of the opiocortin system and ACTH in concert with other hormones should elucidate the mechanism and physiologic implications for the response to various intensities of electric-field exposure.

To maintain homeostasis, mammals possess control mechanisms that react to changes in the internal and external environments. Among these controllers are the interacting neural and endocrine systems, which are among the prime physiological regulators of the body. Subtle influences of electric fields may be expressed by perturbations or adjustments of these coordinating systems. It is quite possible that reported effects of electric-field exposure could be a manifestation of peripheral stimulation, reflected by neuroendocrine/behavioral reactions.

Interacting with these neuroendocrine/behavioral reactions are the endorphin systems in the brain which play a role in the global defensive response to stress. Endorphins may act as hormone-releasing or -inhibiting factors. Stressors known to activate the pituitary-adrenal axis decrease anterior pituitary endorphin and trigger a parallel increase in plasma endorphin and ACTH levels.

It is assumed that if electric fields influence hormone production or utilization, this influence would be manifested early after onset of exposure and could be evanescent rather than protracted or sustained. Experiments have been designed, therefore, to determine if exposure of rats to 60-Hz electric fields influences corticosterone and prolactin levels. Emphasis is on engineering and biological quality control, such as appropriate dosimetry and animal conditioning, with consideration of hormonal circadian rhythms and imposition of minimal stress factors.

MATERIALS AND METHODS

Male Long-Evans rats (Blue Spruce Farms, Inc., Altamont, NY) were used in these experiments. The rats were received at 12 wk of age (300-350 g), maintained at 25 ± 2°C in animal quarters during acclimation to a daily 0600:1800 light: dark cycle, and allowed access to food and water *ad lib.* Prior to being placed on experiment, the rats were conditioned by recording daily colonic temperatures and body mass for 2 wk.

The rats were exposed to a 60-Hz electric field at 80 kV/m on 1 X 1-m aluminum plates with a spacing of 0.5 m between electrodes. Four acrylic plastic posts were used to secure the plates. A corona shield was provided by the addition of 7.6-cm-diameter aluminum tubing welded to the perimeter of each plate. Animals were exposed to the electric field in 20.3-cm^2 X 10.2-cm-high cage modules constructed of polycarbonate (Lexan, General Electric Company). Each module housed one rat during exposure, thus preventing any unacceptable crowding conditions, minimizing animal-to-animal interactions, and field perturbation. Animals were in contact with the reference ground electrode.

Decapitation, the usual method of sampling neuroendocrine endpoints in rats, subjects the animal to handling stress which could influence physiological and, especially, neural responses. We have therefore devised a procedure for serially sampling rat blood without the animal's awareness of our presence. We employ a carotid cannulation technique which permits us to sample the rat's blood through an indwelling carotid artery cannula without disturbing the animal, thereby following the hormone levels throughout exposure and during the postexposure period. This technique permits us to determine whether electric-field exposure affects interhormone relationships without imposing exogenous or endogenous stresses. We can also modulate the neuroendocrine and opiocortin system with drugs such as naloxone without disturbing the rat.

Radioimmunoassay and radiochemical techniques were utilized to examine neuroendocrine stability in the presence of the electric field.

After 1 wk of suitable environmental acclimatization and adjustment to handling, and postsurgical stabilization, 350- to 375-g male rats with carotid cannulae implanted were stabilized for 3 hr. For evaluation of early stress response, rats were subjected to rapid blood sampling, at 14-sec intervals, from 1 min before field onset to 2 min after field onset. Additional blood samples were collected during the 1-hr period (1200-1300) at 5 to 7, 30 to 31, and 59 to 60 min of electric-field exposure.

For cumulative effects assessment, rats were alternately subjected to sham (S) or field exposure (E) or to field then sham conditions for 2-hr periods (1200 to 1400 and 1400 to 1600) at 72-hr intervals. Thus, each rat served as its own control, as well as being compared to a concurrently unexposed animal. At prescribed times before, during, and after exposure, blood samples were obtained for radioassay of corticosterone and prolactin.

Statistical Analysis

Because rat hormone data are non-normally distributed, with unequal variances, a log transformation was used to normalize all data for statistical treatment by analysis of variance. Student's *t*-test was used where possible.

RESULTS

Figure 1 shows the results of the 14-sec rapid sampling (1-hr) study. No statistically significant differences ($P < 0.05$) in corticosterone levels were noted as a result of field onset or between field-exposed and sham-exposed rats. Figures 2 and 3 show the corticosterone response of rats alternately subjected to field and/or sham conditions at 72-hr intervals. The mean corticosterone response for sham-exposed rats placed in the chamber the first time (Figure 2) increased from 18.3 ± 9.0 μg/dL at 1200 hr to 51.7 ± 6.3 μg/dL at 1430 hr (Table 1). A smaller increase (Table 1) in corticosterone was observed between 1300 and 1430 hr, when the animals were sham-exposed for the second time. These results contrast with the smaller increase in corticosterone observed in rats exposed twice to 80 kV/m (Table 1; Figure 2). A statistically significant difference ($P < 0.01$) in corticosterone levels was evident when comparing first-time sham-exposed with first-time exposed rats at 1430 hr; this way also true ($P < 0.05$) at 1600 to 1700 hr (Table 1). The corticosterone response of sham-exposed rats 72 hr prior to exposure (Figure 3) was essentially similar to that of the sham-sham (Figure 2) group from 1300 to 1430 hr. The corticosterone response of these rats when exposed was comparable to that of rats exposed twice. A statistically significant decrease ($P < 0.01$) was noted between first-time sham-exposed and second-time exposed rats at 1300 hr only. Corticosterone results were variable in the rats exposed first to the field and, 72 hr later, to sham conditions (Figure 3).

The prolactin response for rats alternately subjected to sham and field exposure or field and sham conditions at 72-hr intervals was quite similar during all exposure conditions (Figures 4 and 5).

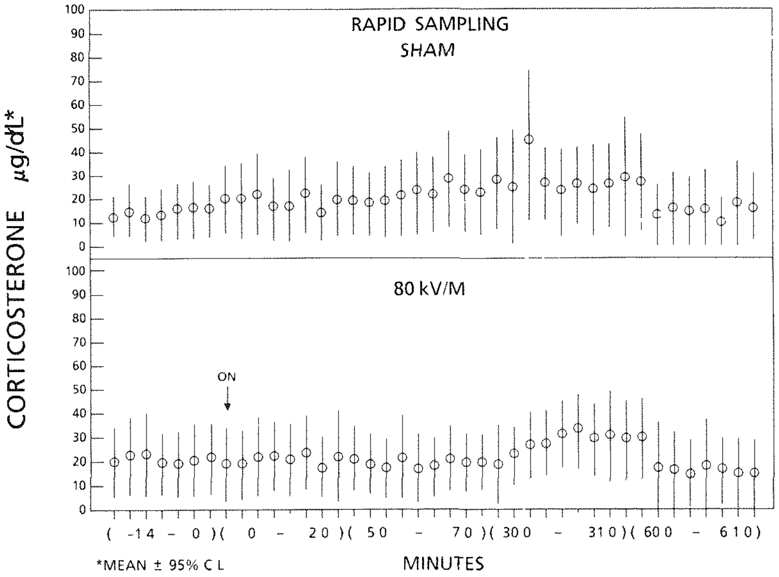

Figure 1. Corticosterone Response in Cannulated Rats Sham-Exposed or Exposed to an 80-kV Electric Field and Sampled for 1 Hr (1200 to 1300; Rapid Blood Sampling). Upper panel, sham exposure; lower panel, 80-kV/m exposure. Data are shown as means ± 95% confidence limits.

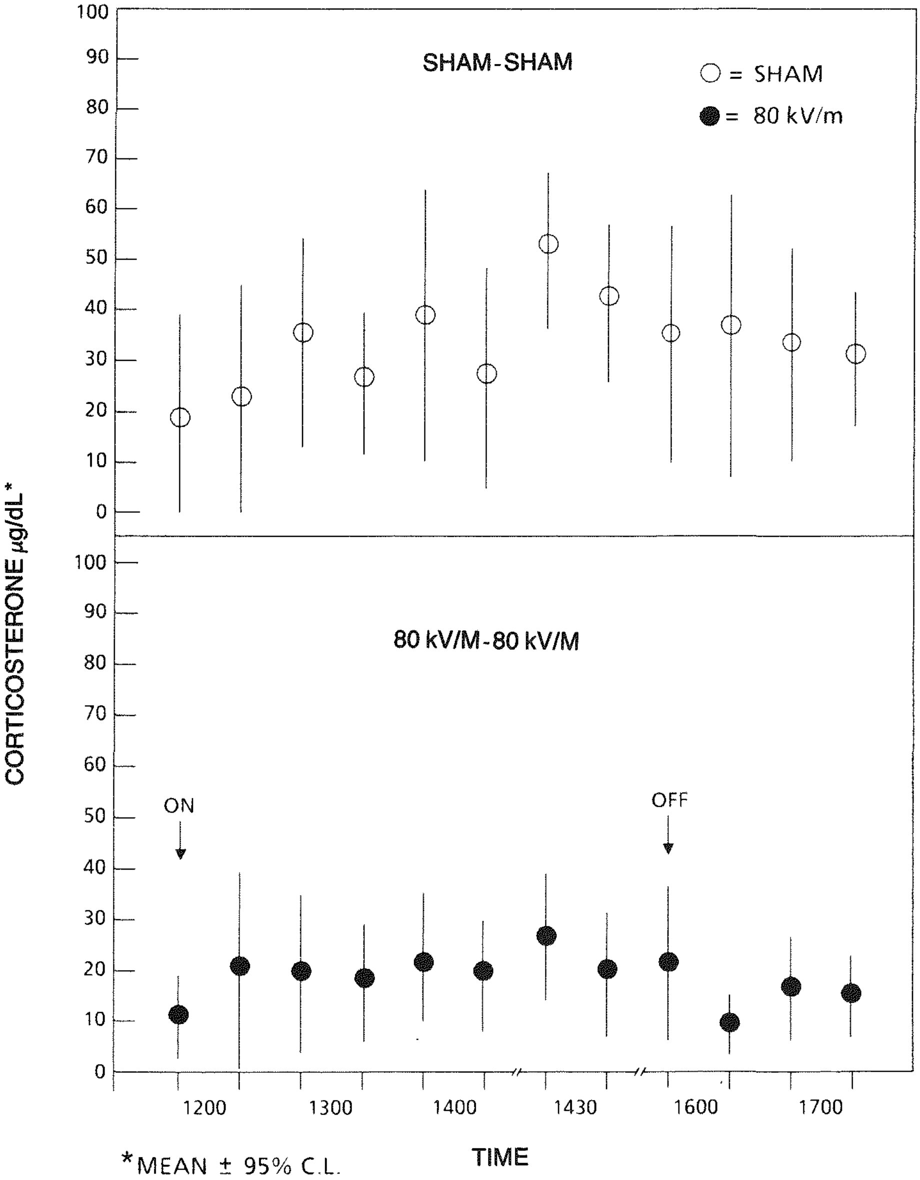

Figure 2. Corticosterone Response in Cannulated Rats Alternately Sham-Exposed and Exposed to an Electric Field at 72-hr Intervals. Upper Panel, first exposure = Sham (o); second exposure = Sham (o). Lower Panel, first exposure = Electric field (●); second exposure = electric field (●). Data are shown as means ± 95% confidence limits.

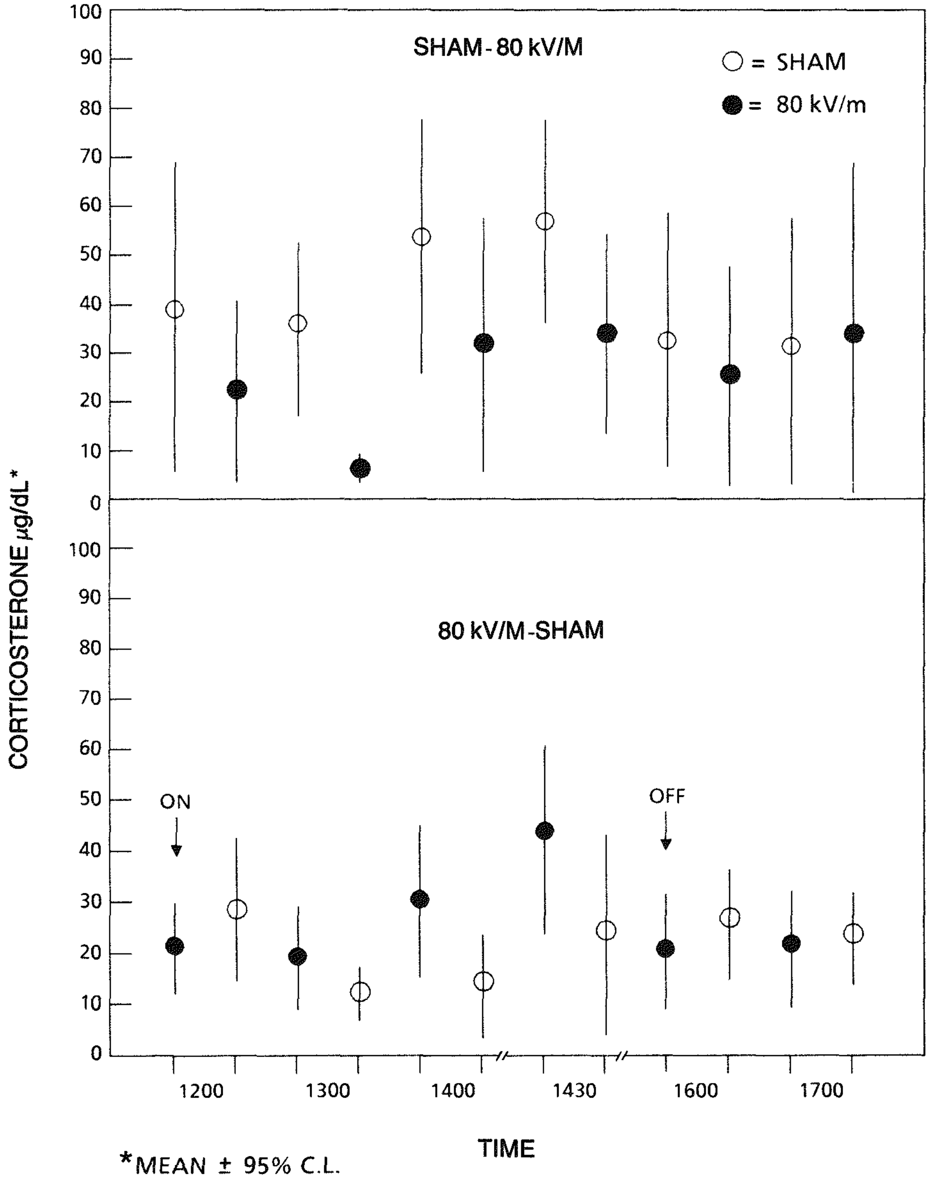

Figure 3. Corticosterone Response in Cannulated Rats Alternately Sham-Exposed and Exposed to an Electric Field at 72-hr Intervals. Upper Panel, first exposure = Sham (o); second exposure = electric field (●); Lower Panel, first exposure = electric field (●); second exposure = Sham (o). Data are shown as means ± 95% confidence limits.

TABLE 1. Corticosterone Response of Cannulated Rats to 80-kV/m, 60-Hz, Electric-Field Exposure (Mean ± Standard Error of the Mean)

		Time of Day (hr)											
Exposure Order		1200		1300		1400		1500		1600		1700	
(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Sham	Sham	18.3	22.0	33.8	25.8	36.9	27.1	51.7[b]	41.7	33.5[a]	35.3	31.4[a]	30.5
		(9.0)	(9.4)	(8.9)	(6.0)	(11.4)	(9.4)	(6.3)	(6.8)	(9.6)	(10.9)	(8.1)	(4.8)
80 kV/m	80 kV/m	11.4	20.5	19.8	18.1	23.0	19.3	27.2[b]	19.9	21.9	9.9	17.0[a]	15.2
		(3.7)	(8.7)	(6.9)	(5.3)	(5.6)	(5.0)	(5.6)	(5.4)	(6.9)	(2.6)	(4.6)	(3.6)
Sham	80 kV/m	37.1	21.8	35.0[a]	6.8[a]	52.2	32.0	56.9	34.2	33.2	25.6	31.1	33.0
		(12.0)	(7.1)	(6.9)	(1.0)	(10.6)	(10.0)	(8.6)	(7.9)	(10.6)	(8.1)	(10.5)	(12.8)
80 kV/m	Sham	21.2	29.1	19.5	12.7	30.0	13.9	42.6	23.8	20.4	26.0	20.9	23.2
		(4.1)	(6.6)	(4.7)	(2.6)	(6.7)	(4.5)	(8.1)	(8.2)	(5.2)	(5.0)	(5.2)	(4.1)

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[a] = $P < 0.05$
[b] = $P < 0.01$
(1) = First time
(2) = Second time

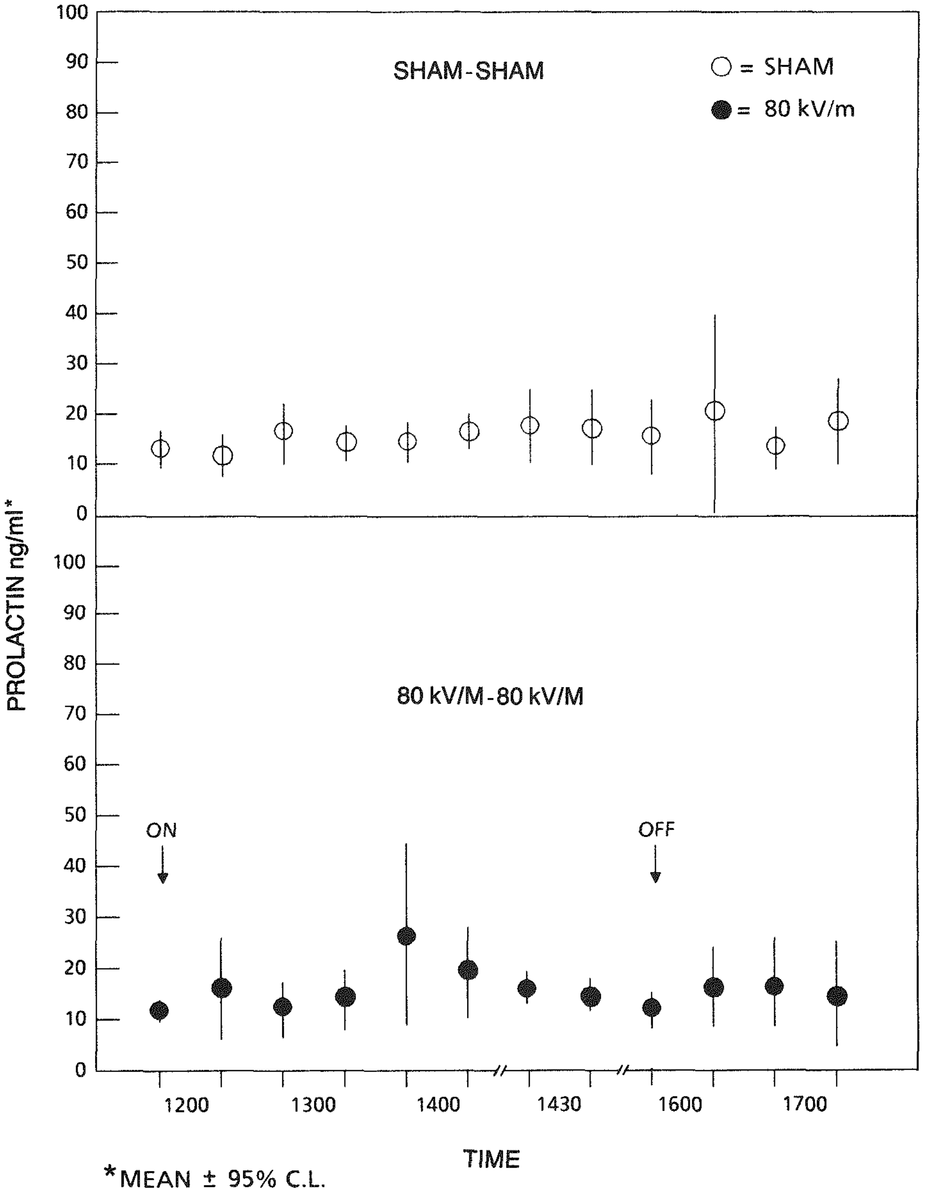

Figure 4. Prolactin Response in Cannulated Rats Alternately Sham-Exposed and Exposed to an Electric Field at 72-hr Intervals. Upper Panel, First exposure = Sham (o); second exposure = Sham (o). Lower Panel, First exposure = electric field (●); second exposure = electric field (●). Data are shown as means ± 95% confidence limits.

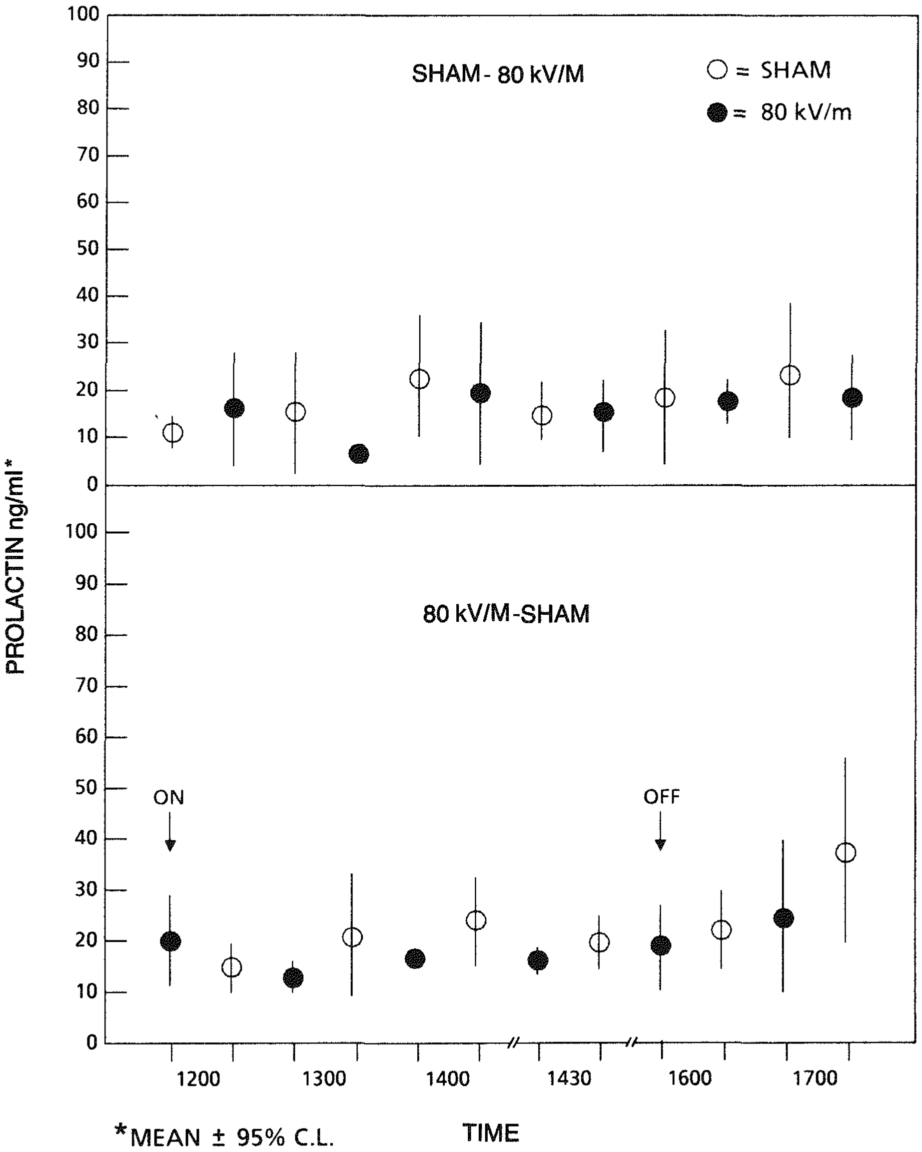

Figure 5. Prolactin Response in Cannulated Rats Alternately Sham-Exposed or Exposed to an Electric Field at 72-hr Intervals. Upper Panel, first exposure, Sham (o); second exposure = electric field (●). Lower Panel, first exposure = electric field (●); second exposure = Sham (o). Data are shown as means ± 95% confidence limits.

DISCUSSION

Our studies indicate that a rat can maintain endocrine balance while in an 80-kV/m electric field. The results of the rapid sampling did not reveal any change in corticosterone levels during 1 hr of exposure. We suggest that the lack of a transient corticosterone increase or alerting response immediately after electric-field onset, as seen by other investigators (Hackman and Graves, 1981, Rosenberg et al , 1983), is a function of our method of blood sampling, carotid cannulation. The rats in the referenced experiments may have responded to stimuli present prior to and during decapitation or the retro-orbital puncture procedure used for blood collection. Furthermore, the rats in our studies are equilibrated for 3 hr prior to field onset.

During the 4-hr exposures there was a tendency toward a lower corticosterone response on repeated exposure, although the prolactin level under the same conditions remained unaltered. This suggests an attempt on the part of the animal to accommodate or adjust to the exposure conditions whether or not it was exposed to the electric field. Lymphocyte changes, in a reciprocal relationship to the circadian corticosterone changes, were also evident

The relaxed attitude of the rat during exposure, attenuation of the corticosterone response, and little or no change in prolactin levels may reflect an attempt to maximize a desirable or minimize an undesirable stimulus by subtle endocrine adjustments, as shown by the altered circadian oscillation of corticosterone but not of prolactin. Such responses are consonant with the concept that endogenous b-endorphin may be modulating ACTH release, thus influencing the rat's response to the electric field. Recent studies (Govoni et al., 1984) in the human show a direct correlation between cortisol and beta- endorphins in stressed and unstressed subjects, suggesting a role for β- endorphins in the control of adrenal cortex metabolism. Yelvington et al. (1984) have reported that an increase in rat corticosterone level can act to attenuate the prolactin response to physical stress. The very relaxed nature of the rat during exposure, as evidenced by minimal activity and periodic sleeping during exposure and sequential blood sampling, further suggests the possible influence of endogenous opiates

Since we have central and peripheral ACTH and endorphin assays we plan a more definitive study of ACTH and endorphin interactions. We will use foot-shock stimulus to standardize the neuroendocrine response to a stressor. We hope that our future studies of the opiocortin system and ACTH in concert with other hormones will elucidate the mechanism and physiologic implications for the response to various intensities of electric-field exposures.

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EFFECTS OF EXPERIMENTAL EXPOSURE TO POWER-FREQUENCY ELECTROMAGNETIC FIELDS ON THE NERVOUS SYSTEM

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ABSTRACT

The nervous system is composed of complex, excitable cell systems, presumably affected by exposure to extremely low-frequency (ELF) electromagnetic fields. This statement is supported by results obtained both in vitro and in vivo by biochemical, pharmacological and behavioral studies. This report summarizes research performed during the last few years, using mainly light and electron microscopic methods. Further evidence will be presented, based on immunohistochemical and immunochemical techniques, that the long-term exposure of animals, i.e., rabbits, pigs, rats and mice, at moderate or high-intensity electromagnetic fields (50 or 60 Hz) results in reactive changes in nerve tissue. The animals were exposed either during their first 4 wk of life or from conception to 4 wk of age. The cerebellum was chosen for the study because of its very strict organization, with only a limited number of well-characterized cell types, enabling detection of even minute changes. Furthermore, its main development and differentiation takes place during the first postnatal month. The large Purkinje nerve cells in the cerebellum showed, to a variable degree,rearrangement of their Nissl bodies, i.e, profiles of endoplasmic reticulum, arranged in parallel. Concomitantly, there was a reduction in the number of hypolemmal (subsurface) cisterns. The most extensive alterations were noticed in rabbits exposed outdoors in a substation; rabbits, rats and mice exposed in a laboratory environment showed a lower frequency of lamellar bodies. Glial reactions, demonstrated ultrastructurally by quantitative immunohistochemical methods, using antibodies against the glial-cell marker protein S-100 and glial fibrillary acidic protein, showed an increased concentration of S-100 in the cerebellar hemispheres of rabbits that received long-term exposure to power-frequency electric fields. We conclude that the changes described are due to disturbances in the interaction between plasma membrane structures and the cytoskeletons of cells in the nervous system.

Evidence has been previously presented indicating significant biological effects on animals and humans exposed to extremely low frequency (ELF) electromagnetic fields (Sheppard and Eisenbud, 1977; Adey, 1981; Becker and Marino, 1982; Sheppard, 1983). In a previous report (Hansson, 1981) we demonstrated nerve-cell changes in the cerebellum as well as in other areas of brains from rabbits exposed to 50-Hz electromagnetic fields. These animals were exposed from conception and during the first weeks of their lives to 50-Hz electromagnetic fields (14 kV/m) in a substation.

The Purkinje nerve cells in the cerebellum were chosen for study because of their regular organization pattern, which is oriented perpendicularly to the brain surface and to the direction of the folia. The large dendrites arborize according to a strict pattern in the molecular layer, making thousands of synaptic connections with other nerve-cell processes. Furthermore, the Purkinje nerve cells are known to be highly sensitive to any type of external influence, either physical, chemical or inflammatory.

The nerve cells in the human cerebellum greatly outnumber those in the cerebral cortex (Palay and Chan-Palay, 1974), but the Purkinje nerve cells constitute less than one per thousand of the total number of nerve cells. The Purkinje nerve cells thus have the unique combination of being regular in their organization, relatively few in number and easily identifiable, and susceptible to a wide variety of external influences.

The aim of our studies was to examine, by light and electron microscopy, the nervous system (especially the cerebellum) for possible ELF electric-field effects. This report summarizes our results, obtained by analyses of nerve tissue from several species exposed under different conditions. Results obtained indicate that significant alterations may be induced in nerve cells, although to a highly variable degree.

EXPERIMENTS ON RABBITS

Rabbits were used in the initial experiments (Hansson, 1981), in which two different exposure systems were used. In one, rabbits were exposed outdoors, from conception to 3 mo of age, in a 400-kV substation. The animals were kept in plastic cages that had been demonstrated not to interfere with electric fields. A stainless steel sheet that formed the bottom of the cage was connected to the ground system in the substation. The cages were frequently rinsed with purified water to minimize contamination with organic and inorganic material. The animals were fed ad libitum with pelleted food, vegetables and water. The latter was provided via a system of plastic tubes placed on the stainless steel sheet.

Both Lop-Eared and Albino rabbits were continuously exposed to a 50-Hz electric field of approximately 14 kV/m, from conception (i.e., in utero) to the age of about 6 mo. Most days, exposure was for nearly 24 hr, interrupted only for animal care. At the same time, other rabbits were kept either in cages surrounded by grounded metal nets (Faraday cages) or outside the area of measurable electric field. At preselected time intervals, groups of at least five exposed and five control rabbits were killed, and tissues were fixed by transcardial perfusion with buffered glutaraldehyde or formaldehyde.

The second exposure system used was in a laboratory with a controlled environment. The exposure cages, time schedules and the handling of animals were similar to those in the outdoor exposure system. The electric field was measured as 14 kV/m at 50 Hz. Exposure time was 23 hr per day, 7 days per week, for time periods ranging up to 8 mo, starting at conception. As in the outdoor situation, controls were either shielded from the field by Faraday cages or were unexposed rabbits.

The rabbits exposed outdoors from conception to 7.5 wk of age did not show the same weight gain as their corresponding controls or the unexposed animals (Hansson, 1981). However, no such difference could be demonstrated in the experimental series performed in the laboratory. It is possible that part of the difference in weight gain may be due to the fairly severe weather conditions prevailing in the substation. Tentatively, factors like the interaction of weather and a combination of electric and magnetic fields in the substation may have produced these results.

Light and electron microscopy of cerebellar tissues from exposed rabbits revealed changes in practically every Purkinje nerve cell examined (Figures 1a, b, c). The Nissl granules formed by clusters of granular endoplasmic reticulum arranged in parallel that were seen in control animals had almost vanished and were replaced by lamellar bodies. Such structures were in continuity with the endoplasmic reticulum, thereby reducing the surface area of endoplasmic reticulum exposed to the cytoplasmic matrix and available for metabolism. These changes extended into the dendrites. Furthermore, the microtubules, normally straight and regularly distributed throughout the dendrites of the Purkinje nerve cells, showed altered distribution and a reduction in number (Figures 1d, e). Filaments and, occasionally, membranous structures were observed in increased frequency.

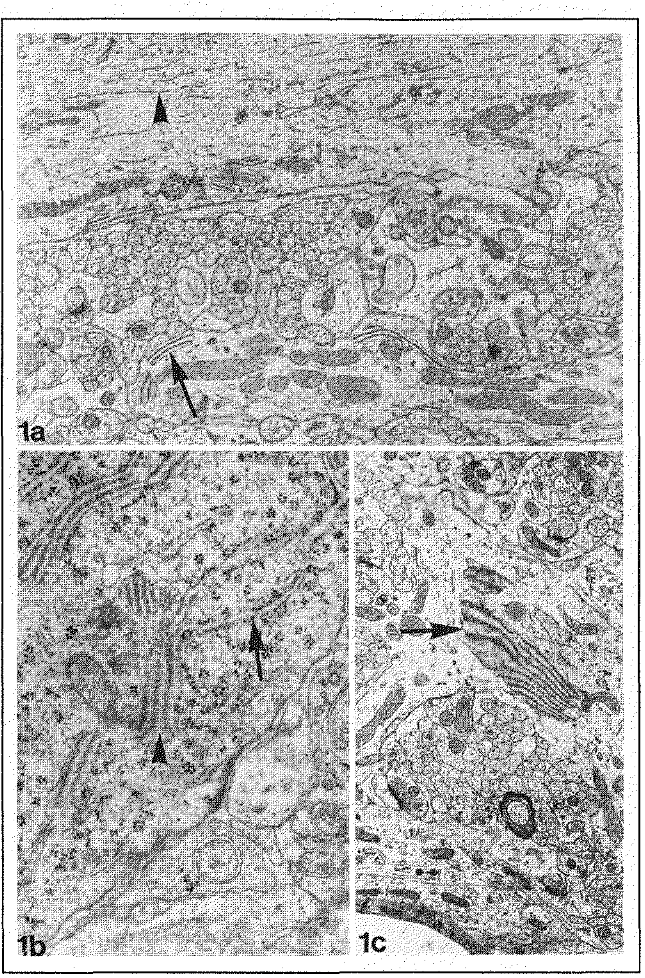

Figure 1. Electron Micrographs of Cerebellar Posterior Vermis from Rabbits Exposed in Utero and to 6 wk of Age to a 14-kV/m, 50-Hz Electric Field for 23 hr per Day. a) Several lamellar bodies (arrow) are seen. Note the paucity of cytoplasmic components in the Purkinje nerve cell dendrites, with their scattered irregular microtubules (arrow head). b) Purkinje nerve cell perikaryon with granular endoplasmic reticulum (arrow) in continuity with lamellar bodies (arrow head). c) Large lamellar body (arrow), sectioned obliquely, in a Purkinje nerve cell dendrite.

Figure 1 d) Higher magnification, showing two lamellar bodies (arrows), the one in the center is cut at an oblique angle Note the fuzz in the cytoplasm and the irregular microtubules (arrow head) e) Purkinje nerve cell dendrite with persistent hypolemmal cistern (hc), rarely seen in long-term-exposed rabbits, a lamellar body (arrow), and microtubules (arrow head)

The adjacent supporting glial cells were assessed at both light and electron microscopic levels and by an immunohistochemical procedure Antibodies to either the brain-specific protein S-100 or glial fibrillary acidic protein (GFA) were used. The normally slender processes were replaced by shorter, thicker, more irregular ones

Further, the nuclei of the glial cells could be stained with S-100 antibodies, which was never observed in the controls. There was also an increased number of large astrocytes in the granular layer. These glial cell changes were observed in rabbits that had received 4 or more weeks of exposure postnatally.

Immunochemical measurement of the amount of S-100 in lateral hemispheres of the cerebellum revealed significant increases in concentration (per total protein as well as per wet weight of tissue). Similar changes to those described above were also observed in the hippocampus and some other areas.

It is not likely that the lamellar bodies are results of artifacts due to improper fixation or mechanical damage. Control tissues were handled and fixed concurrently with exposed tissues. Proper fixation technique was used; i.e., glutaraldehyde solution was infused through the left ventricle at a pressure of 100 mm mercury, which is similar to normal pressure in the rabbit aorta. The validity of these observed field effects was further supported by the demonstration of reactive glial changes only in exposed animals. We therefore concluded that the cerebellar tissue of rabbits is sensitive to electromagnetic-field exposure.

RAT EXPERIMENTS

Albino rats of both sexes were exposed to electric fields (60 or 50 Hz, 14 kV/m, for 22 to 23 hr per day) in order to repeat the experiments in an animal system different from that previously used, i.e., rabbits. Dams and offspring were exposed from conception to 4 wk of age. Exposed and control animals were then killed, and tissues were prepared for light and electron microscopy and immunohistochemical examination.

Electron microscopic analyses of the cerebellar tissue from exposed animals (Figures 2a, b, c) revealed that, in several of the animals, most of the Purkinje nerve cells showed no lamellar bodies. However, in other animals, lamellar bodies were present both in the Purkinje cell dendrites and in the cell bodies. Microtubular changes were also evident in exposed animals; i.e., microtubules appeared irregular to an extent not observed in controls.

Immunohistochemical analyses confirmed that glial reactions had occurred in exposed animals. The Bergmann glial cells, with their radiating lamellar processes, similar to those in the exposed rabbits, appeared hypertrophic. Hypertrophic astrocytes were also observed in the inner granular layer from exposed rats.

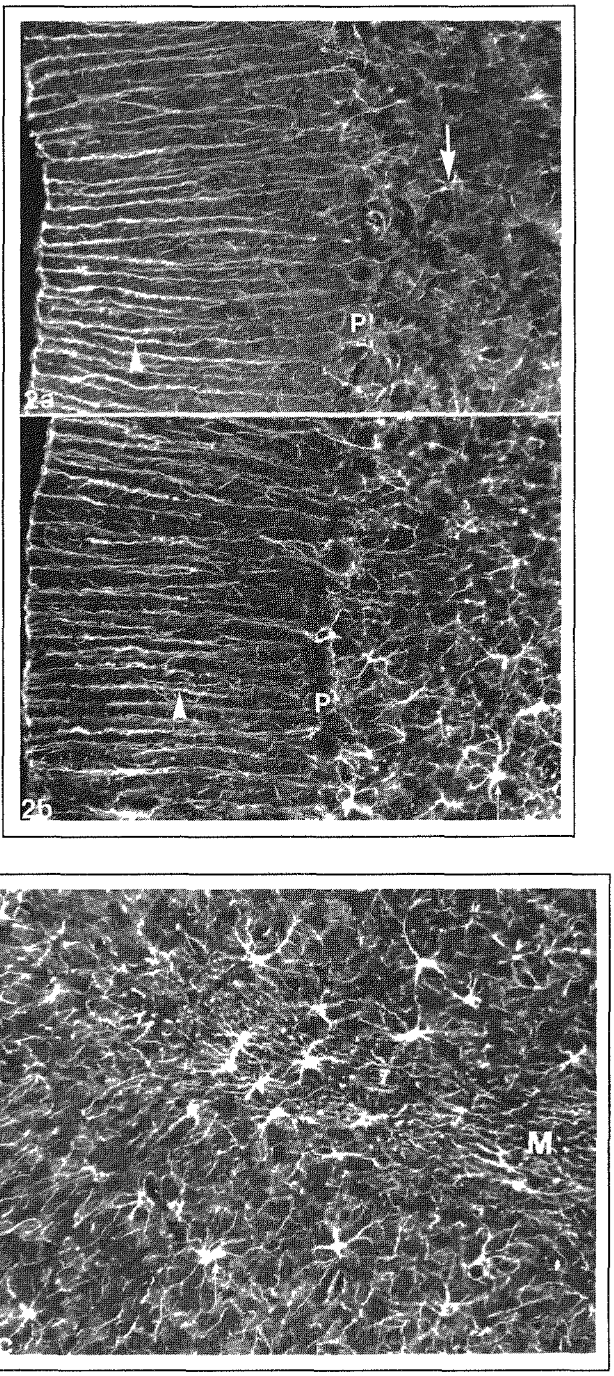

Figure 2. Lateral Hemisphere of Rat Cerebellum after Exposure (Figure 2b), from Birth to 4 wk of Age, to a 60-Hz, 14-kV/m Electric Field. Age-matched control in Figure 2a. Sections stained for demonstration of neuroglial cells (arrows) containing gliofibrillary acidic protein in their cytoplasm. Note the increase in staining (Figure 2b) after long-term exposure. c) The most conspicuous increase in number of GFA-containing neuroglial cells, i.e., astrocytes, was observed at the top of the medulla (M) in the centre of the folia.

MICE EXPERIMENTS

Albino mice were exposed to 60-Hz electric fields (about 10 kV/m) from birth to the age of 4 wk. Weight gain and behavior were recorded and analyzed for possible differences compared with those of controls. At preselected time periods, exposed and control animals were killed. Tissues were fixed by transcardial perfusion with buffered glutaraldehyde and further processed for light and electron microscopic examination.

With rare exceptions, only very few lamellar bodies or related structures were observed in Purkinje nerve cells. Specimens from other parts of the brain also contained few lamellar bodies. Microtubular changes as well as an accumulation of filaments were observed in exposed animals.

Immunohistochemical analyses of the distribution of S-100 protein showed it to be a good marker for reactive glial cell changes in the cerebellum. Glial cells from exposed mice were greater in number and size when compared to those of unexposed controls. Additionally, there were conspicuous changes in the distribution of immunoreactivity in exposed cells. Because astrocytes in the granular layer showed little activity, no further studies were performed on that material. Quantification of data is in progress.

ANALYSES OF PIG BRAIN STRUCTURES

Minipigs exposed for almost a year and a half to electric fields (60 Hz, 30 kV/m, 20 hr per day; and their controls) were killed, and brain tissue was fixed in formaldehyde by immersion. The cytoplasm of the Purkinje nerve cells did not differ from that of controls at the light microscopic level. Ultrastructurally, severe disorganization of the cells was observed, which we interpreted as the result of examination and handling procedures used. However, the distribution of the S-100 protein as well as that of the GFA (analyzed by immunohistochemical techniques) suggested glial cell reactions similar to those observed in other exposed species, as described above. Quantitative measurements of glial cell changes, i.e., hypertrophy and/or hyperplasia, are in progress.

CONCLUSIONS AND DISCUSSION

The most consistent finding in the long-term-exposed animals was the occurrence of reactive glial cell changes as reflected by immunohistochemical demonstration using anti-S-100 and anti-GFA. It appeared that there was an increase in number of glial cells and, as judged by the altered shape of the radiating glial cell lamellar bodies, hypertrophic changes as well. Furthermore, reactive glial cells contained GFA to an increased extent; this was observed mainly in the granular layer. These results were further supported by immunochemical quantitative analyses of the S-100 content in cerebellar hemispheres of rabbits exposed outdoors in a 400-kV substation. However, no significant alteration was obvious in the hippocampus of these rabbits. We interpret the results as supporting a working hypothesis that the cerebellar nerve cells are suitable indicators of the effect on the nervous system of exposure for long time periods to power-frequency electric fields. With rare exceptions, the hypolemmal cisterns which, under normal conditions, are studded along the Purkinje cell dendrites, had vanished in the exposed animals. Continuity could be observed between the endoplasmic reticulum and both the hypolemmal cisterns and the lamellar bodies. We therefore believe that the endoplasmic reticulum had assumed an abnormal configuration. It is likely that important functional abilities of the endoplasmic reticulum have changed with this reorganization. Furthermore, ribosomes could be associated only with a reduced area of the endoplasmic reticulum, which may influence metabolic activities in the lamellar bodies. The functional importance of the hypolemmal cisterns is not known. In contrast to tissues from controls, Nissl bodies were rarely observed in the branching area of the main dendrites in exposed animals. It is tempting to propose that the structural changes in the nerve cells are related to cytoskeletal alterations. Quantitative studies, when available, will allow further conclusions regarding possible mechanisms which might have caused the reorganization of the endoplasmic reticulum, the disturbance of microtubular structure and the appearance of filaments.

Recently, Albert and co-workers (Albert et al., 1984) reported the observation of some lamellar bodies in cerebellar Purkinje nerve cells in rats exposed to 60-Hz electric fields for several weeks. No lamellar bodies were observed in any of the controls. Similar structures (called pancakes) were recognized in pyramidal cells in the hippocampus. All these observations are identical to those observed in rabbit Purkinje nerve cells several years ago (Hansson, 1981). Portet et al. (1984), however, in a study aiming to replicate our above-mentioned rabbit experiments, were unable to observe lamellar bodies in the Purkinje nerve cells. No other obvious changes could be demonstrated in their animals, which were exposed in a laboratory, for 18 hr per day for 6 wk, to a 50-kV/m, 50-Hz electric field. Further studies appear to be necessary to elucidate the reason for these differences in the influence of ELF electromagnetic fields on the structure of nerve cells.

Lamellar bodies have previously been observed after improper fixation of nerve tissue (Herndon, 1963). Also, Hannah (1978) reported lamellar bodies in rat substantia gelatinosa after morphine treatment. Altman and Anderson (1973) published several micrographs of such structures in their study on X-ray- induced experimental reorganization of cerebellar cortex, as did Sotelo (1975) in a study on mutant mice (Weaver mice). Rohkamm (1977) also published micrographs of lamellar bodies in Purkinje nerve cells from rats treated postnatally with intracisternally injected actinomycin D, a drug known to inhibit protein synthesis. Similar structures have also been reported as a result of malnutrition (Chen and Hillman, 1980). Hypolemmal cisterns and Nissl bodies are normal constituents of Purkinje nerve cells, but their absence or reorganization into lamellar bodies is abnormal (Palay and Chen-Palay, 1974; Larsell and Jansen, 1972; Altman, 1972).

It may be concluded that long-term exposure to power-frequency electric fields induces effects on the nervous system of exposed animals. Our initial observation (Hansson, 1981) has, to a certain extent, been confirmed. The variability in the appearance of lamellar bodies, the disappearance of hypolemmal systems, and other cell changes, are puzzling observations and further studies are necessary to elucidate mechanisms of action.

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MONITORING OF CIRCADIAN WAVEFORMS IN RODENTS EXPOSED TO HIGH-INTENSITY STATIC MAGNETIC FIELDS

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ABSTRACT

A system has been developed for the noninvasive monitoring of circadian variables in mice exposed to a 1.50 T (1 Tesla = 10^4 gauss) static magnetic field. The ambient light level, temperature and relative humidity within the exposure chamber are closely regulated, and physiological monitoring systems provide simultaneous measurements of seven circadian variables 1) climbing activity on a triangular bar, 2) migratory activity, 3) body mass, 4) respired carbon dioxide, 5) nutrient consumption, 6) urine excretion, and 7) fecal excretion. Data from the various transducers and environmental monitoring devices within the exposure system are recorded on magnetic tape at 5-min intervals throughout experiments of 50 to 60 days duration, and the circadian waveforms of behavioral and physiological parameters are analyzed by a modification of the cosiner method, using a high-speed computer. Exposure of adult female LAF-1 mice to a 1.50-T homogeneous field for 5 continuous days, or for 10 consecutive days with intermittent daily exposures on an 8-hr-on/16-hr-off cycle, has been found to produce no significant alterations in the circadian waveforms of behavioral or physiological parameters

The maintenance of normal circadian regulation is an important factor in assessing the response of living organisms to static and extremely low-frequency (ELF) magnetic fields. Although there is relatively little information on this subject, several reports in the literature suggest that weak magnetic fields may alter circadian variables. Bennett and Huguenin (1969) reported that diurnal variations in the geomagnetic field intensity may influence the light withdrawal response time of earthworms. A cancellation of the geomagnetic field by Helmholtz coils was found by Bliss and Hepner (1976) to alter the circadian activity pattern of birds when the normal light/dark cycle had been removed. Brown and Skow (1978) observed a modulation of the normal 24-hr circadian activity cycle in hamsters when a static magnetic field with a maximum intensity of 26 μT was applied in 26-hr cycles. Semm and his associates have reported that the electrical activity of rodent and avian pineal cells can be altered by artificial changes in the strength and direction of the local geomagnetic field (Semm, Schneider, and Vollrath, 1980, Semm et al., 1982, Semm, 1983). Welker et al. (1983) observed that the circadian variation in pineal melatonin content and serotonin-N-acetyltransferase activity was also modified by changes in the ambient magnetic field. Electrophysiological measurements by Raybourn (1983) indicate that circadian variations may exist in the sensitivity of turtle retinal cells to static magnetic fields at levels greater than 2 to 3 mT. A recent report by Kavaliers, Ossenkopp, and Hirst (1984) indicates that the nocturnal sensitivity of mice to morphine may be diminished when the subjects are exposed to a rotating magnetic field with an intensity ranging from 0.15 to 9.0 mT

As part of our program to assess the response of living organisms to high-intensity, static magnetic fields, a study of the influence of these fields on circadian variations in rodent behavioral and physiological parameters has been undertaken. In this report a description is given of an exposure chamber that was developed for parallel measurements of seven circadian variables in mice exposed to static fields up to 1.50 T. The environmental control systems within the exposure chamber, the noninvasive physiological and behavioral monitoring systems that are employed, and the data analysis procedures are described in detail. Data from an 8-wk experiment during which rodents were exposed either continuously for 5 days, or intermittently for 10 days, to a 1.50-T static field are also presented.

EXPOSURE SYSTEM AND EXPERIMENTAL METHODS

General Description

A block diagram and schematic drawing of the system developed for monitoring circadian variables in mice exposed to high-intensity static magnetic fields are presented in Figures 1 and 2. A population of 40 mice resided within a square aluminum exposure cage with a floor area of 0.37 m^2. The floor was constructed from cross-hatched aluminum bars with a 1-cm spacing, thereby allowing excreta to drop into a waste-collecting tray below the cage. The exposure chamber lay entirely within the uniform field region of a large-volume electromagnet. The air temperature, relative humidity (RH) and magnetic field intensity within the exposure chamber were continuously regulated and recorded.

The exposure chamber contained monitoring devices for the simultaneous measurement of seven circadian variables: (a) total body mass and migratory activity of the rodent population, determined from the loads registered on four strain gages that supported the corners of the exposure cage; (b) climbing activity, based on the loads registered on two strain gages that supported the ends of a triangular exercise bar; (c) respired carbon dioxide content of the effluent air, measured by an infrared analyzer; (d) rate of nutrient consumption, based on the volume of liquid diet intake; (e) rate of urine and feces excretion, based on a gravimetric analysis of the contents of a feces-collecting screen and urine reservoir, located below the cross-hatched aluminum floor of the exposure cage.

Environmental Controls

Regulation of ambient temperature at 22 ± 1°C and RH at 50 ± 10% was achieved by passing conditioned air from a plenum (Wedco, Silver Spring, MD) through the exposure chamber at a rate of approximately 10 air exchanges per hour. Regulation of the air temperature was achieved by a feedback control circuit which responded to a thermistor probe inserted in the air outlet port of the exposure chamber. Ambient temperature was continuously recorded by copper-constantan thermocouples inserted in the air inlet and outlet ports on the exposure chamber, and the RH was recorded in the outlet port by a Hygrocon probe (Phys-Chem Research Corp., New York).

Uniform lighting throughout the exposure chamber was provided by a light pipe that served as the roof of the lucite support frame. The light pipe consisted of a 1.27-cm-thick sheet of lucite, 1.07 m long and 0.61 m wide. The 0.37-m^2 area over the mouse exposure chamber was sand-blasted in order to diffuse the light. The source of white light was an array of 15 incandescent GE bulbs, each with 18-W output, mounted in an aluminum housing at the end of the light pipe that protruded beyond the magnet gap. In order to focus the light over the 0.37-m^2 sand-blasted surface, the remainder of the light pipe was coated with a layer of silver foil. Complete uniformity of the light intensity over the rodent exposure chamber was achieved by covering the sand-blasted surface of the light pipe with a countergradient filter, composed of a cellulose acetate sheet sprayed with India ink. By appropriate variation of the opacity across the surface of the filter, a uniform light intensity of 155 ± 6 candles/m^2 was obtained over the entire exposure chamber. The incandescent bulbs at the end of the light pipe were cooled by a continuous flow of air through the lamp housing and were protected by an overtemperature regulator. Light/dark cycles were regulated automatically by a timer circuit.

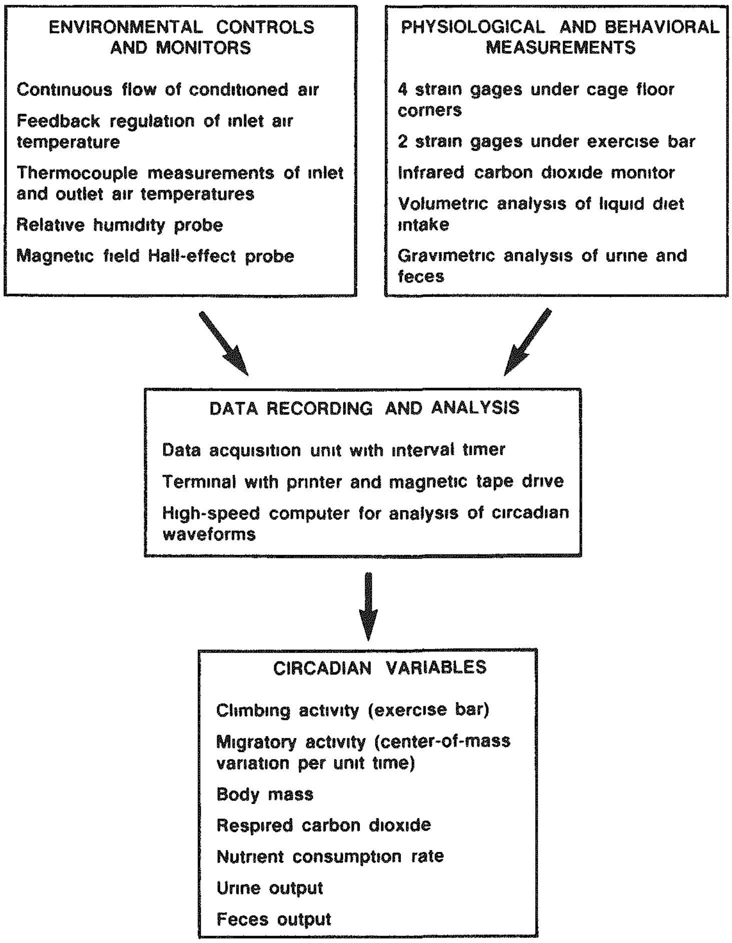


Figure 1. Block Diagram of Magnetic-Field Exposure System and Circadian Variables Measured by Noninvasive Techniques

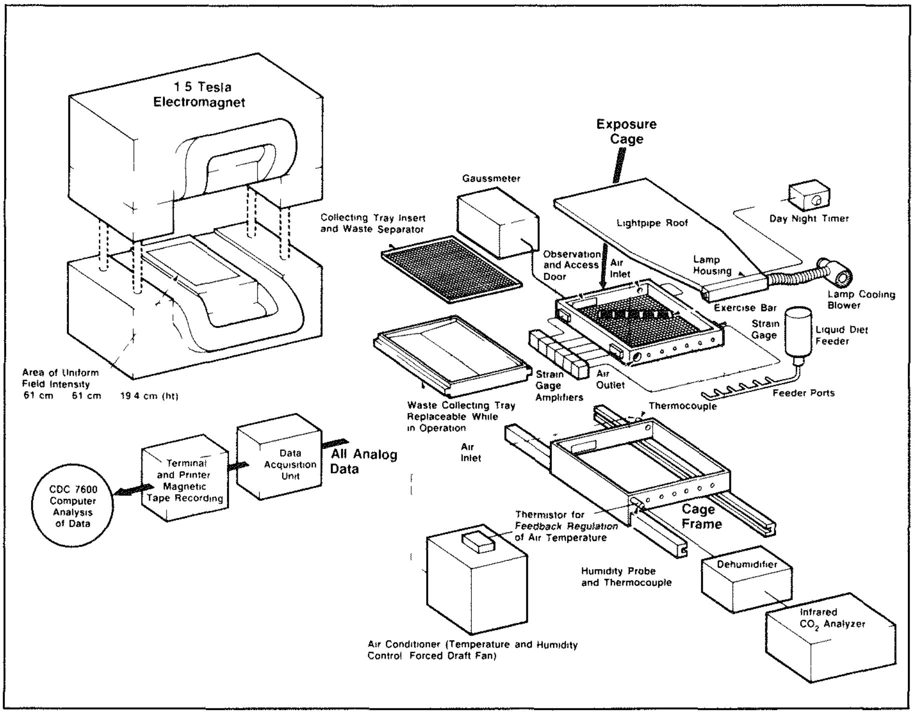


Figure 2. Schematic Drawing of Magnetic-Field Exposure System.

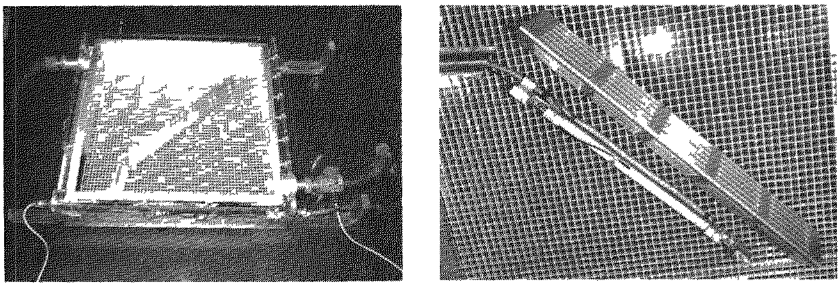
Physiological and Behavioral Monitoring Systems

Strain Gage Measurements. The floor of the exposure cage was supported at the corners by four strain-gage transducers that continuously monitored the variation in body mass and the center-of-mass coordinates of the rodent population. A triangular aluminum exercise bar was located along a diagonal line of the exposure cage, supported on each end by a strain-gage transducer. Photographs of the cage floor, exercise bar and strain-gage transducers are shown in Figure 3. The six strain gages were custom-made by NDT Consultants (Los Altos, CA), using nonmagnetic materials; their voltage outputs are a linear function of the applied load (1 μV/g from the cage-corner strain gages and 10 μV/g from the exercise-bar strain gages). The outputs of the strain gages were amplified by 10^3 in a bank of signal conditioners (2100 System, Vishay Instruments, Malvern, PA) located external to the exposure chamber.

The center-of-mass coordinates of 40 mice within the exposure chamber are illustrated in Figure 4. The data points represent the center-of-mass coordinates, calculated at 5-min intervals from the load applied to each of the four strain gages under the cage corners. These data demonstrate a preference of the rodents for one quadrant of the exposure cage, away from the air inlet port and the six liquid diet feeder ports. Based on a day-to-day analysis of the average center-of-mass coordinates, this preferential location of the rodent population has been shown to be unaffected by the application of a 1.50-T static magnetic field, either continuously for 5 days or intermittently for 10 days in an 8-hr-on/16-hr-off daily cycle. Figure 4 also demonstrates that, in a rodent population entrained on a diurnal light/dark cycle, the scatter of the center-of-mass coordinates as a function of time is much greater during the dark phase. This circadian migratory activity is closely correlated with other behavioral and physiological indices, as illustrated in a later section of this paper. Quantitation of the rate of animal migration was achieved by computing the lineal distance over which the center-of-mass coordinates moved during consecutive 5-min intervals.

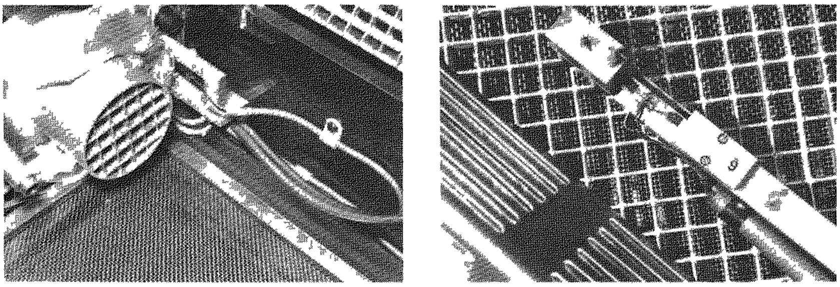
A) Exposure Cage and Support Frame

B) Triangular Exercise Bar Support Frame With Strain Gages and Hall Probe



C) Cage Corner Strain Gage

D) Exercise Bar Strain Gage



E) Urine Collecting Tray and Feces Separating Screen

F) Spring-loaded Nozzle Tip of Liquid Diet Feeder Line

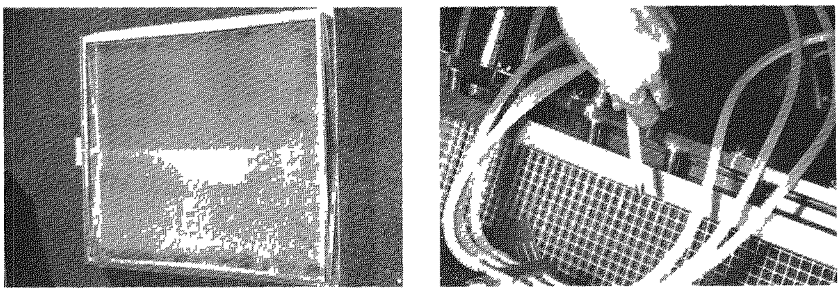


Figure 3. Photographs of Exposure Chamber (with Light-pipe Roof Removed) and Various Accessories Used for Physiological Monitoring

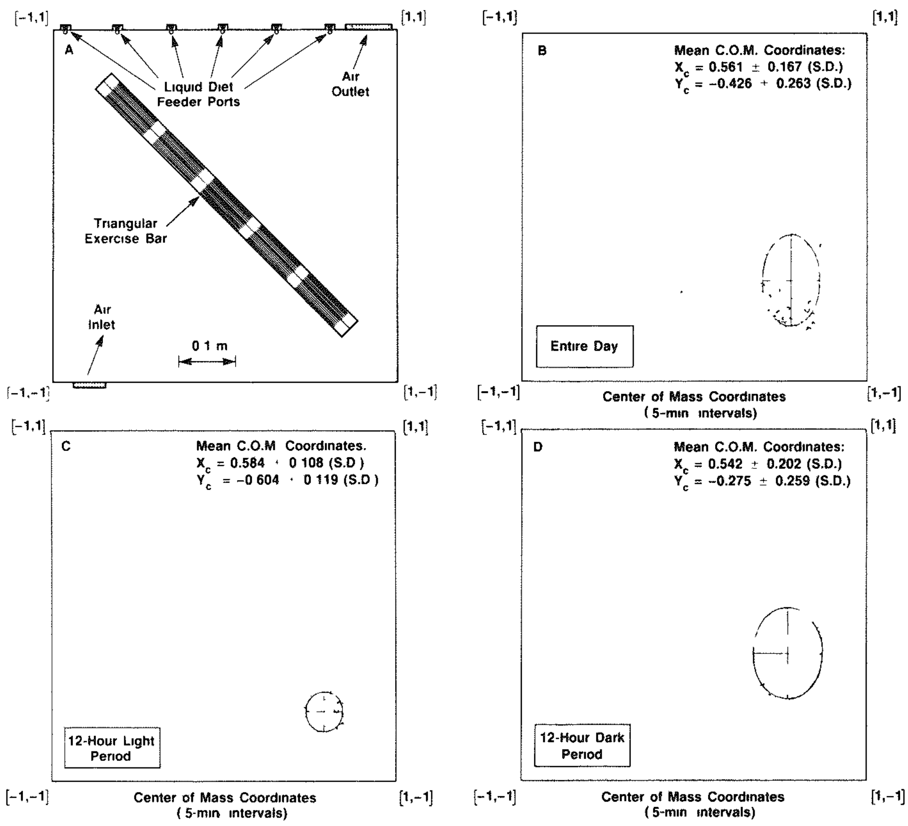


Figure 4. Center-of-Mass (COM) Coordinates Recorded at 5-min Intervals During an Entire Day and During the 12-hr Dark and Light Cycles. The center of the ellipse represents the average value of the center-of-mass coordinates (X_C, Y_C), and the semi-minor and semi-major axes represent one standard deviation of the mean values for the X_C and Y_C coordinates. The coordinates given at the four corners represent the actual dimensions of the exposure cage, expressed in feet.

Carbon Dioxide Analysis. Effluent air from the chamber was pulled by a small pump through a dehumidifier and into a LIRA infrared monitor (Mine Safety Appliances Co., Pittsburgh, PA) to measure carbon dioxide content. The voltage output of the infrared monitor, calibrated with standard carbon dioxide/nitrogen mixtures, had completely linear response characteristics for carbon dioxide concentrations up to 2%.

Quantitation of Excreta. Urine and feces were collected in a tray inserted along lucite guide rails beneath the cross-hatched floor of the rodent exposure cage. The waste-collecting tray consisted of a lucite trough overlaid by a screen made from nonmagnetic stainless steel with a 1.27-mm mesh diameter (Figure 3). The V-shaped trough had sides with a 7° downward slope that facilitated drainage of urine into a reservoir along the center line of the trough. The mesh of the stainless steel screen was sufficiently small to allow collection of fecal pellets with 100% efficiency. The excreta-collecting tray and waste-separating screen can be rapidly removed from beneath the exposure cage and replaced with an identical unit. After removal of the waste collector, the fecal pellets on the waste-separating screen were placed in a preweighed plastic envelope for the subsequent gravimetric measurement of excreted solids. The urine was collected by syringe and placed in preweighed glass vials for gravimetric analysis. The weight of collected urine was converted to units of volume, using a value for the specific gravity of 1.01 g/cc, which was determined by pycnometry of mouse urine samples. The volume of collected urine was corrected for evaporative loss, which varies as a function of RH within the exposure cage (50 ± 10%). Based on studies of the rate of water evaporation from the waste-collecting tray as a function of RH over the range 40 to 60%, empirical formulae have been derived by regression analysis to correct urine volumes for evaporative loss over 3-hr and 24-hr collection intervals. For the 3-hr intervals used in circadian waveform measurements, the percent evaporation is related to the percent RH by the formula ($r^2 = 0.98$):

$$\log_e(\%\ \text{evaporation}) = 9.803 - 1.667 \cdot \log_e(\%\ \text{RH}). \tag{1}$$

For 24-hr daily collection intervals, evaporative loss is described by the formula ($r^2 = 0.96$):

$$\log_e(\%\ \text{evaporation}) = 10.996 - 1.799 \cdot \log_e(\%\ \text{RH}). \tag{2}$$

The temperature within the exposure chamber is regulated at 22 ± 1°C, and no correction is required for evaporative urine loss as a function of temperature.

Following gravimetric analysis, 50 units/ml penicillin and 50 μg/ml streptomycin (Gibco, Grand Island, NY) were added to the collected urine samples, which were then stored at -20°C. Chemical analysis of selected urine samples was performed by The Pathology Institute (Berkeley, CA), using standard clinical procedures.

Quantitation of Nutrient Consumption. From preliminary studies with a conventional metabolic cage, it became apparent that the collected excreta could become significantly contaminated with fragments of the pelleted food supplied to the rodents from a hopper. In order to circumvent this problem, the nutritional and water requirements of the rodent population were met by providing them with ad libitum access to a complete liquid diet (Gibco, Grand Island, NY). The liquid diet was supplied to the exposure chamber from a 250-ml bottle and six lines of PVC tubing. Each tube was terminated by a spring-loaded nozzle to prevent dripping (Figure 3). Six brass guides positioned the nozzles along one wall of the exposure chamber. All of the components of the liquid-diet feeder assembly were autoclaved at the initiation of an experiment to ensure antiseptic conditions. The bottle that supplied the liquid diet was connected to the six PVC tubes via a manifold and a quick-disconnect valve. During the course of an experiment, the bottle was removed once a day for addition of new liquid diet; it was replaced by a freshly sterilized bottle at 2- to 3-day intervals. The consumption of liquid diet by the rodent population was recorded, using volumetric marks on the side of the supply bottle.

Data Acquisition and Recording. Analog outputs from the various physiological and environmental monitoring systems were monitored continuously and recorded at 5-min intervals on an Autodata Nine 100-channel data acquisition unit (Acurex, Mountain View, CA). The Autodata Nine unit was serially linked to a Silent 700 ASR terminal (Texas Instruments, Dallas, TX), which transferred data onto magnetic tape for subsequent analysis on a CDC 7600/6600 computer system (Control Data Corp., Minneapolis, MN).

Performance of Environmental Monitors and Transducer Systems

Prior to the initiation of each experiment, the performance of the physiological and environmental monitoring systems were evaluated for a period of several days as a test of accuracy and stability. The results of tests during a 24-hr monitoring interval are shown in Figure 5. Low-amplitude fluctuations were observed in both the temperature and RH within the exposure chamber, reflecting the feedback regulation of the temperature of the incoming air supplied from the plenum. The average carbon dioxide content of the air varied from 0.03 to 0.04%, with a mean value of 0.035%. The strain-gage transducers that supported the cage floor and the exercise bar exhibited excellent long-term stability, both in an unloaded state, as shown in Figure 5, and under loads applied by calibrated brass weights. Data recorded from the various environmental monitors were routinely fitted to a cosine curve (Figure 5) as a test for diurnal variations that might influence rodent behavior and other physiological indices. In general, the low-amplitude daily oscillations in temperature and RH were found to exhibit an irregular pattern that was not correlated with the circadian oscillations in rodent behavioral and physiological parameters.

Magnetic-Field Exposures

The exposure cage was placed within the gap of an iron-core dc electromagnet that achieved a maximum vertical field strength of 1.6 T. The flat, 73.7-cm x 82.6-cm magnet pole faces were aligned horizontally, with a vertical separation of 19.4 cm. The operating characteristics of this electromagnet have been described in previous publications (Tenforde et al., 1983; Davis et al., 1984). Based on measurements with a search coil and a transverse Hall-effect probe (F. W. Bell Co., Orlando, FL), the magnetic flux density was uniform to within 0.1% throughout the volume of the rodent exposure chamber. A continuous recording of the magnetic field strength during an experiment was made with a Hall probe located at the geometric center of the exposure cage. The probe was covered by the triangular exercise bar for protection against rodent molestation (Figure 3).

Circadian Waveforms and Computer Analysis Techniques

Circadian waveforms were characterized by a modification of the time-series analysis technique described by Halberg et al. (1972). Each of the several circadian variables under study was fitted by a least-squares technique to a function of the form:

$$Y(t) = Y_O + \tilde{Y} \cdot \cos(\omega t + \Phi), \tag{3}$$

where Y(t) is the value of the circadian variable at time t. Y_O, $\tilde{Y}$, ω and Φ are, respectively, the level, amplitude, angular frequency, and acrophase of the cosine function. The angular frequency is equal to 360° divided by the period of the oscillation. The acrophase represents the phase angle at which the cosine function reaches a maximum value. The acrophase can be expressed in clock hours by multiplying the phase angle by (24 hr/360°).

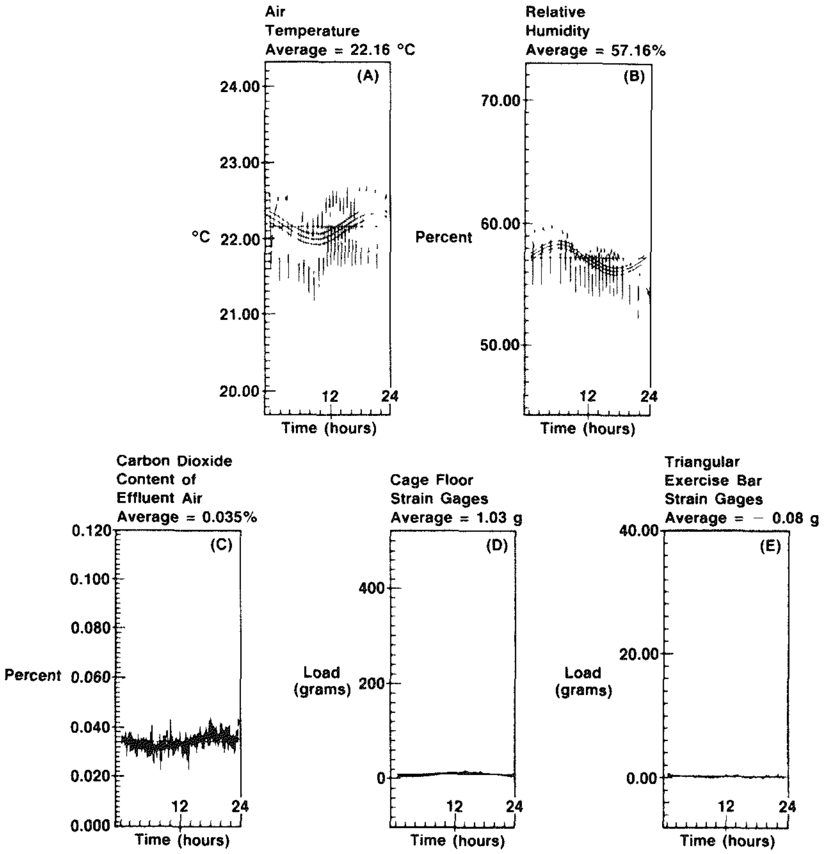


Figure 5. One Day of Data, Recorded at 5-min Intervals, is Shown for Various Environmental Monitors and Transducer Systems with no Experimental Subjects in the Exposure Chamber. The solid curves represent best-fit cosine curves and 95% confidence intervals. (See text for explanation.)

In the time-series analysis technique described by Halberg et al. (1972), the period is assigned a value of 24 hr, and a least-squares analysis technique is used to obtain the best-fit values of the remaining three variables. This technique cannot be used for the analysis of nonstationary circadian states in which the period varies during the course of an experiment. A computer code has therefore been developed in which the assigned period is incremented in 15-min steps from 10 to 40 hr, and the best-fit values for Y_0, $\tilde{Y}$ and Φ are determined by regression analysis at each value of the assigned period. The value of the assigned period that produces a minimum sum of squares of the residuals between the raw data and the fitted cosine curve is considered to be the true period of the circadian oscillation. The 95% confidence intervals of the best-fit amplitude and acrophase are calculated following the method described by Halberg et al. (1972).

Examples of circadian waveforms in respired carbon dioxide, body mass, climbing activity registered on the triangular exercise bar, and locomotor activity (determined from changes in the center-of-mass coordinates as a function of time) are shown for a 5-day interval in Figure 6. The population of 40 mice from which these data were obtained had been placed in a free-running circadian state by maintaining constant illumination within the exposure chamber. Under those conditions, the best-fit circadian periods are, typically, 25 to 26 hr. When entrained on a daily light/dark cycle, the best-fit periods of these circadian variables decreased to 24 ± 0.5 hr, as illustrated by data presented in a later section of this paper. Figure 7 shows circadian waveforms in liquid-diet consumption and excreta, measured over a 2-day interval for a group of 40 mice entrained on a 12-hr-light/12-hr-dark cycle. The circadian waveforms of these parameters, fitted to data recorded at consecutive 3-hr intervals throughout a 39-hr monitoring session, exhibited large-amplitude oscillations with periods close to 24 hr.

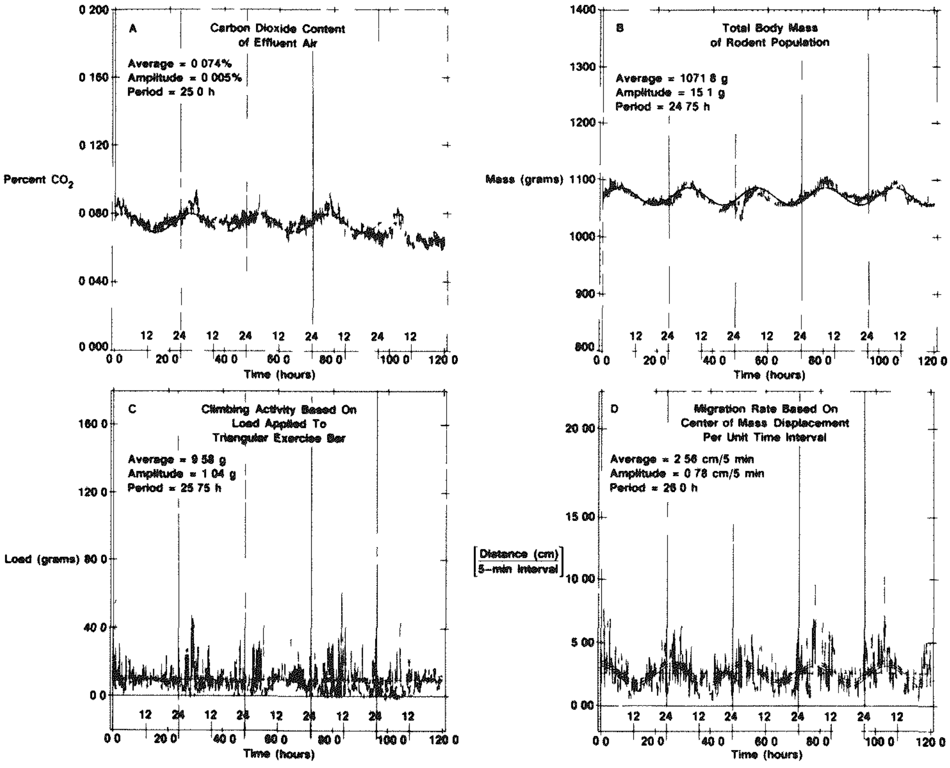


Figure 6. Circadian Waveforms of Respired Carbon Dioxide, Body Mass, Climbing Activity and Migratory Rate are Shown over 5 Serial Days for a Population of 40 LAF-1 Mice Maintained in a Free-Running Circadian State by Exposure to Constant Dim Illumination Within the Exposure Chamber.

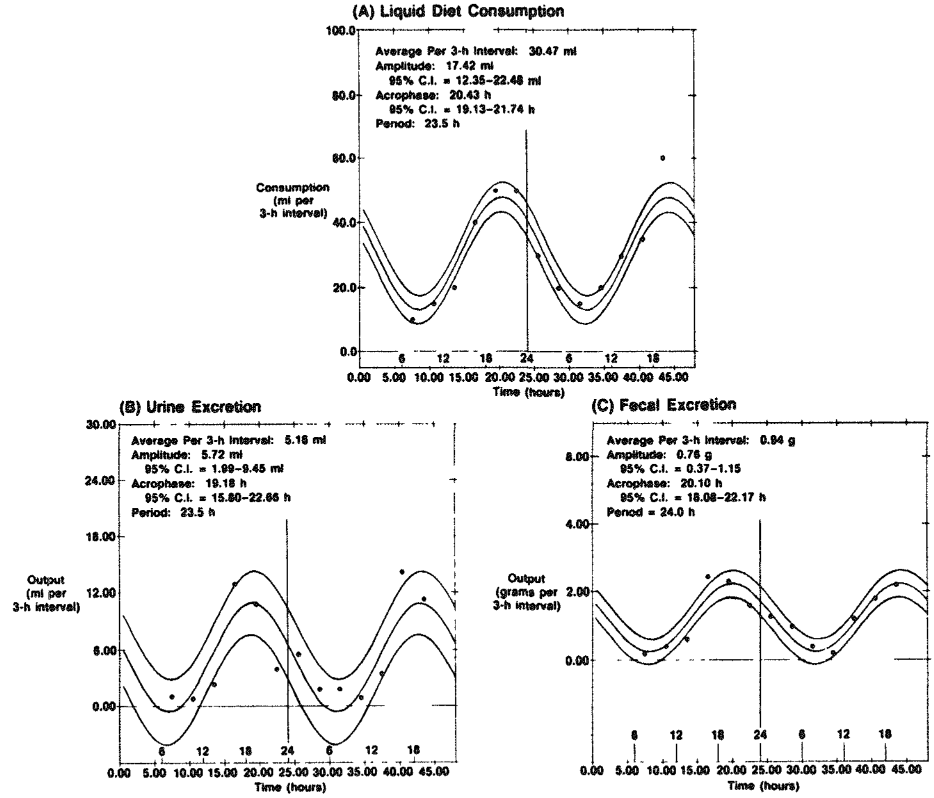


Figure 7. Circadian Waveforms in Liquid-Diet Consumption, Urine Excretion, and Fecal Excretion are Shown for a Population of 40 Female LAF-1 Mice Maintained on a 12-hr-Light/12-hr-Dark Cycle Within the Exposure Chamber.

RESULTS

Following completion of the exposure chamber, several pilot tests with durations up to 2 wk were carried out to analyze the long-term transducer performance and animal adaptation to the chamber environment. A series of three experiments, each of 2 mo duration, was then undertaken to assess behavioral and physiological variables in rodent populations exposed to a 1.50-T static magnetic field. The first two experiments were conducted with mice entrained on a 12-hr-light/12-hr-dark cycle, and the third was carried out with rodents maintained in a free-running circadian state by constant dim illumination. The first experiment will be described in detail as an illustration of the physiological and behavioral data obtained with the exposure system.

Experimental Design

Experimental subjects were female LAF-1 mice from the Jackson Laboratory (Bar Harbor, ME). The mice, 16 wk old at the initiation of the experiment, were entrained on a 12-hr-light/12-hr-dark cycle, with the light phase from 0600 to 1800 hr daily. Three separate groups of mice were randomly selected from the lot: (A) 40 mice were placed in the exposure chamber; (B) 10 mice were placed in a conventional plastic cage with a wire top and were fed liquid-diet nutrient ad libitum; (C) 10 mice were placed in a conventional plastic cage with a wire top and were fed pellet food and water ad libitum. The primary purpose of control groups (B) and (C) was to assess the influence, if any, of sustaining the experimental subjects with a liquid diet for a 2-mo period. The cages for groups (B) and (C) were placed in the magnet facility at a distance of approximately 0.6 m from one corner of the electromagnet. The stray magnetic field at the location of the control cages was 0.2 mT when the magnet was energized to a 1.50-T level.

Following an initial 3-day period in which the rodents acclimated to the exposure chamber environment, the baseline circadian parameters of the 40 experimental subjects were monitored for 8 days (designated as Control Period No. 1). The mice were then subjected continuously for 5 days to a 1.50-T static field, followed by an 18-day control monitoring period (Control Period No. 2) to assess the occurrence of any delayed effects subsequent to the magnetic-field exposure. The mice were next subjected for 10 consecutive days to an intermittently applied 1.50-T field in an 8-hr-on/16-hr-off daily cycle, followed by a 13-day control monitoring period (Control Period No. 3).

Measurements, at 5-min intervals, of respired carbon dioxide, body mass, climbing activity, and migratory activity were made continuously throughout the experiment by the automated techniques described above. Measurements of circadian variations in nutrient consumption, urine excretion and fecal excretion were made at consecutive 3-hr intervals over a 39-hr monitoring period in the latter half of each of the five segments of the experiment. In parallel with these measurements on the experimental rodent population, recordings were also made during each of the five 39-hr monitoring sessions of the rates of liquid diet, pellet food and water consumption by the two control rodent populations [groups (B) and (C)].

Circadian Variables in Exposed and Nonexposed Rodent Populations

The results of time-series analyses across the five segments of the experiment are shown in Figure 8 for the four continuously recorded circadian variables. Based on a nonparametric Wilcoxon U-test (van der Waerden, 1969), none of the four circadian parameters showed significant shifts at the $P < 0.05$ level when analyzed across consecutive segments of the experiment. One apparent exception was the change in body-mass circadian parameters between Control Period No. 1 and the 5-day magnetic field exposure that followed ($P = 0.015$). From a day-to-day analysis of the best-fit circadian parameters across these two segments of the experiment, it was evident that the change in body-mass data distribution was primarily associated with a rapid weight gain of 3.4% during the first 4 days of Control Period No. 1. When the second half (4 days) of Control Period No. 1 was compared with the subsequent 5-day magnetic-field-exposure period, the difference in body-mass data was not significant ($P > 0.25$). This result indicates that the change in body-mass circadian data was not associated with the magnetic-field exposure per se, but most likely reflected an adaptation to the liquid-diet nutrient. This conclusion is further supported by the finding, discussed below, of a significant increase in body mass over the same period of time by the mice in control group (B), which were also maintained on liquid-diet nutrient.

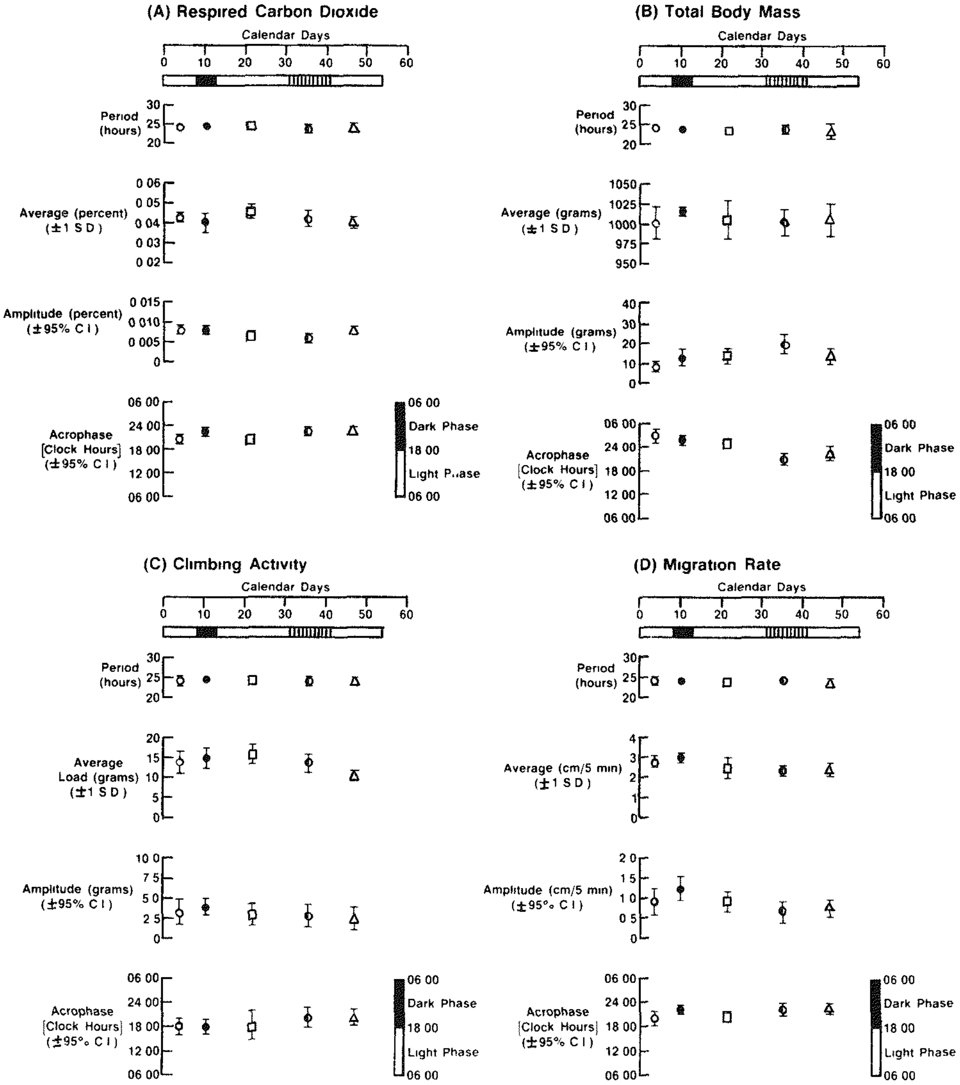


Figure 8. The Results of a Time-series Analysis of Four Circadian Variables are Shown During the Five Segments of an Experiment in Which Mice were Subjected to a 1.50-T Static Field Continuously for 5 Days and Intermittently, in Daily 8-hr-on/16-hr-off Cycles, for 10 Days. The average values of the respired carbon dioxide in the effluent air have been corrected for the ambient level (0.04%), determined from pre-experiment monitoring. ○ Control Period No. 1 (8 Days); ● Continuous B = 1.5 Tesla (5 Days); □ Control Period No. 2 (18 Days); ◐ B = 1.5 Tesla, 00:00-08:00 Daily (10 Days); Δ Control Period No. 3 (13 Days).

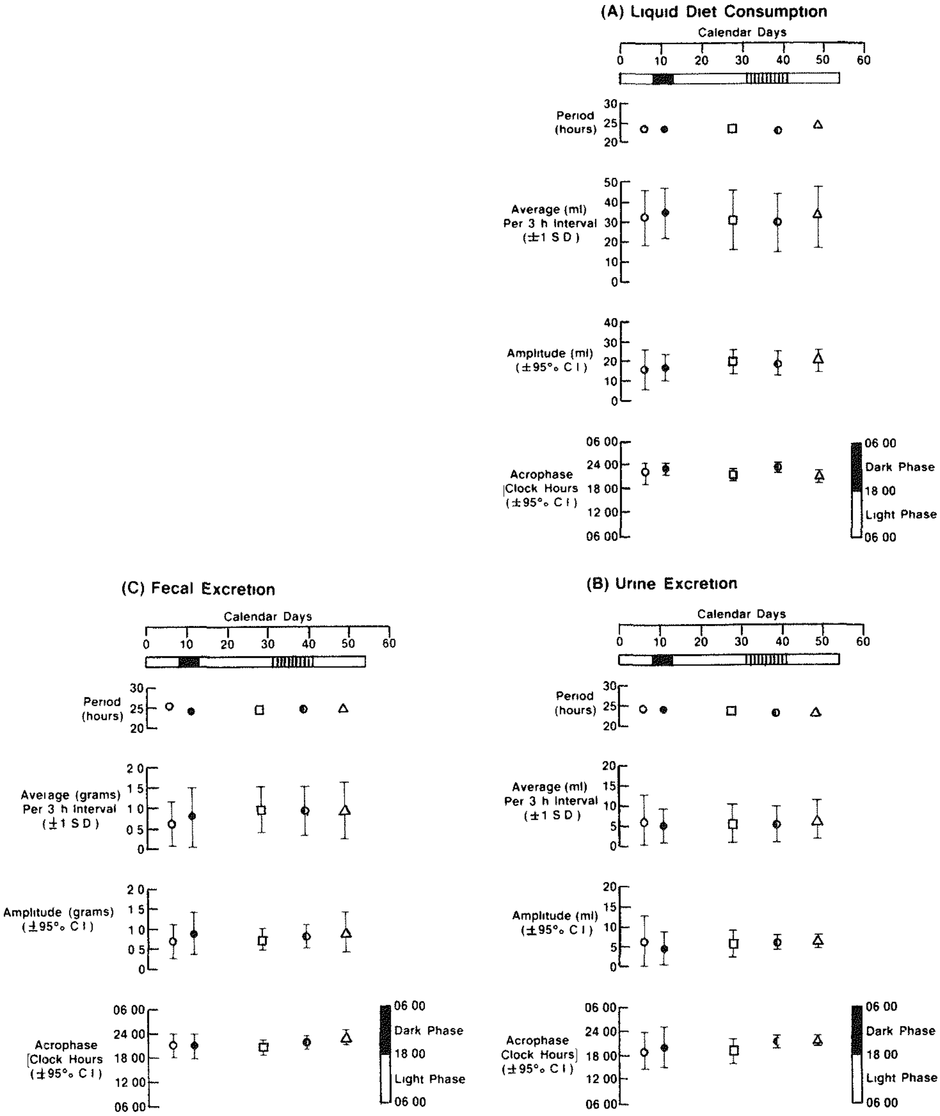
Circadian variables for nutrient consumption and excreta are shown in Figure 9. Based on a Wilcoxon nonparametric analysis of the data distributions between consecutive segments of the experiment, none of these three circadian parameters showed significant changes as a function of "field-on" versus "field-off" conditions. Measurements were also made of circadian variation in liquid-diet consumption by control group (B), and in pellet-food and water consumption by control group (C). None of these circadian variables showed significant changes at the level $P < 0.05$ during the course of the experiment.

In addition to measurements of nutrient consumption and excreta in the experimental rodent population during the five 39-hr monitoring sessions, daily measurements were made of these parameters throughout the course of the experiment (Figure 10). Based on a Student *t*-test of differences between consecutive segments of the experiment, there were no significant changes in these variables associated with exposure to a 1.50-T static field. However, the excreted mass of fecal solids showed a progressive increase during the course of the experiment, and the average daily fecal excreta during Control Period No. 3 was 18.9% greater than the average value during Control Period No. 1. This difference was statistically significant, based on a Student *t*-test ($P < 0.001$), and may be an effect associated with prolonged maintenance on a liquid-diet nutrient.

Daily measurements were also made of liquid-diet, pellet-food, and water consumption by the mice in control groups (B) and (C). In addition, the body masses of these rodents were measured on a pan balance at 3- to 4-day intervals throughout the experiment. These data are presented in Figure 11. Based on a Student *t*-test of data obtained during consecutive weeks of the experiment, none of these five parameters exhibited a change with the exception of the average body mass of rodents in control group (B), which was fed liquid diet. Like the experimental rodents maintained on liquid diet in the exposure chamber, the rodents in control group (B) exhibited a significant (2.4%) increase in average body mass during the first week of the experiment ($P = 0.03$). These control mice also showed a qualitative trend toward increasing weight throughout the 8 weeks of the experiment, although the consecutive week-to-week changes were not statistically significant after the first week.

Analysis of Organ and Tissue Parameters

The pooled urine samples from each of the five 39-hr circadian monitoring sessions were subjected to routine clinical chemistry analysis. The concentration ratios of five major urine components during field-on versus field-off conditions were: electrolytes (Na^+, K^+, Cl^-): 0.95; protein: 1.02; creatinine: 0.94; urea: 1.04; 17-OH ketosteroid: 0.91. As compared to unity, all of these ratios were within the variability of the values determined for the three urine samples collected during Control Periods 1, 2, and 3, indicating the absence of any significant magnetic-field effect.


(A) Liquid Diet Consumption

(B) Urine Excretion

(C) Fecal Excretion

Figure 9. Results of a Time-series Analysis of Circadian Variations in Nutrient Consumption and Excreta in a Rodent Population (40 Female LAF-1 Mice) Subjected to a 1.50-T Static Field Continuously for 5 Days and Intermittently, in Daily 8-hr-on/16-hr-off Cycles, for 10 Days. The best-fit circadian parameters are plotted at the midpoints of the five 39-hr monitoring sessions that were conducted during the course of the experiment. ○ Control Period No. 1 (8 Days); ● Continuous B = 1.5 Tesia (5 Days); □ Control Period No. 2 (18 Days); ◐ B = 1.5 Tesia, 00:00-08:00 Daily (10 Days); Δ Control Period No. 3 (13 Days).

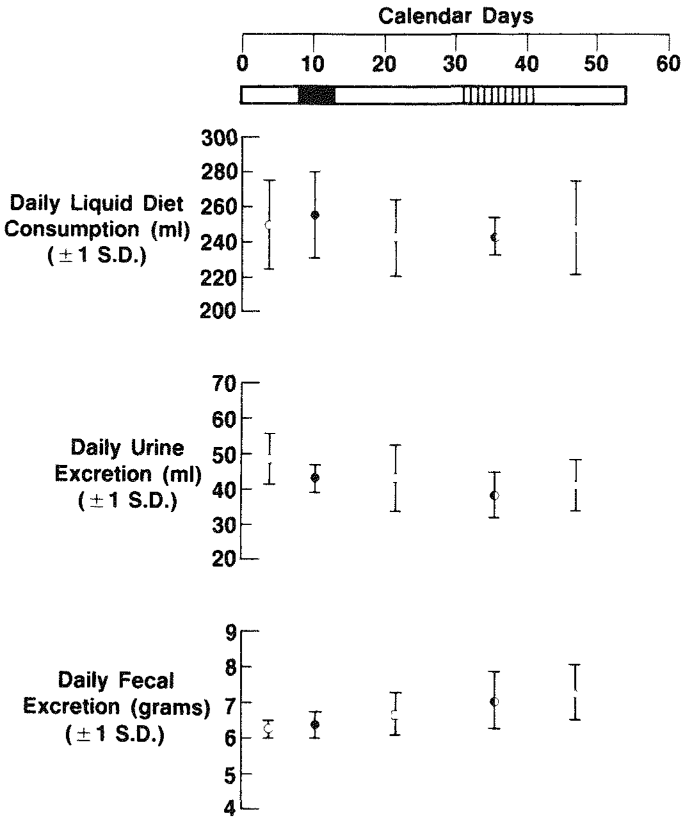


Figure 10. Daily Nutrient Consumption and Excreta in Exposed Rodent Population (40 Female LAF-1 Mice). Average daily values for nutrient consumption and excreta are shown for the five segments of an experiment in which mice were subjected to a 1.50-T static magnetic field continuously for 5 days and intermittently, in daily 8-hr-on/16-hr-off cycles, for 10 days. ○ Control Period No. 1 (8 Days); ● Continuous B = 1.5 Tesia (5 Days); ☐ Control Period No. 2 (18 Days); ◐ B = 1.5 Tesia, 00:00-08:00 Daily (10 Days); Δ Control Period No. 3 (13 Days).

Upon termination of the experiment, blood samples were drawn by cardiac puncture from 10 mice in the experimental group and from five mice in each of the control groups (B) and (C). The hematologic parameters for these three groups of mice are summarized in Table 1. Based on a Student *t*-test, none of the blood parameters differed at the $P < 0.05$ level between the experimental mice and the group (B) control mice that were fed liquid diet. The average hematocrit of the experimental mice was significantly higher than that of the group (C) control mice that were fed pellet food and water ($P = 0.02$). However, the larger average hematocrit of the experimental mice was not paralleled by a statistically significant difference in red blood cell (RBC) concentration, hemoglobin, mean corpuscular volume, or mean corpuscular hemoglobin content. This finding suggests that the small, but significant, difference in hematocrit may have been a consequence of variability in the measurement technique or of the small sample sizes used in this analysis. The percentage of lymphocytes also differed significantly (P = 0.04) between the experimental group and the control group (C) mice. It should be noted, however, that the average percentage of lymphocytes was lower in the experimental group, whereas the total white blood cell (WBC) concentration was higher for this group than the average value determined for the group (C) control mice. Because lymphocytes are the major component of the total WBC population, this observation again suggests that the significantly lower concentration of lymphocytes in the experimental group relative to the control group (C) mice may have resulted from measurement variability or from the small sample sizes used in this study.

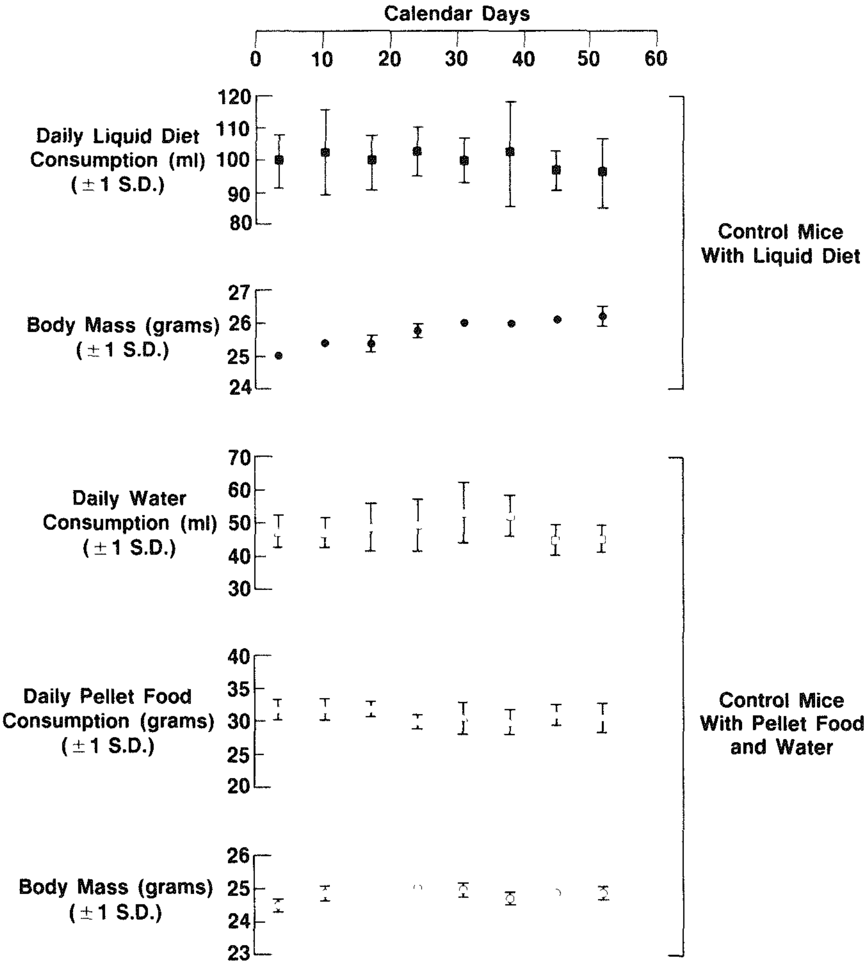


Figure 11. Body Mass and Nutrient Consumption in Control Rodent Populations (10 Female LAF-1 Mice Per Cage). Average values of body mass and daily nutrient and water consumption are shown for two control populations monitored over an 8-week experimental period. ○ Control Period No. 1 (8 Days); • Continuous B = 1.5 Tesia (5 Days); □ Control Period No. 2 (18 Days); ⊙ B = 1.5 Tesia, 00:00-08:00 Daily (10 Days); Δ Control Period No. 3 (13 Days).

TABLE 1 Hematology Profiles in LAF-1 Mice Exposed to a 1 50-T Static Magnetic Field and in Controls[a]

Parameter	Exposed Group (N = 10)	Liquid-Diet Control Group (N = 5)	Pellet-Food + Water Control Group (N = 5)
RBC[b], x 10^6/mm^3	8 44 ± 0 12	8 38 ± 0 14	8 25 ± 0 17
Hemoglobin, g/dl	14 7 ± 0 1	14 4 ± 0 2	14 3 ± 0 3
Hematocrit, %	42 2 ± 0 3[c]	40 8 ± 0 7	40 0 ± 0 8
Platelets, x 10^6/mm^3	1 08 ± 0 05	1 03 ± 0 04	1 18 ± 0 04
WBC[d], x 10^3/mm^3	4 13 ± 0 32	4 35 ± 0 37	3 80 ± 0 58
Lymphocytes, %	77 4 ± 1 9[e]	79 8 ± 3 2	84 0 ± 1 9
Segmented, %	18 1 ± 2 9	17 8 ± 3 2	13 8 ± 1 2

[a] All values are given as the mean ± SE

[b] Red blood cells

[c] Compared to the pellet food + water control group, P = 0 02

[d] White blood cells

[e] Compared to the pellet food + water control group, P = 0 04

Three groups of mice were also analyzed for organ weights upon termination of the experiment. These data, presented in Table 2, demonstrate that with one exception there were no significant differences in the average organ weights between the experimental mice and the mice in control groups (B) and (C). The exception was a significantly lower average weight of the adrenals in the experimental mice relative to the mice in control group (C), which were fed pellet food and water throughout the experiment. Because the measurement accuracy of the Sartorius balance (Brinkmann, Westbury, NY) used for the determination of organ weights was estimated to be ± 0.5 mg, the 0.7-mg difference in average adrenal weights between these two groups may be a consequence of measurement variability rather than a true biological difference. After excision and weighing, all of the organs, and sections of femoral bone marrow and jejunum from each animal, were fixed in Bouin's fluid, dehydrated in a graded series of alcohols, embedded in paraffin, sectioned at 5-μm thickness, and stained with hematoxylin and eosin for histological examination. No microscopic lesions were observed in the organs from the three groups of rodents that were suggestive of infection or degenerative changes.

TABLE 2 Organ Weights in LAF-I Mice Exposed to a 1 50-T Static Magnetic Field and in Controls[a]

Organ	Exposed Group (N = 10)	Liquid-Diet Control Group (N = 5)	Pellet-Food + Water Control Group (N = 5)
Adrenals	5 1 ± 0 2[b]	5 2 ± 0 2	5 8 ± 0 5
Brain	444 ± 8	460 ± 11	431 ± 14
Heart	96 ± 10	107 ± 6	102 ± 4
Kidneys	311 ± 5	298 ± 7	297 ± 11
Liver	1169 ± 36	1141 ± 91	1180 ± 47
Lung	165 ± 7	160 ± 4	149 ± 6
Spleen	58 ± 7	63 ± 2	58 ± 3
Stomach (empty)	232 ± 27	212 ± 14	240 ± 24

[a] Organ weights (mg) are given as the mean ± SE The average body masses (g) of the three groups at the time of autopsy were (1) exposed mice 25 66 ± 0 8, (2) liquid-diet control mice 26 25 ± 1 03, (3) pellet-food + water control mice 25 25 ± 0 68

[b] Compared to the pellet-food + water control group, P = 0 03

DISCUSSION

The development of an exposure chamber with completely noninvasive monitoring techniques has made possible the simultaneous analysis of seven circadian variables in rodent populations exposed to a high-intensity, static magnetic field over prolonged time intervals Because of the long-term stability of the environmental controls and the various physiological monitoring systems, the rodent population within the exposure chamber serves as its own control for the analysis of changes in circadian variables over prolonged periods of time and as a function of field-on versus field-off conditions Data from the 8-week experiment described in this paper indicate that no consistent alterations occurred in behavioral and physiological circadian variables in response to the application of a uniform, 1 50-T field This lack of responsiveness to the field was observed both with a continuous exposure for 5 days, and with intermittent exposures in an 8-hr/16-hr daily cycle during 10 consecutive days Various clinical measures of organ and tissue parameters revealed no significant alterations in the exposed group of rodents as compared with nonexposed control animals

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REPRODUCTION AND DEVELOPMENT IN RATS CHRONICALLY EXPOSED TO 60-Hz ELECTRIC FIELDS

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ABSTRACT

Previous evaluations of offspring and fetuses of miniature swine chronically exposed to a strong 60-Hz electric field suggested the possibility of reproductive and developmental changes We now report on two essentially replicate experiments, which were performed to determine if similar changes could be detected in rats exposed under a comparable regime These experiments were scaled to those in swine, using average induced current densities and the chronology of reproductive development as dosimetric and biological scaling factors, respectively Beginning at 3 mo of age, female rats of the F_0 generation, and their offspring, were chronically exposed for 19 hr/day to a 60-Hz electric field (100 kV/m unperturbed) throughout the experiments After 4 wk of exposure, the F_0 females were mated to unexposed males during the period in which the field was off No significant developmental effects were detected in their litters, confirming our previous results with swine and rats The F_0 females were mated for a second time at 7 2 mo of age, and the fetuses were evaluated shortly before term In the first experiment, the incidence of intrauterine mortality was significantly less in the exposed than in the sham-exposed litters, and there was a tendency ($P =$ 0 12) toward an increased incidence of litters with malformed fetuses Neither of these measures were significantly affected in the second experiment Copulatory behavior of the female F_1 offspring, which were bred at 3 mo of age, was not affected in either experiment There was a statistically significant decrease in the fertility of F_1 exposed females and a significant increase in the fraction of exposed litters with malformed fetuses in the first experiment, both of these measures were essentially the same in the sham and exposed groups of the second experiment The fact that the significant effects seen in the first experiment were not seen in the second may be attributed to random or biological variations, alternatively, this may suggest that the response threshold for these effects lies at about this field strength

A few reports have suggested that exposure of rodents to 60-Hz electric fields during gestation or neonatal life may affect their postnatal survival, growth, or development (Knickerbocker, Kouwenhoven, and Barnes, 1967; Marino, Becker, and Ulrich, 1976, Marino et al., 1980; Sikov et al., 1984). The magnitude of the reported changes was small in all cases, and findings were apparently not independently verified. Sikov et al. (1984) found that a 6-day exposure to a strong 60-Hz electric field prior to and during the mating period did not affect the reproductive performance of either male or female rats. In that study, continued exposure of the mated females through 20 days of gestation (dg) did not affect the viability, size, or morphology of their fetuses

Because of the possibility that current flow patterns were different in larger species than in rodents, evaluations of reproduction and development were included as part of a broad screening study performed on Hanford Miniature swine. As described elsewhere in this volume (Sikov et al.), among the early observations in swine was the finding that exposed female offspring (F_1) obtained from the initial mating of the primary herd (F_0) failed to exhibit normal mating behavior when paired with untreated boars at 18 mo of age. Subsequently, these litters had an increased incidence of birth defects. There was also an increase in malformation frequency in fetuses of exposed F_0 females that were bred for a second time after 18 mo of exposure.

A clear association of these changes with gestational exposure, per se, was not demonstrated but it was recognized that a number of possible interacting factors might be superimposed. Accordingly, the studies described in this communication were undertaken in an attempt to develop a small-animal model for evaluating these secondary factors. The experiment was designed to allow us to examine the influence of length of exposure, second-litter effects, and exposure time of the offspring. The chronology for this study in rats was scaled to the temporal sequence of events involved in the swine study and average induced current densities were used for dosimetric scaling.

MATERIALS AND METHODS

Design Considerations

The study was designed as two separate, but essentially identical, experiments since the size and available space in the exposure facility limited the number of animals that could be exposed concurrently. This approach had the ancillary advantage of allowing us to establish that any apparent effects were reproducible, a necessity for validating the model.

There are several possible bases for scaling the temporal sequence of the swine study to rodents: maximum lifespan, median lifespan, reproductive span, age at puberty or sexual maturity, length of the estrous cycle, or duration of gestation. Although the reported data are not completely consistent and extreme values are occasionally noted, most sources provide similar chronologies. The ratio of maximum life spans in miniature swine and rats is 5:1, and the ratio is similar for most of the other measures (Table 1). This value was used as an initial factor for scaling the critical events in the rat study to the swine (Table 2). However, because of the disparity in fraction of life span to pubescence in swine and rats and to maximize the length of the exposure period, the age at initiation of exposure and breeding were slightly adjusted to those shown on the third line for the F_0 animals. The rat offspring (F_1) also were bred at 3 mo of age, which maintained approximate equivalence to the chronology for F_1 swine, which were bred at 18 mo of age.

TABLE 1. Comparison of Chronologies in Rats and Swine

	Age		
	Swine	Rat	Ratio
Maximum life span	180 mo	36 mo	5.0
Median life span	150 mo	26.4 mo	5.7
Maximum reproductive life span	112 mo	12 mo	9.3
Age at puberty/sexual maturity	5 mo	1.4 mo	3.6
Length of estrous cycle	22 days	4.5 days	4.9
Length of gestation	114 days	22 days	5.2

TABLE 2. Selected Age (Months) for Critical Events in Rats and Swine Exposed or Sham-Exposed to 60-Hz Electric Fields

	Start Exposure	Initial Breeding	Second Breeding
Swine	18	22	36
Rats (life-span basis)	3.6	4.4	7.2
F_0 Rats (adjusted)	3.0	4.0	7.2
F_1 Rats	in utero	3.0	—

Exposure System

The exposure system used in these studies and the relevant dosimetry have been described in detail (Phillips et al., 1976; Phillips and Kaune, 1977; Kaune and Phillips, 1980; Free et al., 1981). In brief, this consisted of a parallel plate electrode system that produced a uniform (± 3.5%), vertical, 60-Hz electric field of 100 kV/m, measured without cages or animals in the field. Each system consisted of three tiers in the first experiment and four tiers in the second experiment, with each tier holding three polycarbonate housing modules. The modules were divided into eight individual compartments (12.4 cm wide x 25.1 cm long x 10.2 cm high) in which the rats were housed. During parturition and litter-rearing, however, the rats were housed in identical modules which were divided into only two (Experiment 1) or four compartments (Experiment 2), so that the cages were four or two times as large, respectively, as the standard cages in the two experiments. The wire-mesh floors of the modules were an integral part of the lower electrode so that the rats were in electrical contact with the reference ground. Since nest-building was found to be a necessary activity for the rats prior to parturition, a small amount of Antron-III® (a conductive carpeting material manufactured by Dupont, Wilmington, DE) was kept in the cages during the period in which litters were delivered and reared.

Food and water were freely available to the rats, and they did not receive shocks while eating or drinking. It has been shown that the system does not produce detectable levels of corona, audible noise, or ozone, and vibration of the cages was less than 1.4 mm (60-Hz, peak-to-peak). Perturbation of the field by cages and animals reduced the "effective" field strength to approximately 65 kV/m (Free et al., 1981).

Animals

The study was performed using Charles River CD (Sprague-Dawley-derived) rats from the Portage, MI facility. For each experiment, approximately 175 female and 90 male rats were received at 2 mo of age. They were group-housed in standard wire-bottom cages for 2 wk of quarantine prior to acclimation to the exposure cages. At that time, five females and five males were randomly selected for health evaluation. Gross necropsy and examination of histologic sections from major organs did not disclose any unusual lesions. Cultures of nasopharynx, lung and cecum for bacterial pathogens were negative. Serum was tested and not found to contain antibodies to Sendai virus, H-1 virus, rat coronavirus (RCV/SDA) or *Mycoplasma pulmonis*.

At the initial screening, some rats had elevated antibody titers to Kilham rat virus (KRV) in the first experiment and to KRV and pneumonia virus of mice (PVM) in the second experiment. Tests for viral pathogens in serum collected from F_0 and F_1 rats for teratologic evaluation at the end of the second experiment were negative. Although experimental exposure to KRV has some teratogenic potential, natural exposure in enzootic situations is without significant effect. Tests for other viral pathogens were negative.

An additional 2 wk of quarantine were allowed during an acclimation period, during which the females were housed in cages identical to those in the exposure system. All rats were individually identified by ear tattoo and weighed. The central populations of 144 female rats were randomly distributed into two groups of equal mean and variance, blocking on body weight, yielding initial group sizes of 72 exposed and 72 sham-exposed F_0 female rats in each experiment. Once assigned, the exposure or sham exposure of the animals and their offspring continued 7 days per wk for the duration of the experiment. Initially, the system was energized for 20 hr/day (noon to 8:00 a.m.). When the breeding phase of the experiment began, exposure was decreased to 19 hr/day (1:00 p.m. to 8:00 a.m.) to allow additional time for animal manipulation during the period in which the field was off. The animal rooms were illuminated on a 14-hr light/10-hr dark cycle; the light period extended from 10 a.m. to midnight. This allowed the rats to mate under limited lighting but during the peak of sexual activity, in the morning (Holson et al., 1976), when the field was off. All evaluations were done "blind"; i.e., technicians manipulating the rats did not have knowledge of which group was exposed or sham-exposed.

Male rats to be utilized for breeding were not exposed and were individually caged in an adjacent room which was maintained on the same lighting schedule as the exposure facility. After 1 mo of exposure, the 4-mo-old F_0 females were allowed to mate, under minimal ($\sim$ 0.5 fc) light levels, with these males for 12 consecutive days during the period in which the field was off. The females were transported to the males at 8:00 a.m.; one female from the exposed group and one from the sham-exposed group was placed in the cage with a male for a 2-hr period. Females were considered to have copulated (sperm- positive) if a sperm plug was detected in the vagina or if sperm were detected during microscopic inspection of a vaginal lavage. Sperm-positive females were considered to be at 0 dg on that day and were not bred again.

In the first experiment, 24 sperm-positive females from the exposed and sham-exposed groups were randomly selected to be killed for teratological evaluation; these animals are designated as "F_0, First Pregnancy." To maximize group sizes for evaluating results in second litters, none of the rats of the second experiment were used for a parallel teratologic evaluation. Females which did not mate within 12 days were subsequently necropsied, and their uteri stained with ammonium sulfide (Kopf, Lorenz and Salewski, 1964) to verify the absence of pregnancy.

Sperm-positive females were transferred to littering cages at 19 dg and were allowed to complete gestation, deliver, and to rear their litters (the F_1 generation), which continued on exposure or sham exposure. These females are designated "F_0, First Pregnancy (Births)." Rats which had copulated but had not delivered 2 days after the expected time (i.e., 24 days after coitus) were killed, and their lack of pregnancy and associated ovarian status were evaluated.

The precise length of gestation for F_1 pups could not be established, since litters born after the system was reactivated at 1:00 p.m. could not be detected until the following morning. Accordingly, all litters were considered to be born at 22 days after conception, and the number of offspring were counted on that day. Each F_1 litter was weighed, randomly reduced to a maximum of eight offspring (four males and four females, if possible) at 1 day of age, and kept until weaning at 21 days of age. Offspring were weighed weekly during the daily period in which the field was off before weaning, and again at 5, 8 and 12 wk of age.

To simulate the perturbations of the swine study, all offspring were evaluated for eye opening and incisor eruption at 13, 14, and 15 days of age and subjected to a limited evaluation of neuromuscular development in the first experiment. Each pup was placed in an open box for 1 min; measures scored were movement, rearing, rearing with support, standing, and grooming. The righting reflex was also scored in terms of the number of successes in three attempts. These measures were repeated in the second experiment to keep perturbation constant, although the data were not recorded since no differences between groups were detected in the first experiment.

Litters were weaned at 21 days of age, the offspring were weighed, and the F_0 dams were returned to individual exposure cages. The female weanlings were placed in two adjoining exposure cages. At 5 wk of age, two female offspring (F_1) from each litter were randomly selected to be used for the remainder of the study. Their ears were tattooed to indicate litter of origin and they were foot-marked with India ink to distinguish between littermates. The males and other female offspring were not used for this study.

The F_0 females that delivered litters subsequent to their first pregnancy were bred again at 7.2 mo of age. New groups of male rats, which received identical acclimation and screening regimens to that of the original males, were used for mating. The procedures were the same as those used for the initial matings, except that the breeding period was extended to 27 consecutive days to increase group sizes available for evaluation. The sperm-positive females were killed at 20 dg for teratologic evaluation, as described below, and are designated as "F_0, Second Pregnancy."

When the F_1 females reached 3 mo of age, they were mated with the same unexposed males as used for the second breeding of the F_0 generation. The mating protocol was similar to that used for the F_0 population except that the breeding period was restricted to 8 consecutive days. Females that copulated were subjected to teratologic evaluations at 20 dg and are designated "F_1, First Pregnancy."

Teratologic Evaluation

Females designated for teratologic evaluation were killed at 20 dg by exposure to CO_2 in a euthanasia chamber. The abdomen was opened, the uterus was removed, and the number of corpora lutea in each ovary was counted. The uterus was opened and inspected for abnormalities of the fetal membranes and changes in the color or volume of the amniotic fluid; the number of live and dead fetuses and resorption sites were recorded. Nongravid uteri were stained with ammonium sulfide (Kopf, Lorenz, and Salewski, 1964) to establish that complete early resorption had not occurred.

Live fetuses and placentas were removed, blotted, and weighed. The crown-rump length of each fetus was measured and recorded. Each fetus was examined for gross external abnormalities under an illuminated magnifier. The heads from one-half of the fetuses of each litter (randomly selected) were removed and placed in Bouin's fixative for subsequent examination of morphology, using serial, thin, razor-blade-cut sections (Wilson, 1965). All fetuses were examined for internal abnormalities by dissection under magnification, using Staples' technique (1974). All fetuses were eviscerated and fixed in alcohol; their skeletons were stained with Alizarin red S (Staples and Schnell, 1964) and examined for abnormalities in size, shape, and ossification.

Fetal morphological abnormalities were categorized as major malformations, minor anomalies, or morphologic variations, according to degree of severity and locus of structural change (Palmer, 1977; Peraud, 1976).

Statistical Methods

Binary response variables of exposed and sham-exposed groups were compared by chi-square test for independence or Fisher's exact test (Siegel, 1956). If the combined sample size for the two groups was less than or equal to 69, Fisher's exact test was used; if greater than 69, the chi-square test was used. Binary response variability between experiments was compared using the methods presented by Mantel and Haenszel (1959) and Mantel (1963).

Analysis of variance was used to analyze continuous variable data within each experiment and to test for differences between experiments (Steel and Torrie, 1960). Transformed response proportions ($2 \sin^{-1} \sqrt{p_i}$) were also analyzed by analysis of variance. Repeated-measures data, such as maternal body weights, were analyzed for each weighing and for the entire growth period. A two-tailed *t*-test was used to compare means of exposed and sham-exposed groups at each weighing, and a permutation test (Lindgren, 1963) was used to compare growth curves.

Body weights and crown-rump lengths for live male and female fetuses were analyzed by nested analysis of variance. The litter was used as the experimental unit, and the analysis took into account the effects of treatment, litter, and sex on the body weight and crown-rump length measurements. Fetal weights were subsequently used to calculate which fetuses were stunted; i.e., those whose size was significantly below the normal range of variation of their littermates (McLaren and Michie, 1960).

An actuarial life-table method (Cutler and Ederer, 1958) was used to compare the cumulative number of animals that copulated in exposed and sham-exposed groups, using the day that the animal was classified as sperm-positive as the response. A generalized Wilcoxon test (Breslow, 1970) was used to determine if the exposed and sham-exposed curves were the same. Results that differed at the $P \leq 0.05$ level were considered statistically significant.

RESULTS

Of the original (F_0) exposed and sham-exposed rats, 85 and 86%, respectively, copulated during the 12-day mating period in the first experiment and 81 and 75%, respectively, in the second experiment. Of those that copulated, 89 and 85% were pregnant in the first experiment and 86 and 76% in the second (Table 3). The second mating period was extended for the F_0 animals to maximize group sizes, although most copulations occurred early. Exposure had no detectable effect on copulation or fertility rates, or on the final percentage of animals which copulated or became pregnant in either experiment (Table 3). Copulatory rates were unaffected in the F_1 females of either experiment (range, 83 to 88%). A significantly smaller percentage (77%) of the exposed animals became pregnant than sham-exposed (92%) in the first experiment, but the corresponding values were 93 and 88% in the second experiment (Table 3).

TABLE 3 Effect of 60-Hz Electric Field Exposure on Reproductive Performance and Prenatal Mortality in Rats

	F_0				F_1	
	First Pregnancy[a]		Second Pregnancy			
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number exposed to males	144	144	80	72	105	108
Age (months)	4	4	7 2	7 2	3	3
Number of days mated	12	12	27	27	8	8
Number (%) copulated	119(83)	116(81)	75(94)	66(92)	88(84)	93(86)
Number (%) pregnant[b]						
Experiment 1	54(89)	53(85)	20(67)	20(69)	37(77)[c]	47(92)
Experiment 2	50(86)	41(76)	28(62)	24(65)	37(93)	37(88)
Combined	104(87)	94(81)	48(64)	44(67)	74(84)	84(90)
Gestational weight gain[d]	112 ± 3 8	114 ± 4 1	120 ± 3 2	121 ± 2 8	122 ± 2 2	117 ± 2 3
Extragestational weight gain[e]	52 ± 2 8	48 ± 4 0	55 ± 2 3	60 ± 2 2	62 ± 1 6	60 ± 1 9
Number of litters for teratologic exam	22	21	47	44	74	79[f]
Corpora lutea/dam[g]	15 1 ± 0 36	15 5 ± 0 24	16 3 ± 0 35[h]	16 3 ± 0 35	14 3 ± 0 27	13 9 ± 0 26
Implantation sites/dam[g]	13 8 ± 0 67	14 6 ± 0 26	14 6 ± 0 37	14 5 ± 0 36	13 5 ± 0 30[h]	13 3 ± 0 25
Implantation sites/corpus luteum[g]	0 90 ± 0 04	0 93 ± 0 02	0 90 ± 0 02	0 90 ± 0 02	0 94 ± 0 02	0 96 ± 0 01
Litters with resorptions (%)						
Experiment 1	68	71	55[c]	90	46	60
Experiment 2			70	88	65	68
Combined			64[c]	89	55	63
Resorptions/litter[g]						
Experiment 1	1 36 ± 0 30	1 52 ± 0 43	0 75 ± 0 19[c]	2 15 ± 0 41	0 78 ± 0 19	0 86 ± 0 13
Experiment 2			1 41 ± 0 31	1 75 ± 0 24	1 16 ± 0 22	1 68 ± 0 41
Combined			1 13 ± 0 20[c]	1 93 ± 0 23	0 97 ± 0 15[h]	1 24 ± 0 21
Implantations resorbed (%)[g]						
Experiment 1	10 0 ± 2 0	11 0 ± 3 0	6 0 ± 1 12[c]	15 1 ± 2 58	6 9 ± 1 26	7 9 ± 0 99
Experiment 2			12 2 ± 2 94	12 1 ± 1 34	9 3 ± 1 58	12 9 ± 2 74
Combined			9 7 ± 1 78	13 5 ± 1 38	8 3 ± 0 99[c]	10 3 ± 1 40
Live fetuses/litter[g]	12 4 ± 0 61	13 0 ± 0 49	13 4 ± 0 44	12 6 ± 0 36	12 5 ± 0 31[c]	12 0 ± 0 30

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[a] Experiment 1 only

[b] (Number pregnant − number copulated) x 100

[c] Statistically significant (P < 0 05) difference from corresponding value in sham-exposed group

[d] 20 dg weight minus 0 dg weight (g ± SE), weights are shown only for rats that were pregnant and for which all weights are available

[e] Gestation weight gain minus uterine weight (g ± SE)

[f] Five pregnant rats were not available for teratologic evaluation due to technical error

[g] Mean ± SE

[h] Statistically significant (P < 0 05) difference between experiments, pooled values are presented when values were similar and no treatment difference was detected

The initial random assignment resulted in identical weight distributions of rats in exposed and sham-exposed groups, and the mean weights of the two groups were the same at the time of copulation for each segment (F_0 First Pregnancy, F_0 Second Pregnancy, F_1 First Pregnancy) of the study. Weight gains of the exposed and sham-exposed F_0 rats were similar during their first and second pregnancies (Table 3). The exposed F_1 females gained significantly more during gestation than did the sham-exposed females in the first but not in the second experiment, and there was no overall difference when data from both experiments were combined. Extragestational weights (body weight at 20 dg minus the weight of the gravid uterus) were also calculated to evaluate maternal status without the influence of embryotoxicity and litter size. Neither total nor extragestational weight gains differed between the exposed and sham-exposed groups in the F_0 rats, although extragestational weight gain was significantly greater in the exposed F_1 rats than in the sham-exposed of the first experiment.

None of the measures of reproductive status (Table 3) were affected by exposure in the first pregnancy of the F_0 animals (evaluated only in the first experiment). In the second litters of the F_0 animals, and in the F_1 rats, measures of reproductive fitness (e.g., number of corpora lutea/dam or number of implantation sites/corpus luteum) were similar between experimental groups and across experiments. In the second litters of the F_0 rats of the first experiment, there was a statistically significant decrease in the percent of exposed litters in which there were resorptions, as well as a trend ($P = 0.08$) toward a decreased mean number of resorptions per litter among litters with resorptions. As a result, there was a significant decrease in the mean number of resorptions per litter and in the percentage of implants resorbed in the exposed group relative to the sham-exposed group. In the second experiment, however, these measures were essentially identical in the exposed and sham-exposed groups. There was also a consistent decrease in prenatal mortality in the litters of the exposed F_1 group in both experiments. As a result, the difference in the overall incidence of resorptions was statistically significant (Table 3).

Male fetuses were heavier than females, as expected. Fetal and placental weights and crown-rump lengths were consistent between experiments; no differences between the exposed and sham-exposed groups could be detected (Table 4). Occasional exposed and sham-exposed litters contained stunted fetuses, but there were no significant effects of exposure on incidence. Approximately 50% of the fetuses were males in most exposed and sham-exposed groups of both experiments. No biological significance is attributed to the single statistically significant difference in sex ratio that was found in the second pregnancy of the F_0 rats of the first experiment.

Teratologic evaluations of the first litters of the exposed F_0 rats were performed in the first experiment only; only one malformed fetus (minor malformation) was detected in the exposed group, and none were observed in the sham-exposed (Table 5). The incidence of reduced ossification of the skull was significantly less in first litters of the exposed than in those of the sham-exposed F_0 population. In the first experiment, two malformed fetuses (from different litters) were detected in the sham-exposed group of the second pregnancy of the F_0 animals, but eight malformed fetuses from six litters were found in the exposed F_0 group. This difference in the proportion of litters with malformed fetuses was not statistically significant ($P = 0.12$). The incidence of reduced ossification of the sternebrae was significantly increased in the exposed group of the second breeding of the F_0 animals. In the F_1 females evaluated at 20 dg in Experiment 1, six of the exposed and one of the sham-exposed litters contained one or more malformed fetuses (Table 6); this difference in incidence was statistically significant.

TABLE 4 Effect of Electric Field Exposure on Measures of Fetoplacental Size and Sex Ratio, Expressed as Mean of Litter Means ± SE, Except as Noted

	F_0				F_1	
	First Pregnancy[a]		Second Pregnancy			
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number of litters examined	22	21	47	44	74	79
Number of live fetuses	274	274	631	554	928	952
Body weights, g						
Female	2 90 ± 0 09	2 99 ± 0 10	2 83 ± 0 03	2 89 ± 0 04	2 88 ± 0 03[e]	2 86 ± 0 03
Male	3 08 ± 0 10	3 21 ± 0 10	3 00 ± 0 04	3 03 ± 0 04	3 02 ± 0 03[e]	3 00 ± 0 03
Crown-rump length, mm						
Female	33 ± 0 5	34 ± 0 4	34 ± 0 2[e]	34 ± 0 2	34 ± 0 2[e]	33 ± 0 2
Male	34 ± 0 5	35 ± 0 4	35 ± 0 2[e]	35 ± 0 3	34 ± 0 2[e]	34 ± 0 2
Stunted[b]	2(9)	4(19)	9(19)	6(14)	13(18)[e]	17(22)
Placental weight, g	0 51 ± 0 01	0 50 ± 0 01	0 47 ± 0 01	0 46 ± 0 01	0 45 ± 0 01[e]	0 44 ± 0 00
Percent males[c]						
Experiment 1	42 6 ± 2 8	49 4 ± 3 3	42 6 ± 2 5[d]	56 4 ± 3 1	54 3 ± 2 8	47 4 ± 2 7
Experiment 2			47 3 ± 2 5	50 9 ± 2 7	49 1 ± 2 1	51 6 ± 2 7
Combined			45 3 ± 1 8[d]	53 4 ± 2 0	51 7 ± 1 8	49 4 ± 1 9

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[a] Teratology from Experiment 1 only

[b] Number of litters with stunted fetuses (%)

[c] Mean ± SE

[d] Statistically significant (P < 0 05) difference from corresponding value in sham-exposed group

[e] Statistically significant (P < 0 05) difference between experiments Combined data for most measures are presented when values were numerically similar and treatment effects were not detected

TABLE 5 Effect of Electric-Field Exposure on Measures of Fetal Morphologic Integrity in Litters of Parental (F_0) Generation Rats[a]

			Second Pregancy			
	First Pregnancy[b]		Experiment 1		Experiment 2	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number of litters	22	21	20	20	27	24
Number of fetuses examined	274	274	274	245	357	309
Number of heads examined	136	135	138	124	180	153
Major Malformations (total)	0/0	0/0	3/3	1/1	1/1	1/1
Facial cleft	0/0	0/0	0/0	0/0	0/0	1/1
Diaphragmatic hernia	0/0	0/0	1/1	0/0	0/0	0/0
Micro- or anophthalmia	0/0	0/0	2/2	0/0	1/1	0/0
Hydrocephaly	0/0	0/0	1/1	1/1	0/0	0/0
Minor Malformations (total)	1/1	0/0	5/3	1/1	4/1	1/1
Musculoskeletal defects	1/1	0/0	5/3	1/1	4/1	0/0
Ribs	1/1	0/0	5/3	1/1	4/1	0/0
Cardiovascular	0/0	0/0	0/0	0/0	0/0	1/1
Total Malformations	1/1	0/0	8/6	2/2	4/1	2/2
Morphological Variations						
Renal	9/6	10/7	10/6	17/9	28/13	39/14
Supernumerary ribs	2/2	4/2	0/0	2/2	0/0	0/0
Reduced ossification						
Sternebrae	51/14	35/16	80/19[c]	62/14	86/21	61/17
Phalanges	4/3	2/2	3/2	4/3	5/4	0/0
Skull	2/5[c]	18/11	20/7	9/7	18/11	21/11
Pelvis	19/8	11/6	18/8	22/8	6/4	4/2
Vertebrae	144/21	154/21	100/16	114/18	84/25	68/18

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[a] Data are presented as number of fetuses affected/number of litters affected; totals are not the sum of individual entries, since some fetuses had multiple malformations and some litters had more than one affected fetus

[b] Experiment 1 only

[c] Statistically significant (P < 0 05) difference in fraction of litters affected as compared to corresponding value in sham-exposed group

TABLE 6. Effect of Electric-Field Exposure on Measures of Fetal Morphologic Integrity in Litters of Second Generation (F_1) Rats[a]

	Experiment 1		Experiment 2	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number of litters	37	42	37	37
Number of fetuses examined	463	498	465	454
Number of heads examined	231	252	235	225
Major Malformations (total)	3/3	1/1	0/0	3/3
Thoracoshisis/rachischisis	1/1	0/0	0/0	1/1
Facial and or palatal clefts	1/1	1/1	0/0	1/1
Cardiovascular defects	0/0	1/1	0/0	0/0
Micro- or anophthalmia	0/0	0/0	0/0	1/1
Hydrocephaly	1/1	0/0	0/0	0/0
Minor Malformations (total)	6/5	2/1	1/1	0/0
Musculoskeletal defects	4/3	2/1	1/1	0/0
Ribs	3/3	1/1	1/1	0/0
Vertebrae	1/1	0/0	0/0	0/0
Legs	0/0	1/1	0/0	0/0
Cardiovascular	3/3	0/0	0/0	0/0
Ectopia (ovary)	0/0	1/1	0/0	0/0
Total Malformations	8/6[b]	2/1	1/1	3/3
Morphological Variations				
Renal	37/17	29/17	43/18	41/15
Supernumerary ribs	1/1	1/1	1/1	0/0
Reduced ossification				
Sternebrae	91/25	96/28	102/26	88/28
Phalanges	4/4	2/2	1/1[b]	8/7
Skull	34/14	36/17	8/5	12/11
Pelvis	58/21	67/17	39/13	15/10
Vertebrae	179/37	201/42	100/28	113/31

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[a] Data are presented as number of fetuses affected/number of litters affected; totals are not the sum of individual entries, since some fetuses had multiple malformations and some litters had more than one affected fetus.

[b] Statistically significant ($P < 0.05$) difference in fraction of litters affected as compared to corresponding value in sham-exposed group

In the second experiment, only two malformed fetuses (from different litters) were detected in the sham-exposed group of the second pregnancy of the F_0 animals (Table 5). Four malformed fetuses, from a single litter, were found in the exposed group; however, this difference was not statistically significant ($P = 0.46$). The incidence of litters with reduced ossification of the sternebrae, phalanges and vertebrae was slightly greater in the exposed than in the sham-exposed group of the second pregnancy of the F_0; the differences were not statistically significant. In the F_1 females evaluated at 20 dg, one of the exposed and three of the sham-exposed litters contained one or more malformed fetuses (Table 6); this difference in incidence is not statistically significant ($P = 0.31$). The incidence of litters containing fetuses with reduced ossification of the phalanges was significantly less in the exposed than in the sham-exposed F_1 litter. The direction of the change was opposite to that observed for this variation in the F_0 litters.

Mean litter size, deaths during the first day of life, and mortality between 1 day of age and weaning at 21 days of age were similar in the exposed and sham-exposed groups, as were birth weights and growth curves (Table 7).

The fraction of pups with eye opening or incisor eruption was similar between groups, as were the measures of neuromuscular development evaluated on days 13, 14 and 15 after birth.

DISCUSSION

There were no indications of disease or faulty animal husbandry conditions other than an occasional transient loss of weight of individual animals associated with isolated malfunctions of water dispensers. Moreover, the similarity of gestational weight gains across pregnancies and in both experiments suggests that any effects of caging or exposure on the maternal animals were consistent.

A deficit in copulatory behavior was observed in F_1 female swine (Sikov et al., this volume). A comparable deficit was not detected in the F_1 rats, although there was a statistically significant decrease in the fertility of the exposed F_1 female rats in the first experiment. It may be that both effects derive from a common mechanism, although this seems unlikely since the reduced fertility was not replicated in the second experiment.

TABLE 7. Litter Size, Survival, and Weights of F1 Offspring in Litters Exposed or Sham-Exposed to 60-Hz Electric Fields

Measurement	Exposed	Sham-Exposed
Number of litters	81	73
Offspring/litter[a]	12.5 ± 0.3	12.5 ± 0.4
Neonatal mortality[b]	6.7 ± 1.6	7.0 ± 1.6
Juvenile mortality[c]	6.8 ± 1.8	8.5 ± 2.7

Time of Measurement	Weight, g[d]			
	Males	Females	Males	Females
1 day[e]	6.4 ± 0.1	6.0 ± 0.1	6.2 ± 0.1	5.9 ± 0.1
7 days	13.8 ± 0.2	12.7 ± 0.2	13.7 ± 0.2	12.9 ± 0.2
14 days	28 ± 0.4	26 ± 0.4	28 ± 0.4	26 ± 0.4
21 days	47 ± 0.8	44 ± 0.6	47 ± 0.7	45 ± 0.7
5 weeks	---	113 ± 1	---	113 ± 1
8 weeks	---	170 ± 2	---	169 ± 2
12 weeks	---	216 ± 4	---	214 ± 3

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[a] Mean ± SE

[b] Mean percent of newborns dead by 1 day of age (± SE)

[c] Mean percent of offspring that died between reduction of litter size to eight individuals at 1 day of age and weaning at 21 days of age (± SE)

[d] Mean of litter means ± SE

[e] Based only on litters born before noon of 22 dg

The mean values for a number of somewhat associated measures of prenatal mortality were slightly different in the sham-exposed than in the exposed groups. These differences were statistically significant only in the second breeding of the F_0 animals of the first experiment. Although the values were in the normal ranges, one might interpret this difference as suggesting that exposure may have had a beneficial effect on development, i.e., it maintained the viability of embryos otherwise destined to die. Since the values for mortality indices in the first breeding of the F_0 animals were intermediate to those in the second, the more likely interpretation is that the difference should be attributed to random variation from a central value. The lack of effect on fetal size suggests that exposure did not produce embryotoxicity, since fetal size is usually an excellent indicator of such deleterious actions.

The increased incidence of malformations in the second litters of the exposed F_0 rats was neither reproducible nor statistically significant. In the first experiment, malformation incidences (percent of litters affected) were about threefold greater in the exposed than in the sham-exposed group; this result parallels the findings in swine (Table 8). The decreased fertility of the F_1 rats in the first experiment (Table 3) was accompanied by a significantly increased proportion of litters with malformed fetuses (Table 8). This increase parallels the increase in litters with birth defects observed in the F_1 offspring of the exposed group of swine. It appears that these associations are circumstantial, resulting from comparison of small incidence values, since the ratios were in the opposite direction in the second experiment.

TABLE 8. Comparison of Fetal Malformation Incidence for Swine and in Two Replicate Experiments for Rats; All Animals Exposed or Sham-Exposed to 60-Hz Electric Fields

Species	Age, mo	Length of Exposure, mo	Proportion (%) of Litters Affected: Exposed	Proportion (%) of Litters Affected: Sham-Exposed	P
Swine					
F_0 (1st)	22	4	2/7 (28.6)	4/7 (57.1)	0.30
F_0 (2nd)	36	18	12/16 (75.0)	2/7 (28.6)	0.05
F_1 (1st)	18	18	20/28 (71.4)	4/12 (33.3)	0.03
Rats - First Experiment					
F_0 (1st)	4.0	1.0	1/22 (4.6)	0/21 (0)	0.51
F_0 (2nd)	7.2	4.2	6/20 (30.0)	2/20 (10.0)	0.12
F_1 (1st)	3.0	3.0	6/37 (16.2)	1/42 (2.4)	0.04
Rats - Replicate Experiment					
F_0 (2nd)	7.2	4.2	1/27 (3.7)	2/24 (8.3)	0.46
F_1 (1st)	3.0	3.0	1/37 (2.7)	3/37 (8.1)	0.31

Even in the absence of frank malformative change, increased incidence of morphologic variants is sometimes accepted as indicative of the teratogenic potential of an agent (Palmer, 1977). Considering the number of comparisons made, it is not unreasonable to expect that significant differences would be found in a few measures by chance. Since the site of ossification defects observed and the incidence lay in opposite directions in the first and second litters of the F_0 rats, there is probably no biological significance associated with these findings. Nevertheless, the increased incidence of decreased sternebral ossification in the exposed litters of the second pregnancy of the F_0 rats may be of consequence because of the associations between rib and sternal development and the increased incidence of rib malformations.

Our earlier study (Sikov et al., 1984) suggested that there might be an accelerated time of development of a few motile behaviors in the group of prenatally exposed rats and that there might be a decrement in the righting response in this group. However, the evidence for this was not strong, and any effect was definitely transient. The present data indicate that these findings were probably chance events, since they were not replicated under more stringent conditions of evaluation and with prolonged exposure times.

It is obvious that exposure of rats at this field strength does not provide an adequate model for examining the role of contributory factors involved in the swine study. From our results it is impossible to determine whether the observed effects are random variations or if exposure at this field strength and duration lies at the threshold value for producing an electric-field effect.

ACKNOWLEDGMENTS

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EFFECTS OF 50-Hz ELECTRIC-FIELD EXPOSURE ON THE GROWTH RATE OF CHICKS

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ABSTRACT

In the last decade, a variety of studies concerning the effects of 50-Hz electric fields on mammals (mice, rats, rabbits and dogs) has been carried out by ENEL, in cooperation with the Institute of Physiology of the University of Milan, in the framework of the 1000-kV Project. The primary aim of these studies was to identify possible pathology induced by the electric field. To achieve this aim, animals were exposed for periods as long as 60 days to fields up to 100 kV/m. These conditions are much more severe than those normally experienced by human beings under high-voltage lines. Mortality, fertility, reproduction, teratogenesis, cardiovascular system, blood chemistry and hematological variables, resistance to infections, and growth and development were investigated. With respect to controls, only minor changes of some of these variables were found; in particular, a slight, reversible decrease in weight gain in rats exposed to 100 kV/m. To analyze whether this decrease also occurs in birds, a group of adult chickens (F_0) was exposed to an electric field ranging from 2 to 15 kV/m, over 9 mo, under the UHV experimental line in Suvereto. A number of eggs laid by the exposed chickens were incubated in a standard, commercially available incubator, and the corresponding second-generation chickens (F_1) were, in turn, exposed to 15 kV/m for 9 mo. As controls, unexposed F_0 and F_1 chickens were used. No significant differences were observed with respect to F_0 fertility and egg hatchability or F_1 malformations and growth curves. A number of eggs from exposed F_0 chickens were also incubated at 25 kV/m, and the weight gain of the offspring exposed to 15 kV/m was followed for 9 mo. Under these unrealistic conditions, the exposure of the eggs to the electric field seemed to cause a transient reduction of the growth rate, more evident in female than in male chicks.

Since 1974, studies on the biological effects of 50-Hz electric fields on laboratory animals (mice, rats, rabbits and dogs) have been carried out in Italy within the 1000-kV Project, an International Research Program on ultrahigh-voltage (UHV) transmission (Cerretelli et al., 1978; Malaguti et al., 1980; Conti et al., 1981).

The primary purpose of these studies was to carry out a systematic analysis of the biological variables for which there existed, on the basis of the findings reported in the literature, suspected changes due to electric-field exposure.

With the aim of identifying any possible gross pathology induced by the electric field, the animals were exposed to high-intensity electric fields (up to 100 kV/m) for prolonged periods (8 hr/day for up to 2 mo). Long-term experiments at lower electric-field strength (25 and 10 kV/m) were then performed, restricting the investigation mainly to those functions apparently affected by the exposure to the highest electric-field strength.

Basic cardiovascular variables (i.e., blood pressure, heart rate and cardiac output), hematology and clinical chemistry, and growth and fertility were investigated, together with teratogenic effects and changes in resistance to induced infections.

Analysis of the results from these experiments indicated a lack of effects in biological variables following exposure to 10 kV/m; only some slight blood changes were found in dogs chronically exposed to 25 kV/m. At 100 kV/m, the rate of growth of rats appeared to decrease with respect to that of the control group. This change, however, was reversible, with complete recovery of body weight after a few weeks following the end of exposure. Fertility and resistance to experimental infections in rats and mice were not influenced by a 2-mo exposure to 100 or 25 kV/m. No teratogenic effects were found in rats exposed to 100 kV/m.

The availability of the UHV test line at Suvereto (Tuscany) suggested extending the investigation to the natural environment, still offering the possibility of performing long-term exposures to electric fields higher than those normally experienced by living beings near high-voltage lines. In the study reported here, chickens were considered suitable for this type of investigation because:

- they can be freed from maternal influences by utilizing modern, reliable incubation devices;
- they can be easily raised and maintained;
- they offer the possibility of studying the various stages of development in addition to growth rate. Avian embryos, in fact, undergo very rapid changes in cellular growth and differentiation and might therefore be sensitive to external stimuli that might affect such processes;
- a vast wealth of reference data are available on normal development processes;
- the Leghorn breed used for the experiments at Suvereto was adaptable to the climatic conditions there.

The research program, still in progress, includes investigations on egg productivity, fertility, and development. In this paper the results of the study on the growth rate of chicks are presented.

MATERIALS, METHODS AND EXPERIMENTAL PROCEDURE

The exposure area (Figure 1A) is located under the existing test line near the dead-end tower, close to the supply station. The test line, 1 km long, is equipped with three bundle conductors for long-duration corona and insulation tests. One conductor bundle at a time is energized, the other two being earthed. The energization is shifted from one bundle to the other every 24 hr. The conductor-to-ground clearance at the exposure areas is about 18 m.

Three 7 x 7-m enclosures (1, 2 and 3 in Figure 1B), one under each bundle of the line, are available for exposure. Since the three bundles are energized alternately, each enclosure is periodically subjected to similar values of electric field at ground. (The maximum value in each enclosure is about 15 kV/m; see Figure 1B.) At a distance of 500 m from the test line, three similar enclosures are used for controls.

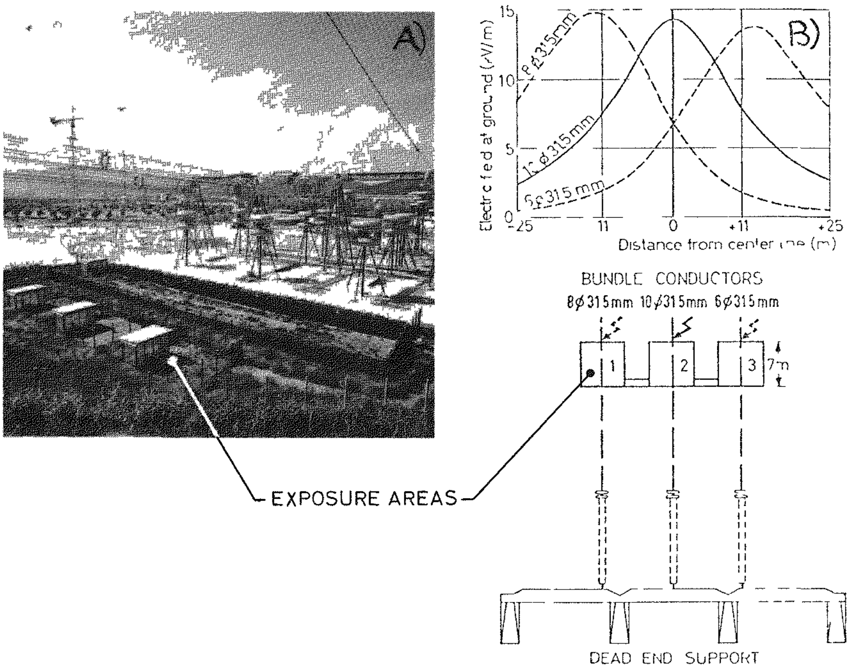

Figure 1 A. View of the Exposure Areas Under the Suvereto 1-km Test Line. B. Layout of the Exposure System and Curves of the Electric Field at Ground for Single-phase Energization of Each of the Three Bundles During the particular study described in this paper, enclosure 2 was covered with a continuously energized net generating an electric field of 15 kV/m at ground.

Forty-seven female hens, 6 mo old, were subdivided into two groups of 24 exposed (F_0-E) and 23 control (F_0-NE) animals, respectively, and housed in enclosure 1 under the UHV test line (2-15 kV/m; weighted mean, 5.5 kV/m) and in a control enclosure, respectively. Two roosters were added to each group.

After 9 mo, eggs were obtained from the two groups. Part of the eggs from the F_0E group were incubated in a commercial incubator (Figure 2, group 2). During the first 3 wk, the newborns (F_1, N = 76, males and females) were kept in a heated cage without being exposed to the electric field. Thereafter, the chicks were housed in enclosure 2 (Figure 1) and continuously exposed to a constant 15-kV/m electric field.

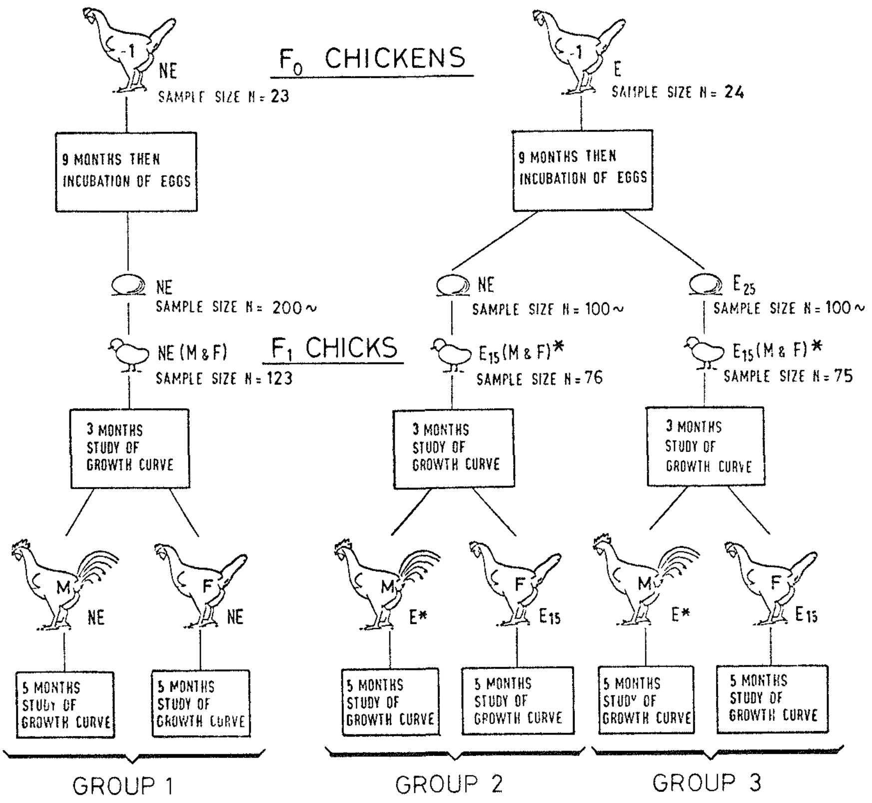

Figure 2. Block Diagram Showing the Different Combinations of Exposure of Parents, Eggs and Chicks.

NE = control (nonexposed);
E = exposed to an electric field varying between 2 and 15 kV/m (weighted mean = 5.5 kV/m; enclosure 1, see Figure 1);
E* = exposed to an electric field varying between 2 and 14 kV/m (weighted mean = 5 kV/m; enclosure 3; see Figure 1);
E_{15} = exposed to a 15-kV/m electric field (enclosure 2, see Figure 1);
E_{25} = exposed to a 25-kV/m electric field (incubator).

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*Subjected to E_{15} after 3 wks of nonexposure.

The eggs from the control hens (F_0-NE) produced chicks (F_1-NE group 1, N = 123, males and females) which were housed in a control enclosure.

At the age of 4 mo, male chicks from both exposed and control groups were transferred to enclosure 3 (2-14 kV/m; weighted mean, 5 kV/m) or to a separate control area. In addition, a number of eggs from the F_0-E group were also exposed to a 28-kV/m field during incubation, to investigate the effect of the electric field on egg development. Some of the eggs were opened on the 20th day of incubation for anatomical and histological studies. The remainder hatched, and the offspring (group 3, N = 75, males and females) were exposed to a 15-kV/m electric field, and their growth curve was drawn. The male chicks from the latter group were also transferred, at the age of 4 mo, to the same separate enclosure as the exposed male chicks of group 2 (2-14 kV/m; weighted mean, 5 kV/m).

In summary, the growth curves of three groups of chicks were studied simultaneously over 8 mo. Each group was characterized by a combination of exposures of parents, eggs and chicks, shown in Figure 2.

RESULTS

No differences in fertility, hatchability or offspring malformations were observed among the three groups investigated.

With regard to groups 1 and 2, no differences were found in chicks' body weight at hatching nor in their rate of growth, for either males (Figure 3A) or females (Figure 3B). On the other hand, the body weights of group 3 at hatching and the rate of growth thereafter were significantly lower than those of groups 1 and 2. However, when male chicks were transferred to a lower- strength electric-field enclosure, their body weights apparently increased, reaching those observed for groups 1 and 2 after 2 mo.

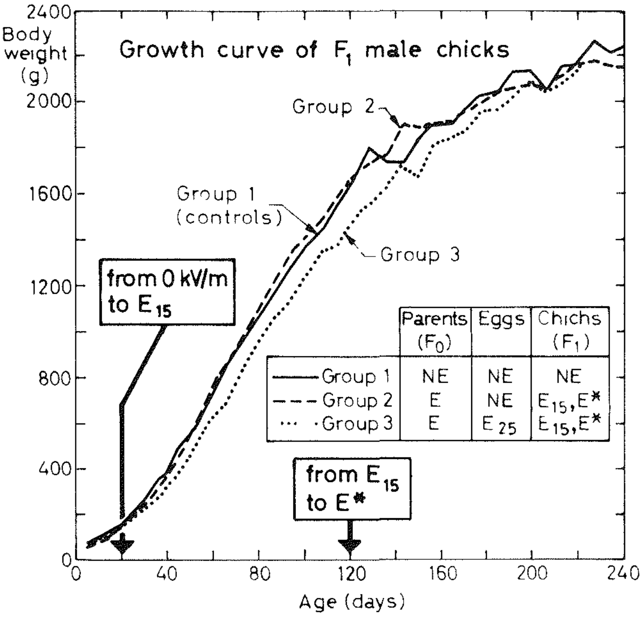

Figure 3A. Growth Curve of Male Chicks of the Three Groups Obtained from Different Combinations of Exposure of Parents, Eggs and Chicks (Figure 2).

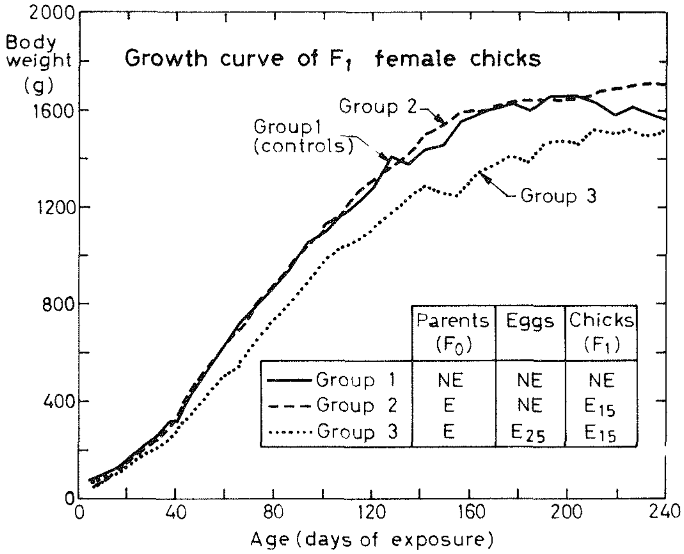

Figure 3B. Growth Curve of Female Chicks of the Three Groups Obtained from Different Combinations of Exposure of Parents, Eggs and Chicks (see Figure 2).

CONCLUSION

It appears that exposure even to continuous electric-field strengths of up to 15 kV/m did not affect either the fertility of eggs nor the growth rate of the chicks. On the contrary, the exposure of eggs during incubation (21 days at 25 kV/m) seemed to cause a transient reduction of the growth rate of the offspring, more evident in female than in male chicks. In no case were teratogenic effects observed.

An extended research program on the possible effects of 50-Hz electric fields on poultry will be carried out by ENEL in the near future. One of the aims of this program is to investigate whether the findings given in this paper are repeatable or fortuitous.

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GROWTH AND SEXUAL MATURATION OF RHESUS MONKEYS CHRONICALLY EXPOSED TO ELF ELECTRIC AND MAGNETIC FIELDS

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ABSTRACT

As part of the Department of the Navy program for ecological and health assessment of exposure to extremely low-frequency (ELF) electromagnetic fields, 30 rhesus monkeys (*Macaca mulatta*), 17 males and 13 females, were exposed for 22 hours per day, 7 days per week, from 1 to 54 months of age, to low-impedance electric and magnetic fields like those generated in earth by the Navy's ELF communications system. A second group of 30 animals served as controls. The project was designed to replicate an earlier study and to evaluate the hypotheses developed concerning the principal finding of the earlier study: an enhanced growth rate in pubescent males exposed to ELF fields. The field parameters (0.2 mT and 20 V/m at a frequency modulated between 72 and 80 Hz) were the same as those used in the initial study. The biological endpoints measured included body mass, bone growth, steroid hormones, hematology, and menstrual cycle data. No differences between exposed and control groups were observed prior to puberty. During puberty, body mass, bone growth, the age at which menarche was observed, and the progressive development of the mature endocrine rhythms of the menstrual cycle were all similar for both the exposed and control female monkeys. Growth rates of exposed and control males in this study were not significantly different from each other, although exposed males grew slightly faster than control males during puberty. None of the parameters measured showed statistically significant differences between the means of exposed and control subjects. The few parameters that showed statistically significant differences in the group-versus-time interaction were not correlated with one another and were judged to be isolated, chance occurrences without physiological significance. The hypothesis regarding general anabolic effects of ELF exposure was rejected. Although the growth rate trends did agree qualitatively with the earlier study, the results of this second project failed to replicate the growth-rate effect of the first study. The data from this project also failed to provide conclusive support for the hypotheses that stimulation of testosterone secretion was the cause of growth enhancement observed in the initial study. Throughout the study, the ELF-exposed animals were in good health and showed no evidence of adverse physiologic effects from the exposure.

Since 1968, the Navy has repeatedly proposed construction of an extremely low-frequency (ELF) system to communicate with nuclear submarines at operational depth and speed (Beam, 1983). Current methods to communicate with these submarines use very low-frequency (VLF) signals and require the submarine to cruise slowly at shallow depths, trailing a long antenna on the surface. An ELF system offers specific technical advantages, particularly in improving the submarine's capability to avoid detection. The Department of the Navy is currently completing an ELF communications system in Wisconsin and Michigan. In Wisconsin, a test facility constructed and operated since 1969 is being upgraded to operational status, and in Michigan a second transmitter and associated antenna system is being installed. These systems have been defined in detail in a report from the Naval Electronics Systems Command (1981). Throughout the history of the Navy's ELF proposals, considerable opposition from the general public has been encountered (Klessig and Strite, 1980). This opposition has been strongest in the areas proposed as antenna sites; namely, Wisconsin and Michigan. To evaluate the environmental and health effects of these fields the Navy has sponsored numerous and varied research studies concurrently with the development of the project. The scientific literature primarily concerns ELF electromagnetic field exposure in air; these are often called high-impedance fields. The fields produced by the Navy ELF system, however, are primarily generated in earth; i.e., these are low-impedance fields. The Navy-sponsored research has, therefore, been designed to provide information on fields in earth; this research has been reviewed several times. The most thorough review of work relevant to ELF communications systems was reported by the Staff of an ad hoc Committee of the National Academy of Sciences (NAS, 1977); a more recent review highlighted work conducted between 1977 and 1980 (Grissett, 1980). The 1977 NAS report concluded that any risks from the ELF system to humans, animals, or the environment would be minimal. Nevertheless, controversy over such effects has continued.

The NAS review included consideration of an interim report on a project at the Naval Aerospace Medical Research Laboratory (NAMRL), in which rhesus monkeys were chronically exposed to ELF electric and magnetic fields designed to simulate those produced by the antenna. Later analysis of data from this project revealed that the exposed males had gained weight at a significantly faster rate than control males. Since the committee did not have these data at the time of the report, the Navy asked the NAS to examine these observations in detail. A special panel was formed for this purpose. The panel concluded (NAS, 1978) that "the thoroughness and quality of the NAMRL study were impressive"; that there were "no obvious errors in method or flaws in execution to account for the reported findings"; that there was "substantial evidence of a real growth effect of the Pensacola exposure conditions on the male animals"; and that "efforts should be made to define the effect further and to explain its mechanism." The data reviewed by this special NAS committee covered the first 52 weeks of exposure of those animals. Following the recommendations of that panel, the exposure was subsequently extended. The final analysis of the project covered 2 years, 41 weeks of exposure. During the last year and a half of exposure, the rate of growth of the monkeys leveled off as somatic development was completed. The size difference that developed during the first year of the exposure remained unchanged throughout this later period, but the variance of the groups (control and exposed) increased. When the full period of exposure (2 yr, 41 wk) was analyzed, the growth rates of the control and exposed groups were not statistically different ($\alpha = 0.09$) from each other. Thus, the observed effect was limited to differences in the growth rate of males during the pubertal growth period ($\alpha < 0.001$). A better understanding of the effect is necessary to assess the physiological significance of the finding and to properly determine if exposure to such ELF fields is the true cause of the growth difference observed.

Three hypotheses were developed for possible mechanisms of the observed ELF enhancement of growth rate: 1) the ELF field has an effect on neuroendocrine function that results in stimulation of pituitary hormones, e.g., gonadotropins and somatotropin which, in turn, stimulate growth. 2) Voltage gradients in the experimental apparatus provide direct testicular stimulation that affects growth rate in males only. 3) The ELF field has a generalized anabolic effect that increases the growth rate in males and females. To test these hypotheses, it was decided to conduct a second experiment, in which newborn rhesus monkeys of both sexes would be chronically exposed to the same conditions as in the first NAMRL chronic study. This would, first and foremost, test to see if the growth effect could be replicated. Secondly, it would, by design, test the three hypotheses developed to explain the first study's findings. If the ELF field had a generalized anabolic effect, then growth differences should be most readily observed in young, rapidly growing animals, and it should occur in both sexes. If the growth effect were due to direct testicular stimulation, then growth differences would be limited to males, would most likely occur after the onset of puberty, and might be indicated by elevated levels of circulating gonadal steroids. More complex possibilities exist if the ELF exposure affects neuroendocrine function. Such an effect might influence growth rate in both sexes, but growth differences might be observed only in the males, since anabolic steroids are produced in much greater quantity by the male gonads than by the female gonads after the onset of puberty. Neuroendocrine effects might also result in a shift in the age of onset of puberty in one or both sexes, or in alterations in the endocrine rhythms associated with sexual maturity in both males and females.

This report records this second study of primates chronically exposed to ELF fields at NAMRL. For details of the first study, previous reports should be consulted (Grissett, 1979; Grissett et al., 1977). In this study (ELF2), 30 rhesus monkeys (17 males, 13 females) were exposed for 22 hours/day from 1 to 54 months of age. A second group of 30 monkeys (17 males, 13 females) served as controls. Field conditions were identical to those of the first study. The biological endpoints examined were body measurements (11 parameters), gonadal endocrine function (4 hormones), hematology (11 parameters), and clinical examinations. No statistical differences in the mean values that were significant at or below the $\alpha = 0.05$ level were observed for any parameter in either sex. A trend in growth rate of exposed pubescent males was observed to be qualitatively similar to the results of the first study, but it was not statistically significant.

MATERIALS AND METHODS

Animal Selection and Pairing

Newborn rhesus monkeys *(Macaca mulatta)*, of both sexes, from the NAMRL rhesus breeding colony were used in this project. When a healthy offspring was 1 month old, the mother and newborn were placed in the ELF exposure facility in a randomly predetermined location. The mother remained with the baby in the same cage until the baby was about 6 months old. At that time, the mother was removed from the ELF facility and returned to the colony. To reduce mortality and behavioral problems associated with growing up in social isolation, after weaning, two infants were housed together in a single cage until the younger of the pair was 2 years old. The animals were paired as male-female except for four pairs of males (two pairs in each group, control and exposed). From then until the end of the study, each animal was housed individually, with only visual contact with other monkeys. Animals of the same sex were placed in corresponding positions in the exposed and control groups. Statistical blocking, based on male parentage, prevented offspring of a given male from being assigned disproportionately to either experimental or control group. As a result, the difference between the number of experimental and control subjects of the same sex from a given father was never more than two.

Animal Chambers

The apparatus and facilities used in this study were essentially the same as those used in the first NAMRL chronic exposure study with rhesus monkeys. This was true of the animal chambers as well, although major parts of these chambers were replaced with new ones built for this study. The chamber, which was built of Plexiglas,® except for the electrical conducting components, had three sections. The bottom included the grid of stainless steel bars, which was the floor of the chamber for the animal, the resistors through which the current passed, and a reservoir beneath the grid floor to hold urine and feces. The main body of the chamber was rectangular, providing a confinement area of 0.6 x 0.6 x 0.93 m for the animal. It contained a food hopper and holder for a water bottle near the top. The chamber was closed by a single sheet of Plexiglas that slid into grooves at the top of the main body of the chamber. The top was perforated with numerous holes through which room air was drawn into the chamber by an exhaust fan that pulled the air out at the bottom and exhausted it to the atmosphere outside the building.

Exposure Facility

The ELF exposure facility was contained in a building totally dedicated to this project. The exposure system was designed in 1974 to simulate the electric and magnetic fields that would be produced by the proposed Navy submarine communications antenna. Since then, the proposed antenna design has been changed (Beam, 1983). One major change has been that the older design called for a buried cable antenna, while the antenna under construction will utilize primarily aboveground cable. As a result of the design changes, the fields used in this study simulate only in part those fields associated with currents in the Department of the Navy's ELF communications system transmitting antennas.

The building consisted of a central core area and two wings. The core area contained offices, cage-washing facilities, a veterinary examination room, a food preparation area, field-generating equipment, and other general-purpose areas. The two wings were symmetrical and were designed so that either one could be used to expose experimental animals. Each wing had identical field-generating equipment. When the experimental animals were in position in the north wing, the control animals were in corresponding positions in the south wing, but only the north-wing field-generating system was energized. This system allowed the two groups of monkeys to be transposed each week, thereby balancing any subtle differences that may have existed in environmental control equipment, data transducers, noise level, vibrations, etc. The Plexiglas chambers housing the 30 animals in each group were situated in a single row in the center of the wing. This row of cages was located directly beneath a row of full-spectrum fluorescent lights. The light cycle was 12:12 hours, light:dark, throughout the project. The transition between light and darkness was abrupt. No extraneous or low-level light was permitted during the dark cycle. Thus, these animals lived from birth in an environment controlled for light and temperature; the temperature of both wings was controlled by the same equipment at 23 ± 2°C (range). These conditions were the same in all animal enclosures, and only minor ($\alpha < 2°C$) seasonal variations existed.

The electric-field generating system was an integral part of the animal chamber, as illustrated in Figure 1. The bars that formed the walking surface for the animal were constructed of 1.27-cm square stainless steel bar stock. These lay in slots, spaced 3.81 cm between centerlines, and rested on thin stainless steel strips, 3.5 cm long, that bridged the floor of each slot. These strips were connected by 3900-ohm resistors. The end resistors were connected to a stainless steel strip that passed down into the trough and terminated on the outer edge of the feces tray. A current source was connected via these terminations to the network of resistors and an electric field gradient of 0.76 V was generated between adjacent bars. Thus, the electric-field gradient along the walking surface of the cage was 20 V/m. The current source for this electric-field simulator was driven by an amplifier with an input from the same modulator used for the magnetic field generator. The wire screens indicated in Figure 1 were placed on each side of the chamber and were connected to the same voltage source that energized the resistor network. These screens created a uniform horizontal electric field similar in orientation to that near the ELF antenna. The electric-field distribution in the animal chambers was measured with a high-impedance electric-field probe, used in conjunction with a wave analyzer. At four elevations in the chambers, measurements were taken near the corners and in the center; they indicated an average electric-field strength of 20 V/m in air. That level exceeds the nominal values of electric fields at the Navy's Wisconsin Transmitting Facility (WTF) and the Michigan Transmitting Facility (MTF) by factors of approximately 150 and 300, respectively. The electric fields associated with transmitting antenna voltage, which are vertically oriented relative to the earth's surface and exist only in air, were not simulated in this experiment.

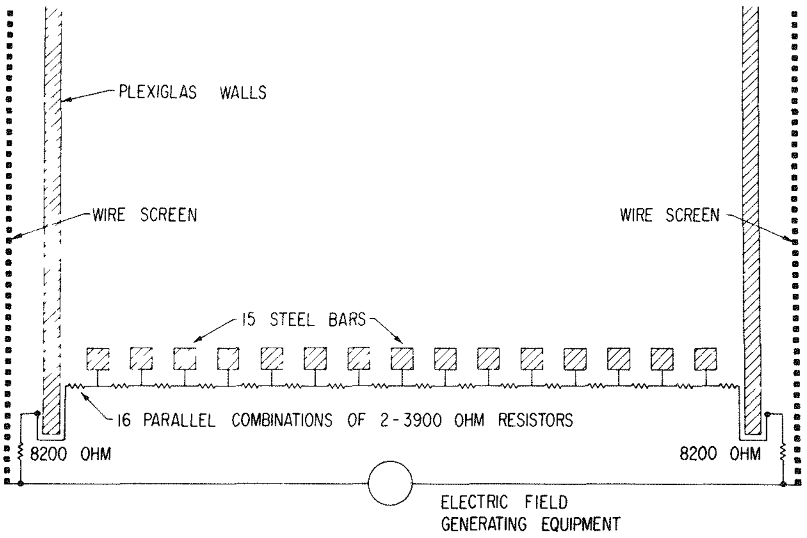

Figure 1. Schematic of the Electric Field Generating System. Identical networks of resistors were at both ends of the bars so that the net resistance between bars was actually formed by two 3900-ohm resistors in parallel.

The magnetic-field generating system was designed to simulate the magnetic field associated with an ELF communications system. Those currents produce magnetic fields that are horizontally oriented near the earth's surface close to the antennas. The field direction was horizontal in the north-south direction. The coil system consisted of three parallel wire bundles, 26 m long, laid in concrete trenches 1.1 m deep and 1.1 m wide. Eighty-six turns were in the center trench, 48 turns in the outer trench and 38 turns in the inner trench. The trenches were covered with plywood, and a row of 30 animal chambers was placed approximately 1.1 m directly above the center coil. The magnetic-field distribution in the animal chambers was measured with a magnetic-field probe, used in conjunction with a wave analyzer. At three elevations, measurements were taken near the corners and in the center. The system generated a field of 0.2 mT (2 gauss) in the chambers and simultaneously generated a null field in the control chambers, which were placed along a parallel line 25.8 m from the experimental chambers. These values exceed the magnetic flux densities produced at the WTF by a factor of 33 and those that will be produced at the MTF by a factor of 66.

The exposure system was driven by a single electric-generating source located in the center of the building midway between the two wings. At pseudorandom intervals the oscillator shifted between 72 Hz and 80 Hz. At the time of the shift the coil system was instantaneously tuned to the correct frequency. This automatic tuning was accomplished by solid-state switching that changed the value of total capacitance in resonance with the coil system. The frequency spectrum of the signal source was determined to be a good simulation of the actual ELF antenna situation.

Experimental Protocol

The basic experimental protocol was for 22 hours of uninterrupted exposure per day, 7 days per week. The fields were turned off at the time the lights came on each morning (0800) and remained off for 2 hours while data collection, feeding, watering, cleaning, and other routine operations were completed. The animals were placed on this regimen at 1 month of age, and continued in the experiment without interruption until they were 54 months old. Data collection was based on a 6-week cycle that began at birth.

A thorough physical examination of each animal was conducted every 6 weeks. Weight and body measurements (or biometrics) were made every 2 weeks until 22 months of age, and every 3 weeks from 22 to 54 months of age.

Blood was sampled (by femoral venipuncture) with the same protocol for both sexes from 6 weeks to 18 months of age; thereafter, protocols were different for each sex. At 18 months of age, blood sample collection was altered for females to provide a protocol designed to document the onset of puberty and the sexual maturation process. For males, a corresponding change was made at age 22 months. This report will deal only with the blood samples collected between 24 and 54 months of age. After 22 months of age, three samples were collected on a particular day (Wednesday) from each male once every 3 weeks. These three samples were drawn at 0900, 1000, and 2200 hours, i.e., 1 and 2 hours after the lights came on in the morning, and 2 hours after the lights went off at night. To accomplish the night sampling, the exposure and light cycle were interrupted for about 1 hour each Wednesday night. One-third of the males had blood drawn each week, with an equal number of animals from each group involved. For females, a single sample was drawn on a collection day twice per week; half of the females were in the Monday-Thursday collection group, the other half were in the Tuesday-Friday collection group.

The two groups of animals, control and exposed, were completely transposed from one wing of the facility to the other each Wednesday. Each animal retained the same position in the row of animals on either side, with the same neighbors in the line. Each monkey was transferred to a clean cage once each week; each was provided a measured amount of commercially available monkey chow and water (900 ml) each day. The daily ration of food was increased as the monkeys grew, from about 150 g/day for a recently weaned animal to about 250 g/day for a 4-yr-old. Many of the animals did not consume all of the food offered. Uneaten biscuits were frequently observed in the waste tray of the chamber.

Biometric Procedures

With one exception, techniques for making the body measurements remained the same throughout the study. Prior to 22 months of age, the measurements were made on alert, unanesthetized animals. After 22 months, the animals were anesthetized, prior to measurement, with 10 mg/kg ketamine hydrochloride intramuscular injection, (Park Davis, Morris Plains, NJ) in order to avoid injury (from the struggle of restraining the animal) to either the monkey or the technician.

In general, the techniques used in this study were similar to those described by Schultz (1929). Our noninvasive measurements were made on an anatomical region rather than on a specific bone. Measurements were made of head width, head length, shoulder width, hip width, upper leg length, knee height, lower arm length and chest circumference, as well as body mass. Calipers were used for all biometric measurements with the exception of sitting height and chest circumference. Head width, upper leg length, knee height, and lower arm length measurements were taken using a sliding compass with adjustable arms. An outside caliper was used to measure head length, shoulder width, and hip width. The ability to replicate biometric measurements required a "touch" for how tightly the calipers fit over the measured area. The calipers had to be tight enough to move the skin over the underlying tissue, but not tight enough to bind. Special care was taken to ensure proper positioning of the animals and correct orientation of the instrument to the area measured. Further details of these procedures have been described previously (Lotz et al., 1986).

During the last 6 months of the study, chest circumference and testicle size were also measured in all males of both groups. While the animal was anesthetized for biometric measurements, length and width of the testicles were measured with sliding calipers. Using the length and width as major and minor axes of an ellipsoid, respectively, the volume of the testicle was calculated.

Blood Sample Analysis

The primary purpose for which blood samples were collected was to determine steroid hormone levels in the circulating blood. It was planned that pituitary hormones, particularly luteinizing hormone (LH), would be measured only if steroid hormone levels showed a difference between experimental groups. The analysis of blood samples was coded so that it was conducted without any knowledge of the group or animal from which the sample was taken. Data from these assays were then entered into the computer by control number and electronically decoded to reestablish the identification with the correct animal. Blood collected was allowed to clot in test tubes at 4 to 10°C for 2 to 8 hours. The blood was then centrifuged, and the serum was removed and stored at -85°C until it was assayed. Occasionally, samples drawn by venipuncture were collected in tubes containing ethylenediaminetetraacetate (EDTA) as an anticoagulant, so that hematological analysis could be performed.

The steroid hormones measured were estradiol-17β (E2), progesterone (P), testosterone (T), dihydrotestosterone (DHT), and β4-androstenedione. Not all of these hormones were measured in every sample analyzed, and not all of the samples collected were analyzed for hormone concentration. However, all of the samples collected from males between ages 28 and 54 months were analyzed. The analysis of these peripubertal male samples always included measurement of T and DHT, and sometimes included measurement of E2 and androstenedione as well. Samples collected from females between 24 and 50 months were always analyzed for E2 and P; some female samples were analyzed for T and DHT as well. Only one of the two weekly female samples was analyzed at the early part of this age range. After increased P levels (indicative of corpus luteal activity) were noted in a specific monkey, every subsequent sample from that female monkey from the age of corpus luteal activity onset up to 51 months of age was analyzed. The steroid hormones were determined by a combination of extraction, chromatography, and radioimmunoassay (RIA) procedures according to the techniques of Resko et al. (Resko, Ploem, and Stadelman, 1975; Resko et al., 1980).

Hematological analyses of the blood samples included a complete blood count with differential. The parameters determined were erythrocyte (red blood cell) count, hemoglobin, hematocrit, mean corpuscular volume, leukocyte (white blood cell) count, and differential counts of white blood cells, noting neutrophils, lymphocytes, monocytes, eosinophils, basophils, and bands. The primary purpose in performing the hematology work was to provide the veterinarians with an additional assessment of the clinical health of the animals.

Veterinary Clinical Examination

As noted earlier, each animal received a thorough physical examination by a veterinarian every 6 weeks. The experimental and the control monkeys from paired cage positions were always given exams on the same day. The veterinarian's examination included the following: observation of ocular motility, direct and indirect pupillary reflexes, facial muscle tone, locomotor and proprioceptor activity, disposition and demeanor; visual and manual examination of head, face, scalp, neck, mouth, teeth, throat, extremities, skin, haircoat, superficial spine, and perineal region; direct ophthalmoscopy; otoscopic visualization of external auditory canal and nares; palpation of abdomen, superficial lymph nodes, femoral pulse, and inguinal canals; and auscultation of heart and lungs. Tooth eruption and development of secondary sexual characteristics were noted.

Under the direction of the veterinarian, rectal swabs were made for bacteriologic examination on a less frequent, but periodic basis. Intradermal tests for tuberculosis were conducted every 6 months. The veterinarian and his technical staff also performed the following tasks daily: visually examined every monkey and chamber, inspected sanitary conditions of the animal areas, the examination room, and the cage-washing areas, and reviewed records and minor health problems of any animals requiring special observation. Beginning at 18 months, the perineal region of each female was examined, twice per week, at the time of blood collection. The presence of dried or fresh blood on the perineal area was considered to be evidence of menstruation.

Statistical Analysis Procedure

Data with a normal distribution or with the capability of being transformed to a normal distribution were statistically analyzed with a two-factor analysis of variance (ANOVA) by using repeated measurements on one of the factors (Winer, 1962). An unweighted means analysis was employed to compensate for unequal cell frequencies encountered because of missing data. In the statistical analysis of these data, two sources of variation were of direct interest in making decisions about the effect of the exposure level upon the animal groups: the exposure level (control or exposed) and the interaction between exposure level and exposure duration. The F-ratio obtained from the exposure level factor can be used to make decisions about the differences between the means of the two groups of animals. The interaction can be used to determine whether the two groups responded differently to the exposure duration factor (a group-versus-time interaction).

The Mann-Whitney U-test (Byrkit, 1974) was applied to those parameters that were not normally distributed and could not be readily transformed to normal distributions. The Mann-Whitney U-test is a rank test that can be used to determine the level of significance.

For the growth parameters (mass and biometrics) and hematological indices, data from the 53-month period of study were condensed by averaging measurements over 6-week intervals. These 6-week average values were then used in the statistical analysis and subsequent graphing of these data. Two derived parameters of growth were added in the condensed data format to evaluate the relative amount and rate of growth. These derivations of body-mass data were body-mass ratio, which relates subsequent mass to the initial body mass at 1 month of age, and growth rate, defined as the gain in body mass per 6-week period.

Data from the hormone measurements were not condensed for analysis because of the rhythmic pattern in circulating levels. Some specific analysis of these rhythms was done on data from individual subjects. In addition, the mean data for the two groups were tested by ANOVA, with the limitation that only the time intervals of 106 to 156 and 157 to 234 weeks of age could be tested (separately) because of limitations in the storage capacity of the computer used.

A difference between treated and control subject data was considered to be statistically significant when the alpha level was $\leqq 0.05$. Differences between the two groups for which alpha levels were >0.05 were not considered to be statistically significant. Statistically significant effects have been noted whenever the alpha level met the above criteria for one or more of the factors of the analysis.

RESULTS

The growth curves for body-mass ratio for males and females are shown in Figure 2; the abscissa represents weeks of age, which is directly related to weeks of exposure. There was about 9 months difference in age between the oldest and youngest males (5 months for females), so these data are not synchronized in chronological time. Thus, data for individual animals, which were averaged to produce a particular point on a graph (e.g., weeks of age = 200) were accumulated over a 9-month period of time for males, and over a 5-month period of time for females. This means that an unusual event (e.g., equipment failure on a given day) that might cause an artifact would affect only a few animals whose data contributed to a specific data point.

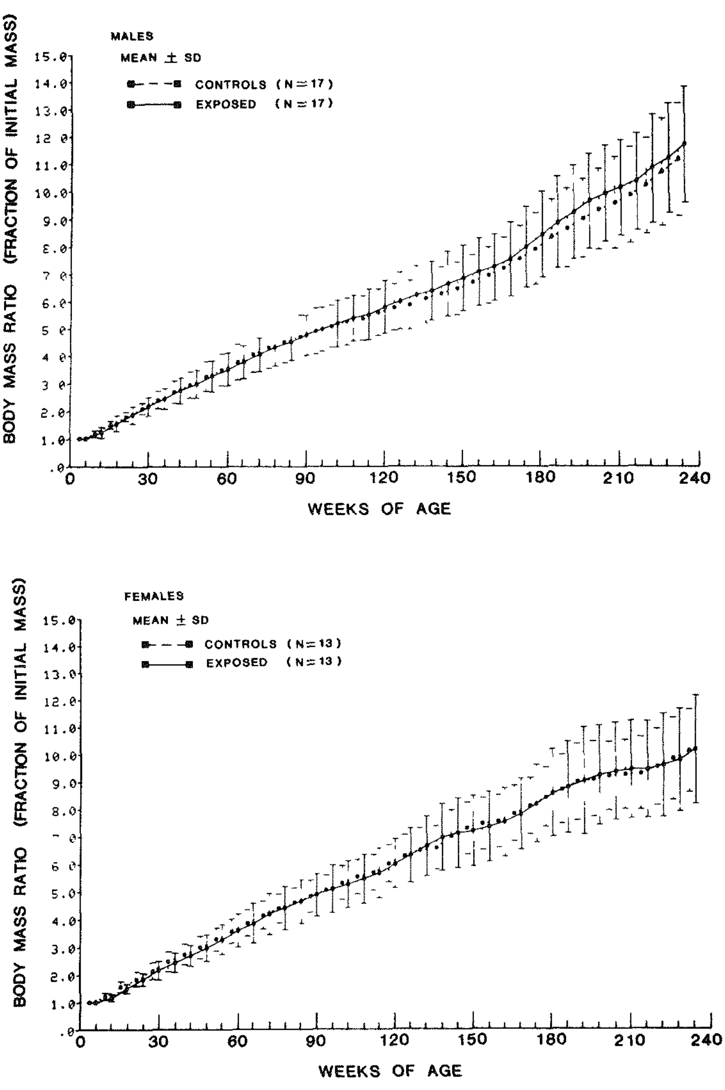

Figure 2. Body Mass Ratio of Control or ELF Exposed Rhesus Monkeys During the First 234 Weeks of Life. The upper graph is for males; the lower graph is for females.

No statistical differences were found (Table 1) between exposed and control groups in these parameters, or for any of the growth parameters, with the exception of head width in males and upper leg length in females. The alpha level (< 0.001) for the group-versus-time interaction term for male head width is a result of some divergence in the curves of the two groups over the latter months of the experiment. The cause or significance of this difference is unclear, since no other parameter of growth shows a similar effect over the same time period.

TABLE 1. Statistical Summary of Growth Parameters for Rhesus Monkeys Exposed to Extremely Low-Frequency (ELF) Electric and Magnetic Fields

		Differences Between Means (ANOVA)			Group versus Time Interaction (ANOVA)		
Parameter	Sex	df	F	α	df	F	α
Body Mass	M	1,32	0.30	0.59	38,1212	0.96	0.54
	F	1,24	0.46	0.51	38,906	0.46	0.99
Body Mass Ratio	M	1,32	0.65	0.57	38,1212	0.92	0.60
	F	1,24	0.01	0.93	38,906	0.15	1.00
Growth Rate	M	1,32	0.62	0.56	37,1180	0.68	0.93
	F	1,24	0.58	0.54	37,881	1.43	0.05
Sitting Height	M	1,32	0.03	0.87	38,1204	0.71	0.91
	F	1,24	0.85	0.63	38,904	0.64	0.95
Shoulder Width	M	1,32	0.00	0.96	38,1204	0.65	0.95
	F	1,24	1.09	0.31	38,904	0.70	0.92
Hip Width	M	1,32	0.12	0.73	38,1202	0.59	0.98
	F	1,24	1.88	0.18	38,904	1.04	0.41
Head Length	M	1,32	0.41	0.53	38,1204	0.82	0.77
	F	1,24	1.26	0.27	38,904	0.55	0.99
Head Width	M	1,32	0.21	0.66	38,1204	2.63	0.001
	F	1,24	0.02	0.89	38,904	0.48	0.99
Knee Height	M	1,32	0.46	0.51	38,1203	0.74	0.87
	F	1,24	2.79	0.11	38,904	1.27	0.13
Upper Leg Length	M	1,32	0.94	0.66	38,1204	0.64	0.96
	F	1,24	1.79	0.19	38,904	1.41	0.05
Lower Arm Length	M	1,32	0.01	0.90	38,1205	0.48	0.99
	F	1,24	0.81	0.62	38,904	0.48	0.99

In females, the significant interaction (group versus time, $\alpha < 0.05$) for upper leg length is also an isolated trend of slight magnitude that is uncorroborated by other parameters. The gradual transposition and divergence of the male growth curves (Figure 2) between weeks 120 and 210 indicate that the exposed males were growing slightly faster than the control males during this period. The two groups of females showed differences in mass that were as large, at times, as those males showed at week 210, but the relative rates of growth of the two groups of females fluctuated up and down throughout the experiment, in contrast to the more uniform trend of the males. This trend toward faster growth in exposed males is more readily apparent in the derived parameters, particularly in body-mass ratio. The absence of any consistent difference in growth rates of females is also more readily seen in body-mass ratio. A pubertal growth spurt is clearly evident for both groups of males beginning at about week 180 (Figure 2). No similar growth spurt in females was observed. Neither chest circumference nor testicle measurements were appreciably different between male groups over the last 6 months of the study.

Menstruation, in females, and an evening elevation in testosterone level, in males, were taken as respective indicators of the onset of puberty. The first ovulation, evidenced by elevated P values, is also a clear and significant event in sexual development. Slight differences in the mean age of the occurrence of these events (Table 2) between exposed and control animals of either sex were not statistically significant ($\alpha < 0.05$). Nor were there significant differences between the mean E2 levels of exposed and control females, nor in the number of ovulatory menstrual cycles of the two groups of females, nor in the total number of menstrual cycles observed in both groups. However, there was a significant group-versus-time interaction (df = 50, 1178; F = 1.48, $\alpha < 0.02$) for E2 levels over weeks 106 to 156. This interaction is a result of differences in the last half of this interval that did not continue into the subsequent period (157-234 weeks), where the interaction was not significant ($\alpha < 0.05$). Figure 3 shows, for a representative female, the relationships of observed menstruation with P and E2 spikes in semi-weekly blood samples from which ovulations were determined. An E2 surge always preceded a spike in P (resulting from corpus luteal activity after ovulation), and menstruation followed the decline in P levels. This female clearly demonstrated a seasonal pattern in ovulations that was apparent in all the females. Subject 20 (Figure 3) represents one of a small group of older females that began to ovulate during the fall or winter following their second birthday (1981-82). Four animals of each group (exposed and control) showed such a pattern. Seven of these eight animals, including subject 20, then became anovulatory during the following spring and summer. Other females did not ovulate until the fall or winter following their third birthday (1982-83). In fact, no animal was observed to ovulate for the first time between April and September. One control female never ovulated during this study, although she did have menstrual cycles. The peak month for first ovulation was December, when eight females first ovulated. This seasonality was not as strong in the second summer associated with ovulatory activity. Ten of the 25 females continued to ovulate regularly during the spring and summer in which they turned four years old (1983).

TABLE 2. Occurrence of Key Events in Sexual Development[a] of Rhesus Monkeys Exposed to Extremely Low-Frequency Electric and Magnetic Fields and Their Controls

	Females, First Menses	Females, First Ovulation[b]	Males, First Testosterone Spike[b]
Control	122.1 ± 5.2	169.4 ± 6.2	142.0 ± 3.4
Exposed	119.2 ± 4.3	168.2 ± 6.2	136.9 ± 3.4

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[a] All values are expressed as mean ± SE, in weeks of age.

[b] Determined from hormone measurements; testosterone spikes were noted in night (2200 hr) samples.

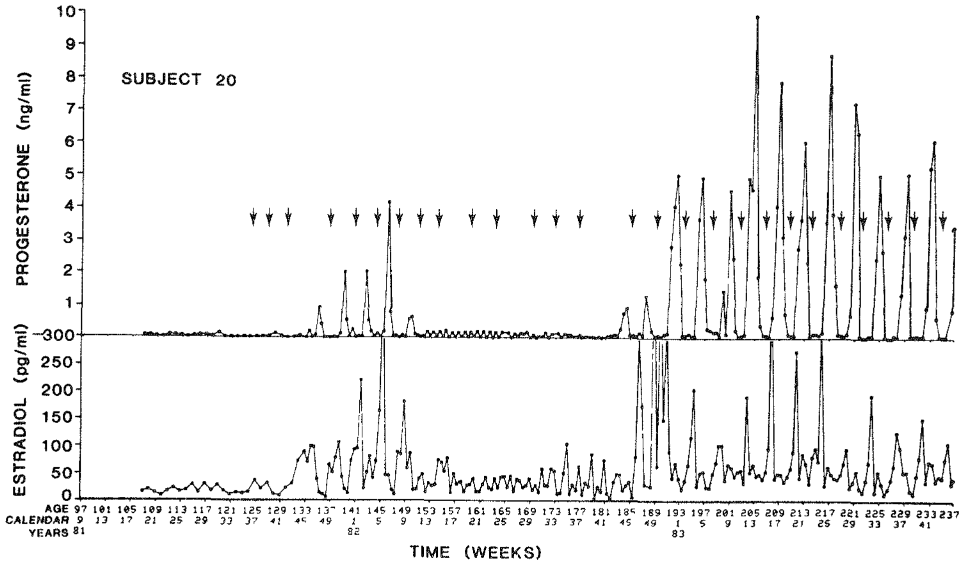

Figure 3. Estradiol and Progesterone Levels of Subject 20, an ELF-Exposed Female, from 106 to 234 Weeks of Age. Observed menstruations are indicated by arrows above the progesterone curve. The abscissa has multiple labels to indicate age and calendar weeks.

Menstruation was not as seasonal as ovulation, in either onset or pattern, following its first occurrence. The month of menarche showed no seasonal peak or lull among these animals. Only slight reductions in the frequency of menstruation were observed in the spring and summer periods during which ovulatory activity diminished.

For the males, the sharp rise in circulating testosterone levels that is a marker event for the onset of puberty occurred abruptly at a particular age for each male (Table 2). As the animals matured, both morning and evening levels of testosterone showed additional increases (Figures 4 and 5). The age at which testosterone levels began to rise corresponds to the age at which the growth curve of the exposed group began to cross over the growth curve of the control group (Figures 2 and 5). During the early period of increasing testosterone levels, the exposed group showed a trend toward higher mean testosterone levels than those in control males (Figures 4 and 5). The differences in mean values were not statistically significant, but the interaction term for both morning (df = 26,778; F = 1.73; α = 0.01) and evening (df = 25,763; F = 1.56; α = 0.04) levels was significant for the period from 157-234 weeks of age. This significant interaction term indicates that the testosterone levels in the two groups were not changing with time in an equivalent manner. However, since no consistent trend is apparent for this period (157-234 weeks), the interaction term may be a result of random variation. Thus, the differences in testosterone levels probably have little or no physiological significance. No significant differences in DHT levels were observed between the groups.

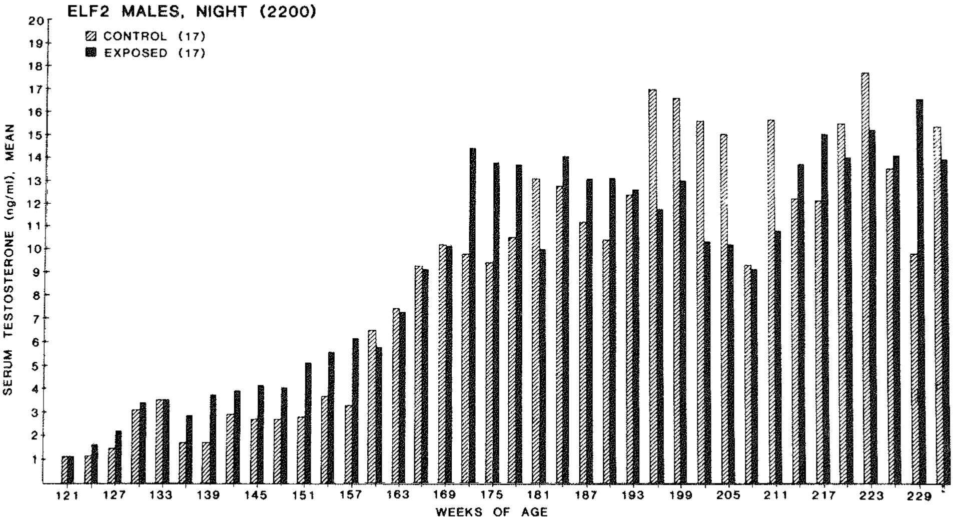

Figure 4. Mean Night Testosterone Levels in Control and ELF-Exposed Male Rhesus Monkeys from 121 to 234 Weeks of Age. Error bars were omitted for clarity. The standard error of the mean was usually 15 to 20% of the mean value.

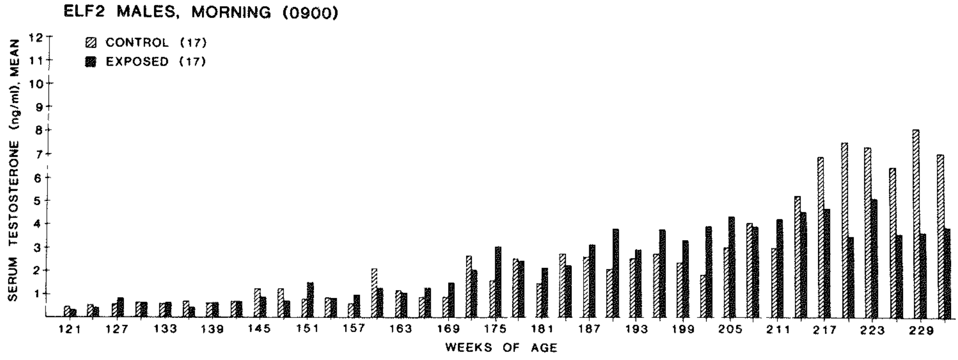

Figure 5. Mean Morning Testosterone Levels in Control and ELF-Exposed Male Rhesus Monkeys from 121 to 234 Weeks of Age. Error bars were omitted.

No statistically significant differences were found between exposed and control animals of either sex for the 11 hematological parameters measured. In general, the health of all of the monkeys in this project, both exposed and control, was excellent. Minor problems, common in rhesus monkey colonies, were noted in both groups, including abrasions, regional alopecia, gingivitis, and hematoma. No substantive differences between the two groups were noted. Results of intradermal skin tests for tuberculosis, performed every 6 months were negative. Bacterial enteritis was also periodically evaluated with rectal swab and culture; no enteric pathogens were identified in these animals.

Tooth eruption was noted during each physical examination. An interim report on these data has been published (David, Harris, and Bley, 1983). No differences between groups were found in the mean age at which permanent teeth erupted.

DISCUSSION

As a followup study, the purposes of this project were to replicate the first ELF chronic study at NAMRL (ELF1), validate the growth-rate-enhancement finding and, if it recurred, to determine the process that caused this growth-rate change. From a statistical viewpoint, ELF2 did not replicate the finding of ELF1 that chronic ELF exposure enhanced the growth rate in pubescent male rhesus monkeys. This study did show, however, that exposed monkeys had a slightly higher growth rate during puberty than their control group counterparts. Thus, in both NAMRL studies, there was a slightly higher growth rate during puberty in ELF-exposed males, but the degree of this enhancement was not as large in ELF2. The effect shown in ELF1 remains qualitatively credible in light of the findings of ELF2, but it was not replicated by ELF2.

As in any other case where an experiment is replicated, but the results are different, it is impossible to unequivocally state which finding is valid. Neither experiment invalidates the other, although an effect that cannot be readily reproduced may be considered so weak as to be inconsequential. It may be that the exposure in question is near a threshold intensity for producing the effect, and that higher intensity exposures would reproducibly stimulate growth in males. Since the monkeys were exposed to ELF fields much stronger than those that will be created by the Navy's ELF submarine communications system, no effect on growth would be expected at the ELF intensities associated with the actual antenna.

The influence of other environmental factors, particularly social isolation, on the monkeys in this study is difficult to assess. As noted in the Methods section, great care was taken to see that the exposed and control groups experienced like conditions in every respect. No comparable data exist from the NAMRL colony from which these monkeys were taken. Very little data exists in the literature that can provide meaningful comparisons to the NAMRL data. For growth, the data of Van Wagenen and Catchpole (1956) covered similar ages for captive-born rhesus monkeys at Yale University, but the housing conditions of the animals were not specified. The mean body mass of NAMRL ELF2 monkeys was nearly identical to that reported by Van Wagenen and Catchpole during the first 2 years of life. Our animals were somewhat smaller than those at Yale after 2 years of age. At 3 and 4 years of age, the mean for our animals (male or female) was approximately one standard deviation below the mean for the Yale monkeys. The monkeys of this study also showed similar growth rates to those reported by Kerr, Scheffler, and Waisman (1969). The hematology results and veterinary examinations for the monkeys in this study indicate that the animals were in excellent health, and not under any unusual stress. The differential white blood cell counts, which are classic indicators of stress, are consistent with a lack of stress among the monkeys.

Of the three hypotheses set forth as plausible explanations of the ELF1 growth-rate effect, only two are possibly compatible with the results of ELF2. Since no differences in growth rate were seen in prepubertal monkeys of either sex, the hypothesis of a generalized anabolic effect can be rejected. Even the small differences in male growth rate observed in ELF2 seemed to be dependent on the higher testosterone levels of puberty. It is still difficult to evaluate the two hypotheses regarding neuroendocrine function. The trend toward slightly higher growth rates in exposed pubescent ELF2 males was coincident with the onset of increased circulating testosterone levels in puberty. In the absence of measurable differences in the testosterone levels of the two groups, there is nothing to directly correlate hormone levels to growth rate in this study. Nor do we believe that analysis of serum samples for luteinizing hormone is likely to clarify the picture. Considerable evaluation of endocrine rhythms in both males and females failed to indicate any aspect of reproductive endocrinology that was affected by ELF exposure. Therefore, this study offers no support for the hypothesis of a generalized neuroendocrine effect. Not only were overall numbers of menstrual cycles in females equal in exposed and control monkeys, but seasonal patterns of ovulation in the female rhesus were similar between groups. The presumed seasonal aspect of ovulatory patterns was especially interesting in view of the fact that these animals were in rigidly controlled light and temperature conditions from birth. We do not think that the significant interactions in E2 and T levels noted in Table 1 have any profound meaning for the study. Indeed, the interactions noted did not carry over into (or from) the adjacent period analyzed. The possible physiological significance of an E2 interaction for females is strongly overshadowed by the similarities in menstrual and ovulatory activity of the two groups. For the males, the interactions were created by oscillating levels of testosterone that, over the entire period, showed control values higher than exposed values at some times and lower at other times. This variability tends to discount any systematic effect that would have physiological, in addition to statistical, significance.

Because it was an observed habit of the male monkeys to sit on the conducting bars of their cages with their scrotums in contact with those bars, we gave considerable attention to the possibility of direct stimulation of the testes by electrical current in ELF1. The monkeys in ELF2 also spent a considerable amount of time in a similar posture, sitting on the bars of the cage. We do not know if there were any quantitative differences in the time spent with the scrotum in contact with the bars during the two studies. Thus, the statistically significant growth effect found in ELF1 males, and the qualitatively similar trends observed in ELF2 males, are consistent with possible direct current stimulation of testicular secretion of testosterone.

In summary, statistically significant differences in the growth, endocrine, or hematological parameters studied were, with minor exceptions, not found in rhesus monkeys exposed to ELF electric and magnetic fields for the first 54 months of life. Growth rates of body mass were slightly, but not significantly, higher in exposed males during puberty than in control males. A transient trend toward higher circulating testosterone levels in exposed males was also observed at the age corresponding to the divergence of the body mass curves. Although these findings did not replicate the previously observed enhanced growth rate in pubescent male monkeys exposed to ELF fields, they did agree qualitatively with the earlier study. However, the results of the second project failed to provide conclusive support for the hypothesis that stimulation of testosterone secretion was the cause of growth enhancement. Based on these two long-term studies of rhesus monkeys at NAMRL, no effects of ELF exposure associated with the submarine communications systems have been observed that appear to be detrimental to the health of the animals.

ACKNOWLEDGMENTS

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The animals used in this study were handled in accordance with the Guide for the Care and Use of Laboratory Animals prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council, DHEW, NIH Publication No. 80-23, 1980.

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EFFECTS OF HIGH-INTENSITY, 60-Hz ELECTRIC FIELDS ON OPERANT AND SOCIAL BEHAVIOR OF NONHUMAN PRIMATES

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ABSTRACT

The Department of Energy conducted a series of experiments at Southwest Research Institute to examine the feasibility of using nonhuman primates in studies on the behavioral effects of electric fields The effects of intermittent exposure to 30-kV/m (unperturbed field strength) electric fields on performance of three different operant tasks were examined In each experiment, one male and one female baboon were used as subjects for each task Analysis of variance on numerous measures of performance revealed few significant field effects Two of the four vigilance subjects had longer or more variable response latencies when the field was "on " One subject on the match-to-sample task responded more slowly to incorrect stimuli when the field was on One subject on the multiple-schedule (fixed-ratio and spaced-responding) had increased variability in response latency for correct responses made on the spaced-responding schedule when the field was on It appears, in these preliminary studies, that exposure to high-intensity electric fields does not appreciably affect the ability of nonhuman primates to perform operant tasks Two groups of four baboons also received intermittent exposure to 30-kV/m electric fields, social behavior data were collected using the methods of primate ethology Analyses of variance in each of 22 behavior categories indicated that the frequencies of five behaviors (Startle, Approach, High Posture, Explore, and Locomotion) were affected significantly by field presence (Durations of Avoid, Autogroom, and High Posture were also affected significantly) Frequencies of six behaviors (Startle, Skin Manipulate, Tension, Allogroom, Avoid, and Approach) and durations of four behaviors (Allogroom, Avoid, Skin Manipulate, and Low Posture) exhibited significant Field x Period interactions In six cases, the differences between field on and off were largest during the first third of the experiment and smallest during the last third High-strength, 60-Hz fields produced measurable changes in social behavior, but the effects do not appear to be permanent or deleterious

Under the sponsorship and direction of the Department of Energy (DOE), we conducted two preliminary experiments that examined the effects of exposure to 30-kV/m (unperturbed field strength) electric fields We have suggested that the close phylogenetic similarity, including complex behavioral capability and relatively human-like body conformation and posture, of the nonhuman primate makes it an excellent model with which to examine and evaluate the effects of electric-field exposure Ultimately, a formalized risk assessment process will be used by DOE to evaluate data from many experiments with nonprimate animal species, a few experiments with nonhuman primates, and limited studies with humans The data from the nonhuman primate experiments will be particularly useful in helping to extrapolate from animal experiments to conclusions about public health

The objectives of the feasibility program were to 1) construct a pilot exposure facility, 2) acquire sufficient operating experience to ensure that an appropriate exposure facility could be designed and constructed in the future, and 3) collect initial data on operant and social behavior so that a definitive research program could be planned

EXPOSURE FACILITY

Design

One of our primary requirements was construction of a baboon-sized facility. The adult male baboon (superspecies *Papio cyncocephalus*) weighs 25 to 30 kg and has a sitting height of almost 1 m. The single outdoor exposure area (Figure 1) included overhead, high-voltage buswork fabricated of welded aluminum conduit and supported 1.9 m above grounded metal grates on fiberglass poles. One grate supported six individual cages for operant subjects; the other grate supported a single larger cage to house four subjects as a social group. The fiberglass cages contained no floors, so that the animals lived primarily on the grounded metal grate. Water was provided through grounded metal Lixit® valves (Laboratory Products, Inc., Hyde Park, MA) mounted low in the cages. The operant cages were fitted with response panels (Figure 2) constructed of materials which did not perturb the field. Each panel included a screen on which visual stimuli could be projected, three manipulanda, and a receptacle for banana-flavored food pellets.

An ac corona test set was connected to the grounded cage-floor grates and to a single high-voltage bus. Measurements of field strength were provided by an optically coupled, spherical dipole probe (Spiegel et al., 1979). Additional descriptions of the facility and data on facility operation are given in Feldstone et al. (1981) and Cory et al. (1984).

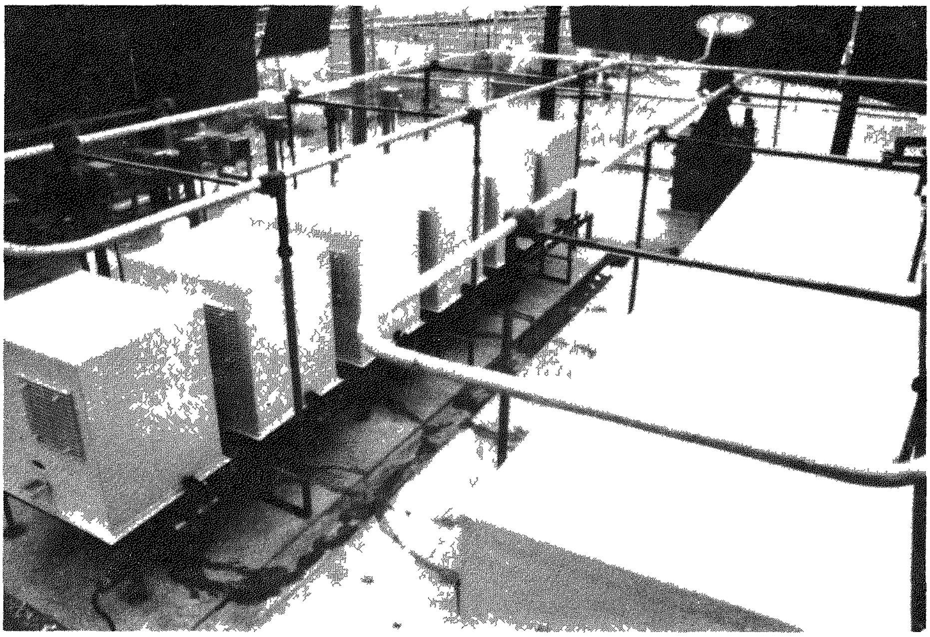


Figure 1 General View of Outdoor Primate Exposure Area, Showing Operant Cages, Social Cage, Grate, Bus, and Transformer

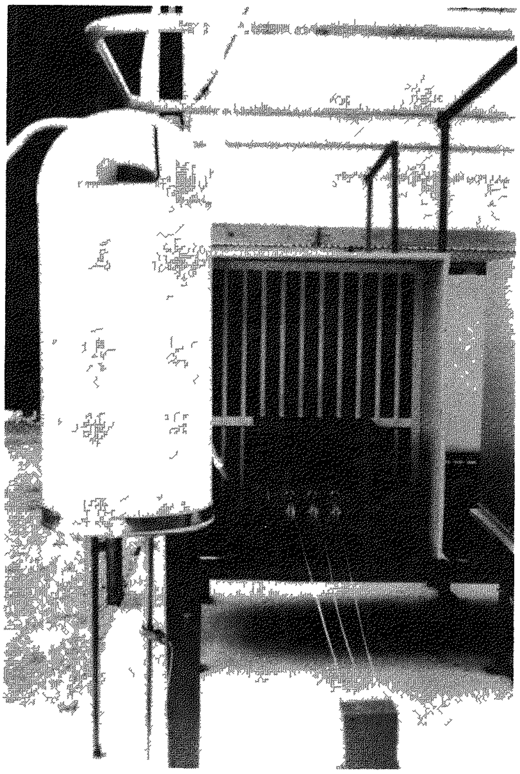


Figure 2. Operant Panel, Including Screen for Visual Cues, Three Pull Switches Serving as Manipulanda, and Pellet Dispenser Covered by Corona Guard

Operating Characteristics

During the exposure periods, the average electric-field strength measured by the probe was just under 30 kV/m (Table 1). Auditory checks for corona sounds were made daily; whenever corona sounds were heard, nocturnal inspection trips were made to isolate and correct the source either by cleaning or by applying corona dressing to the bus or support. Measurements of sound levels and ozone concentration in the outdoor exposure area failed to differentiate between field-on and field-off conditions in either calm or windy weather. Measurements while animals drank indicated current flows of about 80 μA from the animal through the Lixit to ground.

OPERANT EXPERIMENTS

Design

Each experiment used six prepubertal baboons, three male and three female, as operant subjects. The schedule provided for 4 hr of intermittent exposure over a 6-hr period each weekday; a quasi-random alternation between field-on and field-off conditions was made every 30 min. The duration of the electric-field exposure period of the first experiment was 25 days; in the second experiment, it was 58 days.

TABLE 1. Summary of Primate Exposure Facility Operating Characteristics

Measure	Units	Data
Field strength	kV/m	Mean = 29.78, SD = 1.732
Homogeneity	± %	Relative to reference
Overall		11 for 95% of volume
Operant		10
Social		12
Harmonics	db	Relative to 60-Hz
First		none measurable
Second		none measurable
Third		-32.5
Fourth		-50.2
Fifth		-40.2
Drinking current	μA	80 in 30-kV/m field

Operant Tasks

Three operant tasks, vigilance, match to sample, and a multiple schedule with two components, were used. One male and one female performed each task. All six subjects of each experiment were tested daily in randomized order. The subjects were fed at the end of the day; water was available continuously. Complete descriptions of methods used in these experiments are given in Feldstone et al. (1981).

Vigilance. One of three stimuli was projected for a period of either 5 sec (experiment 1) or 10 sec (experiment 2) after variable intertrial intervals averaging 210 sec in the first experiment and 180 sec in the second. Response to the correct stimulus caused delivery of a food pellet. Thus, the animal's job was to avoid missing presentation of any of the stimuli and to identify the correct stimulus when it was presented. The vigilance subjects worked for 3 hr a day.

Match to Sample. This task is considered a test of short-term memory. A "probe" stimulus, one of 10 different, simple, colored geometric shapes, was projected for a period of not more than 30 sec; the subject's job was to pull the center lever. This response produced a delay interval of either 2 sec (experiment 1) or 25 sec (experiment 2), during which no stimulus was present; then stimuli consisting of different pairs of colored shapes were projected over both the right and left levers. The baboon had either 30 sec (experiment 1) or 15 sec (experiment 2) to select, by pulling the lever beneath it, the stimulus pair including the figure used as the probe on that trial. Correct responses earned banana-flavored pellets. Probe stimuli were projected with an average intertrial interval of either 105 sec (experiment 1) or 90 sec (experiment 2).

Multiple Schedule. Depending on which of two stimuli were projected, the baboon's job was to respond appropriately. With one stimulus displayed, the baboon received a reward for every 20th response; i.e., fixed ratio (FR), 20:1. If the other stimulus was displayed, the baboon had to wait at least 5 sec, but not more than 10 sec, before responding. This is a spaced responding (SR) task with a 5-sec limited hold for reinforcement availability. (In experiment 2, the delay was increased to 9 sec, the longest period for which 90% successful performance was achieved during the pre-exposure training period; the limited hold remained 5 sec.) This problem can be considered a test of timing ability; if the baboon responds either too soon or too late, no reward is earned. Because this task requires the baboon to inhibit responses and to depend on internal (timing), rather than external (response-counting) cues, it is regarded as a more difficult task.

Because of computer limitations, these tasks were discrete trials. The FR cue light remained on for 60 sec, and the SR cue light remained on for 20 sec. Receipt of a reward terminated the trial. The intertrial interval was either 105 sec (experiment 1) or 90 sec (experiment 2), and five consecutive trials on continuous reinforcement were given before the task was changed from FR to SR or vice versa.

Data Analyses

Because a large number of trials were conducted under both field-on and field- off conditions, it was possible to conduct separate data analyses for each operant subject. Multiple *t*-tests were used to compare field-on and field-off data from experiment 1. For experiment 2, analysis of variance (ANOVA) was used to examine the effects of 1) field (on or off), 2) period (quarters of the experiment), and 3) the interaction of field and period.

For both experiments, means and standard deviations (SD) of all possible performance measures, including numbers of correct and incorrect responses, intertrial interval responses, response latencies, etc., were analyzed. Thus, a total of 70 dependent variables, 7 per subject for the vigilance task, 11 per subject for the match-to-sample task, and 17 (8 on the FR schedule and 9 on the SR schedule) for the multiple-schedule task, were analyzed in each experiment. When conducting multiple tests on the data from a single animal, alpha values much smaller than 0.05 were used on each test to keep the overall Type I error rate at $P < 0.05$.

Results

Only five statistically significant field effects were observed as a result of the extensive data analyses (Feldstone et al., 1980). In the first experiment (Table 2), the female vigilance subject had a twofold greater response variability while making correct responses when the field was on. None of her six other performance measures was affected significantly. The male vigilance subject and the four other baboons of both sexes working on the other two tasks exhibited no statistically significant changes in their operant behavior.

In the second experiment, both the mean and SD of response latency to the correct stimulus in the vigilance task for the female subject were slightly greater when the field was on (Table 2). As in the first experiment, the male vigilance subject exhibited no statistically significant field effects. However, in contrast to the first experiment, the male subjects working on the match-to-sample and multiple-schedule tasks showed slight performance decrements during electric-field exposure; the mean latency for incorrect responses on the match-to-sample task and the variability in latency for incorrect responses on the SR component were increased. As in the first experiment, the female baboons working on the match-to-sample and the multiple-schedule tasks showed no field-related changes in operant behavior.

TABLE 2. Summary of Statistically Significant ($P < 0.05$) Electric-Field Effects on Operant Behavior of Baboons

Subject	Sex	Task	Effect
Experiment #1			
2149	F	Vigilance	SD of latency on correct response On = 1.03 Off = 0.52
Experiment #2			
2559	F	Vigilance	Mean latency on correct response On = 2.184 sec Off = 2.020 sec
2559	F	Vigilance	SD of latency on correct response On = 0.538 Off = 0.417
2421	M	Match to Sample	Mean latency on incorrect response On = 2.130 sec Off = 1.439 sec
2419	M	Spaced Responding	SD of latency on correct response On = 2.115 Off = 1.772

In addition to the four field effects, two field x period interactions were detected in the second experiment. For the female vigilance subject (Figure 3), the difference in mean response latency between field-on and field-off conditions was present only in the first 14 days of exposure. A field x period interaction was also detected for the response latency on the SR component (Figure 4). Here, the difference between field-on and field-off conditions appeared only during the first 28 days of exposure.

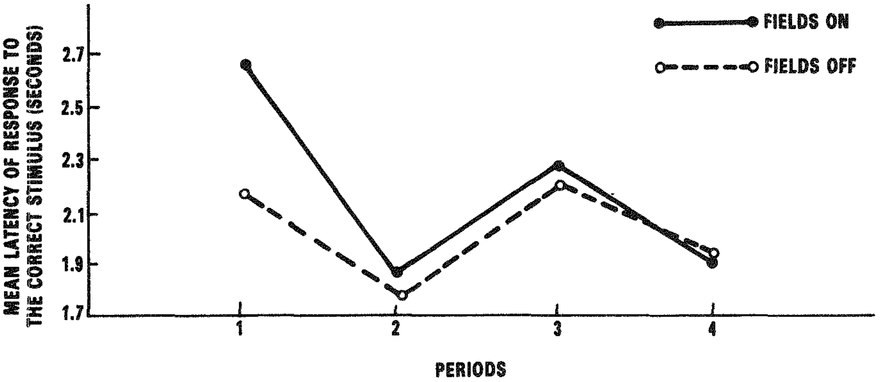
Discussion

The results from these limited, preliminary experiments do not strongly suggest that electric-field exposure affected operant behavior. All observed effects involved response latencies; accuracy of performance and number of responses were not affected. In experiment 2, where data analysis included a comparison of early through late exposure periods, two of the four subtle performance decrements detected disappeared after only 4 wk of electric-field exposure. Possibly, distraction by the cutaneous consequences of exposure to an intense electric field (e.g., hair stimulation) was involved in both the appearance and disappearance of the observed effects.

SOCIAL BEHAVIOR EXPERIMENT

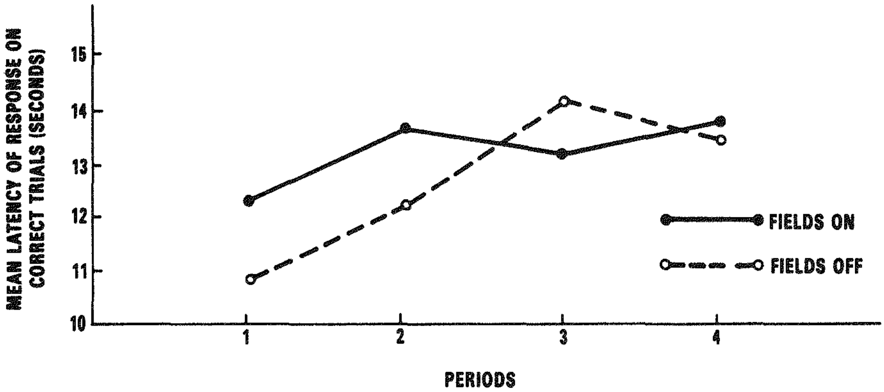
Design

When the operant experiments described above were completed, the social behavior of groups of subadult baboons (two males and two females per group) was studied, using the quantitative observational methods of primate ethology.



PERIODS BY FIELDS INTERACTION FOR VIGILANCE – SUBJECT NO. 2559 (FEMALE)

Figure 3. Field x Period Interaction for Response Latency on Correct Trials by Subject 2559.



PERIODS BY FIELDS INTERACTION FOR MULTIPLES SCHEDULE (SPACED-RESPONDING COMPONENT) – SUBJECT NO. 2419 (MALE)

Figure 4. Field x Period Interaction for Response Latency on Spaced Responding for Subject 2419.

Observational Tasks

Focal Animal Observation. In order to acquire quantitative data on social behavior, a focal animal observational procedure (Coelho and Bramblett, 1981) was used. For 10 min, everything that a single animal did, and everything done to it by other animals, was recorded through an electronic terminal to provide a complete sequential listing, with durations, of all behavioral acts. (A trained observer can recognize the "pieces" of baboon behavior just as reliably as a trained technician can record readings from the scale of a meter.) A sampling schedule was used to ensure that each subject was observed equally often throughout the day. Combination of results from many tests allows determination of the average frequency and duration of occurrence of each of the behavior categories.

Instantaneous Scan. In experiment 2 another behavioral sampling technique, the instantaneous scan procedure (Altman, 1974), was used in an effort to learn more about the subjects' use of space in the electric-field environment. Twice per hour, an observer took a "mental snapshot" of the scene; then, using one of eight standard locations, the observer recorded each animal's position in the cage.

Results

Focal Animal Data. To increase the sample size and simplify presentation and interpretation of results of the focal animal tests, the data from the first 25 days of each of the two experiments were combined. (The same observational techniques were used in both experiments.) Using separate ANOVA, both frequency and duration data for each of the 22 behavior categories were examined (Rogers, 1982). The factors in the analysis were group (1 and 2), field (on or off), and period (early, middle, or late portions of the exposure period). The use of the group and period factors was to facilitate performing tests on the questions of primary interest. The objective was to detect statistically significant field and field x period interaction effects; group and period effects per se are not of interest in the context of this report.

The nine statistically significant field effects revealed by the 44 ANOVA are listed in Table 3. Generally, the magnitude of the differences is relatively small. Both the frequency with which one animal approached another and the length of the period before another behavior occurred after that increased when the 30-kv/m field was on (Gibson, 1984). The duration of an avoid was shortened, and frequency of self-grooming increased by 33%. When the field was on, the frequency of locomotion and explore were less, and both the frequency and duration of high postures decreased. Although the rate of startle behavior is very low, it occurred three times more often during field-on conditions.

There were also 10 statistically significant field x period interactions. For three categories (grooming of other animals, avoidance of other animals, and rapid self-grooming; Table 4), both the frequency and duration of the behavior depended on both field condition and period. A graphical representation of one of these behaviors, the frequency of allogroom, is given in Figure 5. Initially, the field-on condition produced an increase in the frequency of grooming of other animals, but the animals quickly adapted to the new environment, and the frequency of allogroom returned to normal. The rate of allogroom during field-off conditions was constant. This example is prototypical; some of the interactions were not readily interpretable, either because the behavior differed irregularly across periods or because temporal changes in behavior occurred in field-off as well as in field-on conditions. In addition, the frequency of approach, startle, and tension behaviors (Table 4) and the duration of low-posture behaviors showed field x period interactions.

TABLE 3 Summary of Statistically Significant ($P < 0.05$) Effects of 30-kV/m Electric Fields on Behavior in Baboon Social Groups

Behavior	Measure	Field On	Field Off	P <
Approach	Frequency[a]	63	51	0.01
Approach	Duration[b]	79	69	0.005
Avoid	Duration	6.4	7.4	0.05
Autogroom	Duration	36	27	0.02
Explore	Frequency	2.3	3.0	0.02
High Posture	Frequency	11	13	0.01
High Posture	Duration	99	114	0.03
Locomotion	Frequency	39	48	0.03
Startle	Frequency	0.24	0.07	0.001

[a] Mean frequency per 10-min test
[b] Mean duration (sec) per occurrence

TABLE 4 Summary of Statistically Significant ($P < 0.05$) Electric Field x Period Interactions Detected in 30-kV/m Experiment with Baboon Social Groups

Behavior	Measure	Field Status	Period Means 1	Period Means 2	Period Means 3
Allogroom	Frequency[a]	On	1.50	1.14	0.98
		Off	0.98	0.98	0.99
Allogroom	Duration[b]	On	91	96	94
		Off	82	83	118
Avoid	Frequency	On	2.3	1.9	1.6
		Off	1.9	2.1	2.5
Avoid	Duration	On	6.3	6.0	5.1
		Off	6.6	7.2	8.4
Skin Manipulate	Frequency	On	0.47	0.16	0.08
		Off	0.09	0.11	0.03
Skin Manipulate	Duration	On	55	42	36
		Off	26	31	23
Approach	Frequency	On	6.9	6.2	5.7
		Off	4.8	5.1	5.4
Low Posture	Duration	On	196	192	216
		Off	241	217	205
Startle	Frequency	On	0.47	0.16	0.08
		Off	0.09	0.11	0.03
Tension	Frequency	On	2.6	2.2	1.8
		Off	1.3	2.3	1.6

[a] Mean frequency per 10-min test
[b] Mean duration (sec) per occurrence

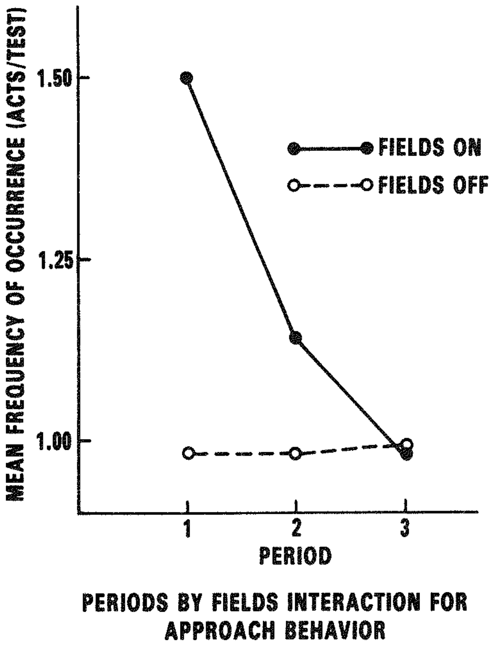


Figure 5. Field x Period Interaction for Frequency of Approach Behaviors.

The results of all analyses are summarized below:

Summary of Statistically Significant (P < 0.05) Effects of 30-kV/m Electric Fields on Behavior of Baboons Living in Small Social Groups

<u>Social Behaviors (n = 9)</u>

- Affinitive Contact
- Agonistic
  - Anxious
  - Aggressive
- Allogroom (A, C)[a]
- ↑↑Approach (A)
- ↓Avoid (C,C)
- Play
- Sexual Contact
- Tension (A)

<u>Solitary Behaviors (n = 7)</u>

- ↓Explore[b]
- ↓Locomotion
- Posture
  - ↓↓ High
  - Low (C)
- Sexual Arousal
- ↑Startle (A)
- Stereotypy

<u>Maintenance (n = 6)</u>

- ↑Autogroom
- Defecate
- Drink
- Eat
- Skin Manipulate (A, A)
- Urinate

[a] A, C Pattern of field x period effect; A = Adapt, C = Complex
[b] ↑↓Direction of field effect

Half of the major behavior categories were affected in some way. Six behaviors exhibited statistically significant field effects, and 10 exhibited field x period interactions. Six of the interactions fit an "adaptation" pattern; the remaining four are not easily interpreted.

Scan Observations. Frequencies observed for the eight cage positions were tabulated, and the frequencies expected for use of each position were computed (Table 5). The animals' use of their cage space varied significantly with electric-field condition. When tested individually, the use of only two locations differed significantly for field-on and field-off conditions. The perch was used less frequently (chi square = 19.88, df = 1, $P < 0.001$), and the animals were in contact with the upper portion of the cage bars significantly less often (chi square = 4.91, df = 1, $P < 0.05$) when the field was on. Follow-up analyses also indicated that the animal's use of the top versus the bottom of the cage (Table 6) was significantly affected by the presence of the electric field. Comparing three locations associated with the top of the cage with five locations on the bottom of the cage indicated a significant reduction in the frequency of use of the upper cage region when the field was on.

TABLE 5. Observed and Expected Frequency[a] of Baboons' Use of Cage Locations During Electric-Field-Off and Field-On Conditions

Cage Location	Field Off		Field On	
	Observed	Expected	Observed	Expected
Upper Portion of Cage				
On Perch[b]	69	45	65	89
Front Bars[c]	17	11	16	22
Side or Back	39	39	77	77
Lower Portion of Cage				
Front Bars	241	227	432	446
Side or Back	67	71	142	138
On Grate	700	732	1469	1437
Food Hole	61	69	143	133
Lixit	13	13	27	27
TOTAL	1207		2371	

[a] chi square = 28.57, df = 7, $P < 0.001$
[b] $P < 0.001$
[c] $P < 0.05$

TABLE 6. Observed and Expected Frequency[a] of Baboons' Use of Cage Top and Bottom Locations During Electric-Field-Off and Field-On Conditions

Condition	Top of Cage	Bottom of Cage
Field Off	125 (95)	1082 (1112)[b]
Field On	158 (188)	2213 (2183)

[a] chi square = 14.97, df = 1, $P < 0.001$
[b] expected frequency

Discussion

The baboons clearly responded to introduction of the high-intensity 60-Hz electric field, perhaps because the field is a novel stimulus; the species has no evolutionary history of exposure to strong electric fields. When exposed, the baboons made modest changes in their grooming behavior, social behavior, and use of space. However, these often temporary changes all appeared to be successful adaptations. It is reasonable to assume that they were responding to the same sensory consequences, presumably cutaneous, which human primates report when they are exposed to strong electric fields. Thus, increased self-grooming, reduced use of vertical postures, and increased use of low postures are likely responses: human primates in strong electric fields tend to do the same things.

The increased approach and reduced avoidance behaviors might have been efforts to reduce effective field strength through mutual shielding. This is another reasonable response to exposure to a strong electric field. However, for baboons, staying close together has two important consequences: 1) they cannot be doing other things, such as moving about the environment; 2) proximity may violate the rules of baboon etiquette about use of space. Being "too close" can increase behaviors indicating tension; baboons reduce tension by social grooming. Apparently, this process occurred initially in this experiment.

Although normal social behavior was altered, no adverse effects resulted; an existing social mechanism was used to successfully solve the closeness problem until the animals learned that the strange environment was not important and returned to their normal ways.

Presumably, the animals used positions allowing them to touch the upper portions of the front cage bars less often when the electric field was on because such vertical postures resulted in maximal field perturbation and enhancement. It appeared that the animals were reluctant to return to the grounded grate from the ungrounded perch when the field was on; presumably, they received microshocks when returning to the grate.

Perhaps more important than the behaviors that changed as a result of exposure to electric fields are the behaviors that did not change. The latter were of two key types: 1) Basic maintenance behaviors, such as eating and drinking, were not affected, so the animals' basic health was not changed to any important degree. Although care of the body surface increased, it did not lead to damaged skin. 2) The baboons' social stress behaviors were not affected. The normal patterns produced by primate evolution continued; behavioral pathology, such as increased aggression, did not occur. Neither the individuals nor their society appeared to be impacted adversely by the 30-kV/m electric field.

CONCLUSIONS

The feasibility program met its goals. Based on this experience, an experimental program was developed, and an exposure facility was designed. As described earlier in this meeting (Cory et al., 1984), the High-Voltage Primate Exposure Facility has been constructed, and funding to conduct the research program has been obtained.

ACKNOWLEDGMENT

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EVALUATION OF REPRODUCTION AND DEVELOPMENT IN HANFORD MINIATURE SWINE EXPOSED TO 60-Hz ELECTRIC FIELDS

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ABSTRACT

Evaluations of reproductive and developmental toxicology, including teratology, were included as part of a broad screening study in Hanford Miniature swine (HMS) to detect effects attributable to exposure to electric fields. One group (exposed [E]) was exposed to a uniform, vertical, 60-Hz, 30-kV/m electric field for 20 hr/day, 7 days/wk; sham-exposed (SE) swine were housed in a separate, environmentally equivalent building. The first-generation (F_0) gilts were bred after 4 mo on study; some were killed for teratologic study at 100 days of gestation (dg), and the others produced an F_1 generation of offspring. The pooled incidence of terata in these litters (for both the teratologic study and live births) was similar in the E and SE groups. The F_0 females, which produced the F_1 generation, were rebred after 18 mo of exposure and were killed at 100 dg. Malformation incidence in E litters (75%) was significantly greater than in SE litters (29%). No consistent differences in litter size, fetal weight, or weight of fetal organs were detected. The F_1 gilts were bred at 18 mo of age; there were indications of impaired copulatory behavior and decreased fertility in the E animals. Defective offspring were found in significantly more of the E litters (71%) than in SE litters (33%). The F_1 sows were bred again 10 mo later, and teratologic evaluations were performed on their second litters at 100 dg. The percentage of litters with malformed fetuses was essentially identical in the E and SE groups (70 and 73%, respectively). The change in malformation incidences between generations and between the first and second breedings makes it difficult to unequivocally conclude that chronic exposure to a strong electric field causes developmental effects in swine, although there appears to be an association.

Studies in rodents generally have failed to detect any indications of significant teratologic effects resulting from exposure to 60-Hz electric fields during prenatal development (Sikov, Montgomery, and Smith, 1979; Sikov et al., 1984). There have been only a few sporadic reports of exposure-related effects on reproduction (Coate et al., 1970) or on various measures of the postnatal growth or viability of the offspring in rodents (Knickerbocker, Kouwenhoven, and Barnes, 1967; Marino, Becker, and Ullrich, 1976; Marino et al., 1980).

In 1978, we initiated a broad-based screening evaluation in Hanford Miniature swine (HMS) exposed to 60-Hz electric fields. This study was undertaken to detect effects produced by chronic exposure of a large, long-lived species over multiple generations. Although there were few clearly deleterious effects in earlier studies with rodents, the exposure periods were of relatively short duration compared to the extended exposures planned for the study described in this report. Moreover, it was recognized that current densities and flow patterns might be different in species larger than rodents (Kaune and Phillips, 1980). Therefore, the decision was made to include teratologic evaluations as a supplement to the reproductive measures which were inherent components of the protocol for the studies in swine. A brief description of these studies and the results of reproductive and teratological evaluations on the prenatal and postnatal litters of the parental (F_0) and the filial (F_1) generations are presented in this report.

MATERIALS AND METHODS

The facility for exposing miniature swine to a uniform, vertical, 60-Hz, 30-kV/m electric field has been described in detail by Kaune et al. (1979; Kaune and Phillips, 1980). Exposed and sham-exposed populations of swine were housed in separate, environmentally equivalent buildings. Both buildings were illuminated from 5:00 a.m. to 5:00 p.m. each day. Heating, ventilating and air-conditioning systems limited the maximum daily temperature variation to about 3.5°C in the exposure building and 4°C in the sham-exposure building. The average daily temperatures and relative humidities of the exposure and control building were similar, about 23°C and 40%, respectively.

The electric-field uniformity over the area of an empty swine stall was 2.5% at ground-level and ± 8% at the maximum height of a pig. Total electric field harmonic distortion was 0.5%. The swine were not subjected to spark discharges; the current between a drinking pig and its water nozzle was less than 20 μA. There were no detectable levels of audible noise, hum, vibration, or ozone attributable to the high-voltage system. The electric field was energized for 20 hr/day, 7 days/wk. The system was de-energized from 8:00 a.m. to 12:00 noon each day for cleaning and feeding and to allow scheduled experimental activities.

The F_0 generation of 49 parental female HMS was derived from 18 litters produced by 13 closely related sows that were bred by a single boar. Based on the requirement (dictated by the difference in size of the exposed and sham-exposed animal facilities) that group sizes be approximately in the ratio of three exposed to two sham-exposed animals, a final apportionment was made shortly before the oldest animal attained 18 mo of age. The assignments were designed to insure genetic homogeneity, equivalence in body size and shape of the pigs, and similarity of hematologic and serum biochemistry parameters in the exposed and sham-exposed groups. This resulted in 31 animals being assigned to the exposed and 18 to the sham-exposed group. These animals and their offspring continued on their assigned exposure regime throughout the remainder of the study.

After 4 mo in the system, all gilts from the exposed and sham-exposed populations were bred to one of four unexposed boars (Figure 1). Some of these F_0 gilts (18 exposed and 10 sham-exposed) produced a second generation (F_1); they and their litters were continued on the assigned regimen (exposed or sham-exposed [Figure 1]). Their offspring were counted, weighed, and examined for clinical status and gross morphologic aberrations following farrowing, and at regular intervals thereafter. In some cases (exposed and sham-exposed) the entire litter died or was killed immediately after farrowing. These F_0 sows were bred again and, together with the remaining F_0 swine (F_0 swine that were not included in the 18 E, 10 SE that produced the 2nd generation), were killed approximately 14 days before normal parturition. The fetuses from the resulting seven exposed and seven sham-exposed litters were subjected to teratological evaluation at 100 (99 to 101) days of gestation (dg); this group will be called Teratology I.

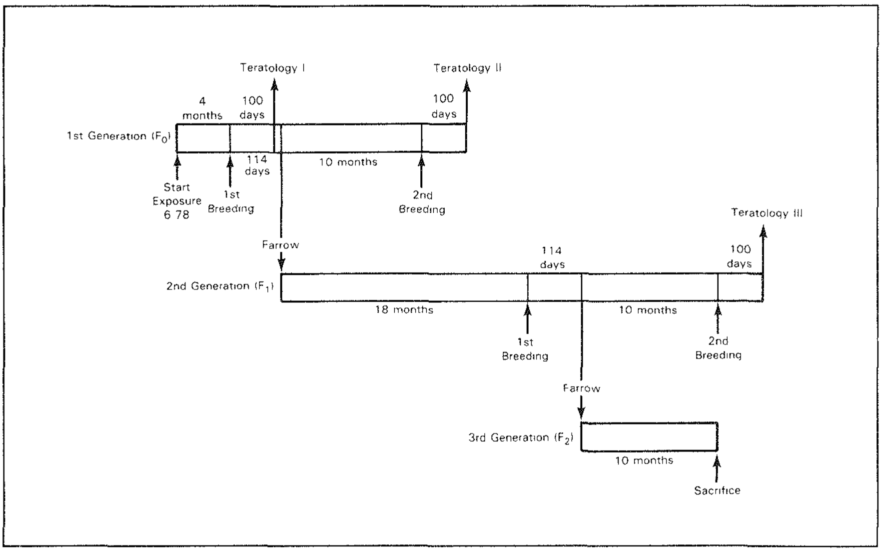

Figure 1. Sequence of Events in Experiment in which Hanford Miniature Swine were Exposed (or Sham-Exposed) to a 60-Hz, 30-kV/m Electric Field.

Symptoms of illness (anorexia, diarrhea, vomiting and lethargy) were noted in several F_0 pigs in the exposed group at a time corresponding to mid-pregnancy of the last three swine of the electric-field-exposed group assigned to Teratology I. This time also corresponded to the last 4 dg in three sows scheduled to deliver their first litters (Figure 1). For this reason, all F_0 animals and their F_1 offspring in both exposed and control groups were treated with Furacin® (4.5% nitrofurazone) in their drinking water for 2 wk. In addition, the F_0 swine received intramuscular injections of penicillin G with streptomycin for 3 days. All symptoms of illness disappeared within 10 days. A decision was made to delete from the study the litters of the three exposed animals assigned to Teratology I that were pregnant during the epidemic. Our rationale was that it would be impossible to unequivocally determine whether or not any developmental toxicity was related to the illness.

The F_0 sows that produced the F_1 generation were bred again to unexposed boars after 18 mo of exposure or sham-exposure. Exposure or sham-exposure continued during the first 100 dg, at which time the sows were killed, and their litters were evaluated. This group (Teratology II) consisted of 19 exposed and 10 sham-exposed sows. Three of the exposed and two of the sham-exposed sows were not pregnant, resulting in group sizes of 16 exposed and 8 sham-exposed litters for teratologic evaluation.

The F_1 females were bred at 18 mo of age and allowed to farrow the F_2 generation, which comprised 28 exposed and 12 sham-exposed litters. Because of the findings in Teratology II, neonatal morphologic evaluations were performed in greater detail than previously. In addition, radiographs were prepared and evaluated on all dead offspring; dead piglets were also dissected, using an abbreviated protocol similar to that for teratologic evaluations.

The F_1 females were bred again after an additional 10 mo of exposure or sham-exposure. They were killed at 100 dg, and teratologic evaluations of their prenatal litters were performed (Teratology III). Of the 29 animals in the exposed group and 14 in the sham-exposed group, two and three, respectively, were not pregnant, yielding group sizes of 27 and 11.

Teratologic Evaluations

Similar protocols were used for evaluating the pregnant swine and for their litters at 100 dg. In Teratology I and II, the swine were first anesthetized with intravenous thiamylal sodium (Suritol®), then maintained on a surgical plane with inhaled fluothane and oxygen. Fetuses were removed at approximately 5-minute intervals, allowing for collection of amniotic fluid and blood samples for other evaluations in the study. In Teratology III, the swine were anesthetized with intravenous sodium pentothal and immediately exsanguinated by severing a major vessel. The gravid uterus, with ovaries attached, was excised and weighed; the fetuses were then removed. The protocols for analysis of reproductive status were expanded in Teratology III to include determination of ovarian weights, number of corpora lutea, patency of the oviducts, and variations in the appearance of the placenta.

Immediately upon removal, each fetus was radiographed in the dorsoventral and lateral positions, then inspected for external malformations. The radiographs were subsequently examined for skeletal anomalies. The weight, crown-rump length, and sex of each fetus were recorded. Four measurements of external skull dimensions (occipital-nose, occipital-frontal, maximum skull width, and interorbital distance) were obtained.

A detailed necropsy of each fetus was performed, including inspection of the palate and counting the number of erupted teeth. Each fetus was dissected, and the organs of the abdominal, thoracic, and cranial cavities were examined in situ; the heart and kidney were incised to detect internal malformations. Selected major organs were examined, removed, weighed, and fixed in 10% neutral buffered formalin (NBF) for subsequent review or for histologic examination.

Anatomic alterations that were considered to arise from deficits in embryogenesis were *defined as malformations, and those that were considered to preclude indepen*dent postnatal survival in the wild or without therapeutic intervention were classified as "life-threatening" malformations. A number of the other fetal lesions that were observed, such as petechial hemorrhages, were apparently induced by anesthesia or by surgical procedures used in Teratology I and II since their incidence was much lower in Teratology III. These lesions were not categorized as malformations and are considered fetal pathologies.

Statistical Analysis

The literature contains several different approaches for statistical analysis of teratologic and developmental toxicity data. Responses of fetuses are not completely independent, since maternal influences and the response of pregnant animals to environmental factors may cause littermates to respond more similarly than fetuses from different litters. Most data were analyzed on the litter basis because statistical test procedures require that basic sampling units be independent. However, the small sizes of the groups can lead to Type II statistical errors, i.e., rejection of a difference that may be real. Accordingly, in addition to analyzing continuous variables on a litter basis, we also tabulated and statistically analyzed data using means of individual responses. The incidences of malformations were also analyzed on an individual as well as on a litter basis.

Fetal weights from each litter were evaluated to detect runted fetuses, using the method of McLaren and Michie (1960), which is based on the objective criteria presented by Dixon (1953).

Continuous univariate results from sham-exposed and exposed groups were compared by two-sample *t*-tests. Equality of variances were tested with an F- test. The *t*-test for separate variances was used when the variances for the two groups were not equal, and the *t*-test for pooled variances was used when the variances were equal. Response proportions, e.g., proportion of prenatal deaths/litter, were also analyzed by *t*-tests after an arcsin transformation, $\theta = 2 \arcsin \sqrt{p}$, where p equals the proportion. A two-tailed *t*-test was used,and the level of significance was 0.05, unless specified otherwise.

Analysis of variance was used to analyze continuous data, such as body weights, organ-to-body weight percentages, crown-rump lengths and skull dimensions. This method of analysis considers not only the electric-field effect but also the litter and sex effects. The chi-square statistic was used for comparison of binary response variables between sham-exposed and exposed groups. Binary response variables included number of litters with malformations and number of litters with runts. This type of data was classified in an R x C contingency table. Usually, the tables were 2 x 2 contingency tables and, if the numbers were small, Fisher's exact test was used rather than relying on the chi-square approximation. Other nonparametric methods were used to analyze data where the underlying distribution was not easily specified; for example, a median test was used to compare the difference between litter sizes of sham-exposed and exposed groups.

RESULTS

Reproductive Outcome and Fetal Status — Teratology Studies

Several measures of reproductive performance and fetal well-being, as determined in the teratology evaluations, are presented in Table 1. There were no statistically significant differences in the fraction of swine which were pregnant or in mean number of implants per litter between the exposed and sham-exposed groups in any of the teratology studies. The mean number of live fetuses per litter was slightly greater in the exposed than in the sham-exposed group in all teratology studies, but the difference was statistically significant ($P < 0.05$) only in Teratology I. There was also significantly less prenatal mortality in the exposed group than in the sham-exposed group of Teratology I when considered on the basis of either the overall fraction of fetuses that were dead ($P = 0.01$) or the mean proportion within litters affected ($P = 0.04$). The differences were not significant when considered on the basis of fraction of litters affected ($P = 0.10$). Similar, but weaker and not significant, trends were detected in Teratology II and III. Mid-gestation deaths, evidenced in swine as mummified fetuses, occurred exclusively in the sham-exposed group of Teratology I and in the exposed groups of Teratology II and III. In Teratology I, the eight mid-term deaths occurred in only two litters, but the four deaths in Teratology II and the eight in Teratology III occurred as single events within litters. As a result, the fraction of affected litters in the exposed group of Teratology III was significantly greater than in the sham-exposed group, but the differences in Teratology I and II were not statistically significant. The biological significance of these findings is uncertain. The values for the remaining measures were similar in exposed and sham-exposed litters of all three teratology studies.

TABLE 1. Reproductive Performance and Fetal Viability in Litters of F_0 Hanford Miniature Swine Exposed or Sham-Exposed to a 60-Hz Electric Field for 4 Months (Teratology I) or 18 Months (Teratology II), or in Second Litters of F_1 Swine Exposed from Conception through 32 Months of Age (Teratology III)

	Teratology I		Teratology II		Teratology III	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Total number assigned	8	7	19	10	29	14
Number Nonpregnant	1	0	3	2	2	3
Group Size	7	7	16	8	27	11
Corpora lutea (mean ± SE)					8.2 ± 0.4	8.9 ± 0.4
Total implants	53	52	142	69	168	67
Implants/litter (mean ± SE)	7.6 ± 0.5	7.3 ± 1.5	8.9 ± 0.5	8.6 ± 0.5	6.2 ± 0.3	6.1 ± 0.3
Live fetuses	53	37	101	43	133	49
Live fetuses/litter (mean ± SE)	7.6 ± 0.5[a]	5.3 ± 0.8	6.3 ± 0.5	5.4 ± 1.0	4.9 ± 0.3	4.4 ± 0.4
Litters with prenatal mortality	0	3	14	8	18	9
Prenatal deaths	0[a]	15	41	26	35	18
Early (resorptions)	0	7	37	26	27	18
Mid-gestation (mummified)	0	8	4	0	8	0
Resorptions/litter (mean ± SE)	0	1.0 ± 0.9	2.3 ± 0.4	3.3 ± 0.7	1.0 ± 0.2	1.6 ± 0.4
Mummified fetuses/litter (mean ± SE)	0	1.1 ± 0.8	0.3 ± 0.1	0	0.3 ± 0.1[a]	0
Prenatal deaths/litter (mean ± SE)	0[a]	2.1 ± 1.3	2.6 ± 0.4	3.2 ± 0.7	1.3 ± 0.2	1.6 ± 0.4
Percent males	49	51	52	49	56	51
Litters with runts	1	0	3	0	1	1
Number of runts	1	0	3	0	1	1

[a] Statistically significant difference between exposed and sham-exposed groups.

Reproduction, Fertility and Perinatal Mortality—Postnatal Litters

Breeding of the F_0 gilts was uneventful. As indicated in the description of the methodology, all of the offspring in some of the litters of both exposed and sham-exposed litters died or were killed immediately after parturition. The incidence was similar in both groups, and results from these litters are not included in Table 2, which presents data regarding the remainder of the population. The fraction of bred gilts that became pregnant and delivered litters was similar in the exposed and sham-exposed F_0 populations (Table 2). The numbers of offspring per litter, and the incidences of stillbirths and neonatal deaths were similar in the two groups.

The first breedings of the sham-exposed F_1 gilts initially proceeded successfully, but most of the exposed gilts repeatedly refused to copulate, even though the same unexposed boars were used in both groups (Figure 2). This presumably led to deteriorating mating performance by the boars and a subsequent copulatory deficit in both groups of gilts. Breeding was temporarily discontinued and revised animal husbandry procedures were instituted. Subsequently, both groups copulated readily, and the percent of mated F_1 animals that maintained pregnancy and gave birth to litters was similar in both groups, as was the percent of prenatal deaths of offspring (Table 2).

TABLE 2. Fertility and Perinatal Mortality in First Litters of Hanford Miniature Swine Exposed or Sham-Exposed to a 60-Hz Electric Field for 4 Months (F_0 Dams), or Exposed from Conception through 18 Months of Age (F_1 Dams)

	F_0 Dams		F_1 Dams	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Total number assigned	20	11	29	14
Number Nonpregnant	2	1	1	2
Number of litters	18	10	28	12
Number born	112	58	149	57
Offspring/litter	6.2 ± 0.5	5.7 ± 0.7	5.1 ± 0.4	4.8 ± 0.4
Stillborn	4	6	6	3
Neonatal deaths	33[a]	20[b]	44[c]	18
Killed by sow	7	12	9	7
Laid on by sow	8	1	3	2
Weak	13	6	31	9
Unknown cause	5	1	1	0

[a] Excludes data from three litters born during epidemic (17 newborn [see text])
[b] Excludes one piglet that died when blood sample was taken
[c] Excludes 12 piglets (two litters) that died apparently because of the failure of the farrowing heater

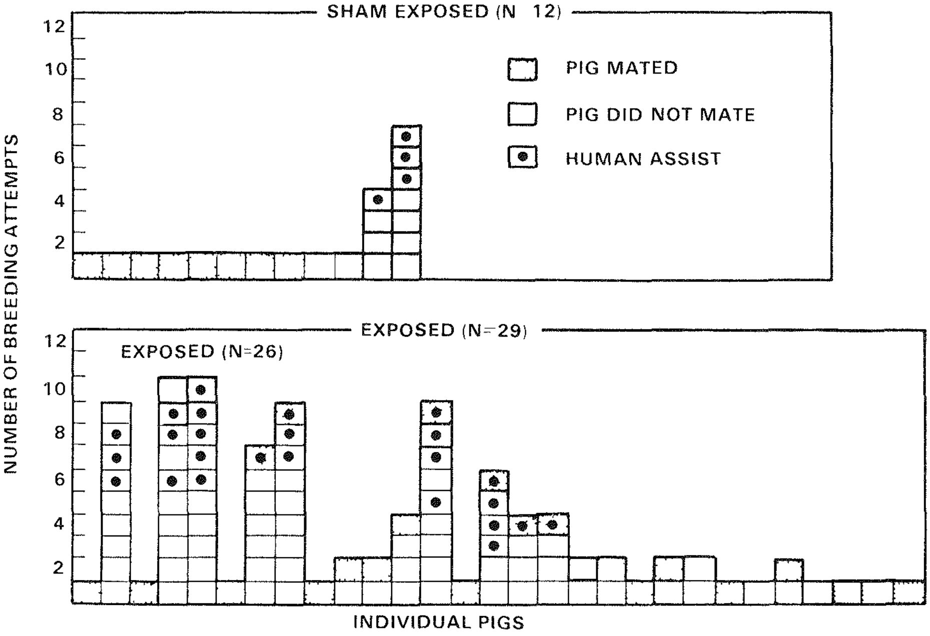

Figure 2. Mating Performance of F_1 Gilts (2nd-Generation Swine) Exposed (or Sham-Exposed) to a 60-Hz, 30-kV/m Electric Field.

Fetal Size and Dimensions—Teratology Studies

There were no statistically significant between-group differences in the weights of dams at breeding or at necropsy, or in their gestational weight gain in any of the teratology studies (Table 3). The mean body weights of both male and female fetuses in the exposed and sham-exposed groups in Teratology I and III were statistically indistinguishable. In Teratology II, however, the exposed male fetuses weighed significantly less than the sham-exposed when analyzed using individual fetuses as the experimental unit. Body-weight differences between exposed and sham-exposed groups were not statistically significant in either males or females when compared on the basis of litter means.

Crown-rump lengths and skull dimensions of the fetuses were calculated both as the means of litter means and as means of the individual values. No statistically significant differences between exposed and sham-exposed fetuses were found in Teratology I or III. In Teratology II (Table 3), the crown-rump length and maximum skull width in male fetuses and the interorbital distance in both the male and female fetuses of the exposed group were significantly smaller than those of the sham-exposed group. To facilitate comparisons, the ratios between various measures were calculated. Although the differences were not always statistically significant, ratios involving the interorbital distance were consistently smaller in the exposed than in the sham-exposed fetuses of Teratology II (Table 3).

Organ weights were tabulated as absolute values and as percent of body weight for individual fetuses and as litter means. Statistical evaluation of the litter data by analysis of variance did not detect any significant differences between fetuses from exposed and sham-exposed litters in any of the teratology studies. There were a few sporadic, statistically significant differences in relative and absolute organ weights when the individual fetus was considered as the unit; these were limited to Teratology II.

TABLE 3 Maternal Weights and Sizes of 100-dg Fetuses in Electric-Field-Exposed and Sham-Exposed Hanford Miniature Swine

	Teratology		Teratology II		Teratology III	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Weight at breeding (kg)^{a}	65 0 ± 3 2	61 8 ± 2 2	63 3 ± 2 2	63 9 ± 1 9	54 7 ± 1 7	55 5 ± 2 5
Weight at sacrifice (kg)^{a}	73 0 ± 2 5	73 4 ± 2 9	65 0 ± 2 7	65 4 ± 2 3	60 9 ± 1 9	59 5 ± 2 4
Fetal weight (g)^{b}						
Males	*422 ± 30*	*378 ± 24*	*371 ± 16*^{c}	*421 ± 18*	*368 ± 17*	*371 ± 29*
Females	401 ± 25	378 ± 23	348 ± 18	380 ± 23	341 ± 17	355 ± 24
Crown-rump length (cm)^{b}						
Males	21 0 ± 0 54	20 2 ± 0 42	20 3 ± 0 27^{d}	21 4 ± 0 32	20 9 ± 0 37	20 6 ± 0 60
Females	21 0 ± 0 37	20 6 ± 0 35	19 7 ± 0 33	20 6 ± 0 47	20 5 ± 0 28	20 1 ± 0 55
Maximum skull width (cm)^{b}						
Males	3 95 ± 0 10	3 85 ± 0 06	3 84 ± 0 05^{d}	4 03 ± 0 07	3 8 ± 0 05	3 8 ± 0 10
Females	3 89 ± 0 05	3 78 ± 0 07	3 80 ± 0 05	3 91 ± 0 06	3 8 ± 0 04	3 7 ± 0 09
Interorbital distance (cm)^{b}						
Males	2 82 ± 0 07	2 76 ± 0 14	2 97 ± 0 05^{d}	3 22 ± 0 03	2 9 ± 0 04	3 0 ± 0 09
Females	2 78 ± 0 05	2 73 ± 0 14	2 89 ± 0 05^{d}	3 12 ± 0 05	2 9 ± 0 04	2 9 ± 0 06
Occipitofrontal ~ crown-*rump*						
Males	0 24 ± 0 003	0 24 ± 0 008	0 24 ± 0 003	0 23 ± 0 003	0 23 ± 0 003	0 23 ± 0 005
Females	0 23 ± 0 003	0 24 ± 0 003	0 24 ± 0 002^{d}	0 23 ± 0 006	0 24 ± 0 004	0 24 ± 0 004
Interorbital distance ÷ occipitofrontal						
Males	0 58 ± 0 020	0 57 ± 0 039	0 63 ± 0 009	0 65 ± 0 006	0 60 ± 0 01	0 62 ± 0 01
Females	0 58 ± 0 016	0 57 ± 0 035	0 62 ± 0 009^{d}	0 68 ± 0 019	0 62 ± 0 01	0 61 ± 0 02

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[a] Mean ± SE

[b] Mean of litter means ± SE

[c] Statistically significant difference between exposed and sham-exposed group when overall means (but not means of litter means) were compared

[d] *Statistically significant difference between litter means of exposed and sham-exposed groups*

Birth Weights

Gains in the body weights of the F_0 and F_1 dams during gestation were unaffected by exposure (Table 4). Birth weights of both male and female offspring (F_1) were similar in exposed and sham-exposed first litters of the F_0 swine. In the first litters of the F_1 animals, however, the exposed offspring (F_2) of both sexes weighed less than the sham-exposed, and the difference was statistically significant for the females (Table 4). The subsequent growth curves of the exposed and sham-exposed F_2 animals were indistinguishable, however, as were those of the F_1 generation.

TABLE 4. Weights of Electric-Field-Exposed and Sham-Exposed Hanford Miniature Swine and their Offspring (Mean ± SE)

	F_0 Dams		F_1 Dams	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Weight at breeding (kg)	65.0 ± 2.3	58.0 ± 2.1	52.9 ± 1.6	53.0 ± 2.0
Weight near term[a] (kg)	76.0 ± 2.8	70.5 ± 2.6	63.8 ± 1.7	62.3 ± 2.1
Birth weight (g)				
Males	553 ± 21[b]	536 ± 14[c]	532 ± 13	576 ± 24
Females	518 ± 18	510 ± 17	488 ± 14[d]	573 ± 23

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[a] *Weights at 109 dg for F_0 dams and at 97 dg for F_1 dams*

[b] Excludes weights of three males and four females cannibalized by sow, and of four females and one male that died from hypothermia

[c] Excludes two males in one litter (cannibalized by sow)

[d] Statistically significant difference between exposed and sham-exposed groups.

Malformation Patterns and Incidence—Teratology Studies

A number of fetuses with malformations were observed during teratological evaluations and, in some instances, the incidence differed between exposed and sham-exposed groups. Statistical analyses were performed in terms of the fraction of litters and of individual fetuses affected; the incidences of life-threatening malformations and of all malformations were analyzed separately (Table 5). The incidence of lesions classified as fetal pathologies did not differ between the exposed and sham-exposed group of any of the teratology studies, nor did the type of lesion or the site affected appear to be related to exposure.

In Teratology I, four of the seven litters from the sham-exposed group had one or more malformed fetuses; two of seven litters of the exposed group each had one malformed fetus. The incidence of all malformations was significantly higher in the sham-exposed than in the exposed group when tested on the basis of number of individual fetuses affected, but the difference was not statistically significant when considered in terms of numbers of litters affected (Table 5). The difference between groups in the incidence of life-threatening malformations in Teratology I was not statistically significant, either on the basis of litter or of individual fetuses. When the incidences of all malformations in Teratology II were compared, the exposed group had a significantly greater incidence, regardless of whether tested on the basis of fetuses (P = 0.03) or litters (P = 0.05). There was no significant difference in incidence of life-threatening malformations in the two groups (P = 0.19). In Teratology III, the incidence of malformations was not significantly different between exposed and sham-exposed litters.

The malformations in each experimental group were also categorized by primary anatomical site affected and by severity. Most of the malformations were associated with the musculoskeletal system, including the tail and limbs, in both exposed and sham-exposed fetuses of all three teratology studies. The musculoskeletal system was also affected in almost all of the fetuses that had multiple malformations. The severity of the skeletal malformations ranged widely, from lesions such as markedly aberrant and misaligned vertebrae or apodia to kinking of the tail or supernumerary dewclaws. Nevertheless, the spectrum of musculoskeletal malformations, and of those affecting other organ systems, was similar in the exposed and sham-exposed fetuses, and among teratology studies.

TABLE 5. Malformations in 100-dg Fetuses from Hanford Miniature Swine Exposed or Sham-Exposed to a 60-Hz Electric Field. Dams of F_0 litters were exposed for 4 (Teratology I) or 18 months (Teratology II) before breeding; dams of F_1 litters were exposed from conception through 30 months of age (Teratology III)

	Teratology I		Teratology II		Teratology III	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number of litters	7	7	16	8	27	11
Number of live fetuses	53	37	101	43	133	49
Number malformed						
Litters affected	2	4	12	2	19	8
Fetuses affected	2	7	18	2	37	16
Number with life-threatening malformations						
Litters affected	0	1	7	1	7	4
Fetuses affected	0	2	8	1	10	6
Probabilities of difference in incidence[a]						
By litter	0.30(0.50)		0.05(0.19)		0.61(0.85)	
By fetus	0.02(0.17)		0.03(0.19)		0.52(0.32)	
Organ system affected[a]						
Multiple	0	0	4(4)	0	3(3)	4(4)
Musculoskeletal	1	3(2)	3(1)	2(1)	9(5)	5(1)
Digits and tail	0	1	4	0	20	4
Central nervous system and eyes	0	2	4(2)	0	1	3(1)
Cardiovascular	0	0	2(1)	0	2(1)	0
Other	1	1	1	0	2(1)	0

[a] Expressed as total malformations (life-threatening malformations)

Malformation Pattern and Incidence—Postnatal Evaluations

The same statistical approaches used for the teratology studies were also used to analyze the malformation results obtained from postnatal evaluations of live and dead offspring born after mating of F_0 and F_1 gilts. A greater fraction of the litters born to exposed F_0 dams contained malformed offspring than did those born to sham-exposed dams, but the difference was not statistically significant (Table 6). A similar fraction of the fetuses in the two groups were malformed.

TABLE 6. Malformations in Offspring (F_1 Generation) from Hanford Miniature Swine Exposed or Sham-Exposed to a 60-Hz Electric Field from F_0 Sows Bred at 4 Months of Exposure and F_2 Offspring from F_1 Sows Bred at 18 Months of Exposure

	F_0 Dams		F_1 Dams	
	Exposed	Sham-Exposed	Exposed	Sham-Exposed
Number of litters	18	10	28	12
Number of offspring	112	57	149	57
Number malformed				
Litters affected	7	2	20	4
Offspring affected	13	4	40	8
Number with life-threatening malformations				
Litters affected	0	0	10	2
Offspring affected	0	0	16	2
Probabilities of difference in incidence[a]				
By litter	0.35		0.05 (0.10)	
By fetus	0.29		0.03 (0.21)	
Organ system affected[a]				
Multiple	2	0	11(9)	2 (2)
Musculoskeletal	10	4	16 (7)	3 (0)
Digits and tail	1	0	10 (0)	2 (0)
Central nervous system and eyes	0	0	2 (0)	0 (0)
Cardiovascular	0	0	0 (0)	0 (0)
Other	0	0	1 (0)	1 (0)

[a] *Expressed as total malformations (life-threatening malformations)*

The fraction of litters with malformed offspring born to exposed F_1 animals was about twice that for the sham-exposed group (Table 6). The overall incidence of malformed offspring was also twice as great in the exposed as in the sham-exposed group. These differences in incidence were statistically significant, regardless of whether tested on a litter ($P = 0.05$) or an individual ($P = 0.03$) basis. The incidence of life-threatening malformations in the exposed groups was also about twice that in the sham-exposed group, although the differences were not statistically significant.

Despite these differences in incidences, the spectrum of malformations was similar in the exposed and sham-exposed groups. The tendency of malformations to be associated with the musculoskeletal system was even more striking than in litters examined prenatally; however, this tendency may be associated with evaluation procedures.

DISCUSSION

Several significant differences were found between exposed and sham-exposed groups throughout the study; there were also striking differences between the patterns of results obtained in the three teratology studies, and between the litters of the two generations that produced offspring. The differences between exposed and sham-exposed groups bred at 4 mo and evaluated in Teratology I included more live fetuses per litter and fewer prenatal deaths in the exposed group. There was also a tendency toward a lower incidence of malformations in the exposed population. These differences may result from the small sample sizes and random variations, although it is possible that inclusion in this population of animals that were rebred after loss of their litters may have introduced an element of bias. In the litters born to the F_0 gilts, which were a subset of the same cohort, malformation incidence tended to be greater among the exposed fetuses. If the two subsets are considered a single population, malformation incidences in the exposed and sham-exposed groups become essentially identical, although the tendency toward larger litter size, in the exposed group, remains. There appeared to be more live fetuses per litter in the exposed than in the sham-exposed group of all three teratology studies and in the two postnatal evaluations, although the difference was statistically significant only in Teratology I. This was accompanied by a tendency toward less prenatal mortality in the exposed groups of all three teratology studies. Since all differences were small, they are probably not of biological consequence and may be considered independent random events, distributed by chance.

The occasional body-weight differences between exposed and sham-exposed groups appear to be of major biological significance only in that they were unique to the parts of the study (Teratology II, litters of F_1 dams) where there were also increased malformation incidences in the exposed group relative to the sham-exposed group. Three alternative explanations are offered for this finding: 1) an effect of exposure; 2) random variation; or 3) an experimental effect not directly related to exposure. Since group sizes were small, and the effect was not robust, it is difficult to unequivocally choose among these explanations, which are not mutually exclusive.

Data on the incidence of spontaneous malformations in swine are limited (Edwards and Mulley, 1981). The estimates that are available may not be accurate since breeders usually discard malformed offspring without documentation. Furthermore, swine are not often used for teratologic evaluation, and most of the reported data are anecdotal case reports. Based on mailed surveys and field studies, epidemiologic studies have estimated an overall malformation incidence of about 0.7% in farm herds (Marienfeld et al., 1967; Selby, Edmonds, and Hyde, 1976). This probably represents an underestimate, since surveys and examination of birth records give lower incidence values than intensive clinical evaluations. Considering data from various sources, Wilson (1973) has estimated that the malformation incidence in human populations is 3 to 5% when based on defects detectable at birth. Incidence rises to 5 to 10% when defects detected during the first 2 years of life are included. Warkany (1981) estimates that about 12% of newborn children would have detectable congenital defects if antenatal deaths and stillbirths did not occur, since malformation incidence is appreciably higher in such cases. This leads us to speculate that the natural background incidence of malformations that could be detected by detailed antenatal examination in the HMS approximates the 12% that is obtained if the sham-exposed fetuses from Teratology I and II are combined into a single population.

From the discussion presented above, it seems reasonable to conclude that malformation incidence was unaffected by electric-field exposure in the population of Teratology I and F_0 first litters. Malformation incidence was clearly higher in the exposed group of Teratology II and the first litters of the F_1 swine compared to that in the sham-exposed group. It is difficult to reconcile the differences between these results and to explain the lack of effect in Teratology III. Explanations relating to the differences in age or duration of exposure at the time of breeding are not consistent with this pattern of change. There were changes in the incidence of malformations in sham-exposed animals across generations and a progressive increase in the incidence of kinked tail in later generations. This might suggest drift or fluctuation in the genetic composition of the populations, although calculations of inbreeding coefficients showed no major genetic differences between parents of successive generations. Random differences in the partition of genetic distributions or natural selection factors relating to exposure or experimental conditions, which may have led to increased response, are remote and untestable explanations for a temporal shift.

Data in the literature demonstrate that infections during pregnancy can lead to malformations (Morison, 1979; Grossman, 1980). It is possible that the outbreak of disease (diagnosed post facto as probably a *Campylobacter* infection), which occurred in the 3- to 10-month period prior to rebreeding the F_0 sows at 18 mo of exposure, had a differential effect on the reproductive outcome of the exposed and sham-exposed swine. However, it seems unlikely that an endemic but subclinical infection (or the effects of an earlier clinical infection) would have persisted after that period. There is no indication in the literature that infections produce residual effects that would alter development during a subsequent pregnancy. Although latent effects could synergize with a subsequent stimulus, there is no evidence to support such a relationship. If earlier infections are considered a contributing factor, one must postulate that they have somehow interacted with exposure to alter morphologic development of the subsequently conceived fetuses.

One of the therapeutic agents used to treat the infection, nitrofurazone, has been reported (Physicians Desk Reference, 1981) to slightly increase the frequency of stillbirths when high doses were administered daily to pregnant rabbits on days 7 to 15 of pregnancy; however, teratogenic effects were not seen in those studies. It therefore seems unlikely that these agents would have a teratogenic effect 3 to 10 mo after administration at substantially lower dose levels.

A number of possibilities may explain why malformative effects were not detected in earlier studies in which rats or mice were exposed to 60-Hz electric fields. The most obvious is that most of the previous studies involved postnatal evaluations, and defective offspring might have been cannibalized by the dam prior to evaluation. In addition, the duration of exposure was different in the rodent studies from that in this swine study because of the differences in gestation periods of rodents and swine, even though (in each case) exposure continued throughout gestation. The total length of exposure, as well as the age of the dams at breeding, differed on both an absolute and a scaled basis between the swine and rodents.

Several studies (reviewed by Marx, 1981) have suggested that small, naturally generated electric currents may be involved in some aspects of prenatal development. Although perturbation of the natural patterns by induced currents, resulting from exposure to exogenous electric fields, might produce effects on development, this seems unlikely in light of the lack of uniformity of effects across groups.

Research by Hjeresen et al. (1982) has shown that swine are capable of sensing a 60-Hz electric field at the levels used in this study. Therefore, another hypothesis is that stimulation of the pregnant dam by the field may be related to the differences in reproductive outcome in this study. The application of this possibility to the observed patterns of change would involve unwarranted extrapolations of stress and adaptation theories. An indirect effect, mediated via maternal perception of the electric field, might be compatible with the pineal neurochemical changes reported by Wilson et al. (1981), and further exploration of such secondary effects may prove fruitful.

The design and logistics of a screening study such as this preclude in-depth exploration of findings or attempts to determine their reproducibility. However, in conclusion, it should be noted that one of the primary differences between groups of miniature swine exposed or sham-exposed to an electric field was a higher incidence of malformations in fetuses of sows exposed for a period of 18 mo prior to conception of a second litter and continued on exposure through 100 dg. The F_1 offspring from the first litters of these exposed sows displayed a deficit in copulation and also a higher incidence of malformed offspring in their first litters than the sham-exposed. A clear association of these higher malformation incidences with exposure cannot be demonstrated since a mechanism has not been identified and a number of potentially interacting factors are superimposed. Although none of these factors is adequate to explain the observed differences, the possibility that they interact with electric-field exposure cannot be ruled out.

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OCCUPATIONAL EXPOSURE OF HIGH-VOLTAGE WORKERS TO 60-Hz ELECTRIC FIELDS, PART 2: ANALYSIS AND RESULTS

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ABSTRACT

Occupational electric-field-exposure measurements for 1861 total exposure days from 135 Bonneville Power Administration employees are presented and analyzed. Electric-field exposures were measured with a small electric-field-exposure monitor (EFEM) which was worn in the shirt pocket. The estimated unperturbed electric-field threshold for exposure measurement with this device was 0.4 kV/m. Exposure data are analyzed in terms of time recorded above the threshold field, time recorded in various field ranges, and total accumulated exposure in units of (kV/m)h. Additional information and estimates of exposure time were provided by the workers in a form that was filled out daily when the EFEM was worn. Measured data have been combined with reported information to quantify exposure as a function of job category and system voltage. The job categories with relatively high exposure were 230- and 500-kV line crews, 230- and 500-kV substation maintenance electricians, and 500-kV substation operators. Exposures measured with the EFEM were considerably less than those based on reported or estimated time in the field.

This paper describes results of a study started in 1979 by the Bonneville Power Administration (BPA) to quantify occupational exposures to 60-Hz electric fields (Chartier, Bracken, and Capon, 1985). In several previous studies, the duration and magnitude of occupational exposures were estimated from the observers' knowledge of work habits, line voltage, and measurements of electric fields in work locations. Exposure estimates based on time spent in a measured field for a particular activity have, typically, been larger than exposure measurements made with various dosimeters (Stopps and Janischewskyj, 1979; Deno, 1979; Lovstrand et al., 1979; Deno and Silva, 1984). In order to provide estimates of 60-Hz electric-field exposure of BPA workers and to identify job categories with the highest exposure, this study was undertaken to collect exposure data for many workers. As described in a companion paper (Chartier and Bracken, this volume), a miniaturized electric-field exposure monitor (EFEM) was developed to continuously monitor the electric-field environment of many workers on a daily basis. The exposure information was stored digitally in a time histogram format. The exposure time recorded in various field ranges (bins) was read out at the end of the workday. From these data, measured electric-field exposure can be given in terms of duration, electric-field time histograms, and accumulated exposure in (kV/m)h.

Mechanisms for effects of 60-Hz electric fields on humans have not been demonstrated. Therefore, the significant parameter to characterize electric-field exposure has not been identified. The EFEM measures the local electric field at the surface of the body, which can be related to other parameters, such as induced current, if necessary.

For convenience in interpretation and because of tradition, the local field measured by the EFEM was converted to an unperturbed electric field through the concept of the enhancement factor (EF).

Data collection in the study has been divided into two phases. In Phase I (June 1982 to March 1983), the workers were given the choice of wearing the EFEM on the hard hat, in the shirt pocket, or on a lanyard around the neck. The workers overwhelmingly preferred to wear the EFEM in the shirt pocket, which is exposed to smaller electric fields than the hard hat (Bracken, 1983). Consequently, in Phase II (April 1983 to May 1984), the sensitivity of the EFEM was increased by a factor of two, and the shirt-pocket location was used almost exclusively.

The data reported were collected for 135 employees during 1861 total exposure days in Phase II.

DATA COLLECTION

Each employee filled out a daily exposure (DE) card at the end of each exposure day. The following explicit information was recorded on the DE:

1. employee identification number,
2. EFEM location,
3. time spent near energized equipment,
4. highest voltage of the energized facility visited,
5. data from 9 EFEM bins,
6. whether nuisance shocks were experienced, and
7. whether clothes were wet.

These data provided two basic measures of exposure: 1) the number of hours spent near energized equipment, as reported by the workers; and 2) measured exposure, the time measured by the EFEM above bin 0. When the EFEM was in the shirt pocket (Phase II), measured exposure was equivalent to time spent in unperturbed fields of greater than 0.4 kV/m.

The other information contained in the DE was used to link the measured and reported exposures to a job category, through the employee identification number, and to identify malfunctioning EFEM.

Each employee was requested to complete a participant form (PF) after completing all exposure measurements. The PF provided information about job classification, relative exposure, and acceptability of the EFEM. Data from the DE and PF were coded and entered in a computer file.

Because this was a pilot study to assess feasibility, no specific design was developed for selecting participants. The EFEM were distributed to crews on the basis of accessibility and convenience. However, efforts were made to gather representative data from all occupational categories, voltages, and geographical locations.

The sample period of 2 to 4 workweeks was not long enough to encompass all tasks and exposures for a particular individual or job classification. The type of work a crew was performing when they received the EFEM determined the level of exposure. No attempt was made to predetermine whether or not a crew would be working on energized equipment while they used the EFEM. However, by collecting data for several exposure days from various individuals, we presumed that a meaningful cross-section of exposure for a particular job classification could be obtained. Obviously, a larger study would require a design to ensure representative exposure sampling.

Several procedures were incorporated into the system to ensure the accuracy of the data. The DE were reviewed for clerical errors; tests were run to check the validity of the EFEM data that were entered in the data base; individual cards with missing or obviously erroneous data entries were identified and corrected to the extent possible. Consistency checks were performed on the total exposed time and the times recorded in high fields.

DATA SUMMARY

A summary of the data for 1861 exposure days in Phase II is given in Tables 1 and 2. Data recorded when wet clothes were reported were not used; the shirt-pocket and lanyard EFEM locations were considered equivalent. About 57% of the DE reported more than 0.5 hr exposure to energized equipment. The reported equipment voltage was 230 or 500 kV for 46% of the DE. A large number of cards (approximately 40%) recorded no maximum voltage. The mean time that the EFEM were worn was approximately 7.5 hr. Nuisance shocks were indicated on 9% of all DE, on 16% of DE with 230 kV reported as the maximum voltage, and on 25% of cards with 500 kV reported as the maximum voltage.

Sixty-seven percent of respondents to the PF indicated that exposure to energized equipment during the period they wore the EFEM was normal for their job. Thirty-two percent of respondents reported less or much less time than normal near energized equipment. Only one person reported more time than usual near energized equipment.

The composition of the exposure data by job category is shown in Table 2. The first four categories are directly involved in operating and maintaining a transmission system. Linemen are included in the transmission-line-crew category. About 60% of the 196 linemen's DE reported work near energized equipment with voltages of 230 kV or greater. The system dispatchers and data system maintenance personnel were considered nonexposed groups. The "other" category included test facility personnel, office workers, and others.

The DE provided two measures of exposure: 1) "reported exposure," reported hours near energized equipment, and 2) "measured exposure," time measured in each bin of the EFEM. Measured exposure was analyzed in three ways. First, duration of measured exposure was total time registered above bin 0; this can be compared with reported exposure. Second, time histograms of electric-field exposure were generated from time recorded in different bins. Finally, the time measured at each field level was accumulated to provide exposure measurement in terms of (kV/m)h for each bin or in the aggregate. Because the bins are of finite width, the latter approach yields ranges for accumulated exposures.

TABLE 1. Summary of Electric-Field Exposure Data for BPA Personnel (N = 135). Data were recorded by a shirt-pocket exposure meter (EFEM) over 1861 exposure days.

Number of Forms Reporting Time Near Energized Equipment

Yes	No
1060	801

Number of Forms Reporting Equipment Voltage

Number	Voltage (kV)
256	115
616	230
247	500
18	Other
724	None

Mean Time EFEM Worn: 7.5 h

Number of Forms Reporting Nuisance Shocks

None	Few	Many	Missing
1266	152	12	431

TABLE 2. Electric-Field Exposure Data, by Job Category, for BPA Personnel

Category	Number of Employees	Number of Daily Exposure Cards Completed
Substation Operators	36	602
Substation Maintenance Electricians	18	208
Transmission Line Crews	30	381
Power System Control/System Protection Maintenance	24	348
System Dispatchers/Data System Maintenance	13	175
Others and Missing	14	139
Total	135	1861

Exposure Duration

Measured exposure duration and reported exposure are compared in Table 3 for the 1861 DE. (Measured exposure is the amount of time registered above bin 0.) The electric-field threshold for exposure time is dependent on the assumed enhancement factor (EF). Using an average EF of 2.5 results in an average exposure threshold of 0.4 kV/m for these data. Reported exposure means 1 or more hours reported near energized equipment. In recording exposure, subjects were instructed to round to the nearest hour.

TABLE 3. Electric-Field Exposure Above Threshold (0.4 kV/m): Measured Versus Reported for 1861 Daily Exposure Cards

Measured Exposure Time	Number of Cards Reporting Exposure Yes	Number of Cards Reporting Exposure No
t < 1 minute	178	634
1 minute < t < 5 minutes	223	88
5 minutes < t < 1 hour	575	86
1 hour < t	84	23
Total	1060	801

The data presented in Table 3 suggest a strong association between measured exposure and reported exposure. Of the 812 DE with measured exposures of less than 1 min, 178 (22%) reported time near energized equipment. Of the 738 with measured exposures greater than 5 min, 659 (89%) reported time near energized equipment. These results indicate that the EFEM generally showed exposure in work situations which are expected to involve exposure; or, conversely, that work near energized equipment generally resulted in measurable exposure. However, the association between measured and reported exposures has not been quantified in Table 3, and the measured exposure times appear to be generally less than the 0.5 hr minimum for reported exposures.

Table 4 compares measured and reported daily exposures in hours. The median and 90th percentile values of exposure time above threshold are given for DE reporting 115, 230, and 500 kV as the maximum voltage. Measured exposures were much less than reported exposures for all voltages. For example, the median reported exposure for 500 kV was about 2 hr, while the median measured exposure was 13 min. Because of lower field strengths, the discrepancies between measured and reported exposures are greatest for the lower-voltage lines, as expected. Measured exposure tended to be higher for higher voltages. However, above the 85% level, the 230-kV exposures were greater. These relatively high exposures are attributed to a larger percentage of linemen in the 230-kV sample than in the 500-kV sample. The 230-kV linemen had the highest exposures of any group at the 90th percentile level.

TABLE 4. Measured and Reported Electric-Field Exposures (Hours per Day) for Time Spent Near 115-, 230- and 500-kV Facilities

Voltage Class (kV)	Number of Daily Exposure Cards	Measured Time Above Threshold		Reported Exposure Time	
		50%	90%	50%	90%
115	256	0.046	0.41	4	6
230	616	0.12	1.11	3	7
500	247	0.22	0.91	2	6
Nonexposed	175	0.00	0.001	0	0

Because the estimated and measured electric fields in and near 230- and 500-kV facilities were above the assumed threshold of the EFEM, we expected closer agreement between reported measurement and measured exposure than is shown in Table 4. The ratio of median reported measurement to measured exposure is roughly 9:1 for 500 kV and double that amount for 230 kV.

Tests with a shirt-pocket EFEM that simulated occupational activities in substations indicated that time recorded in bin 0 was considerably above that expected from electric-field measurements (Bracken, 1983). In addition, the shirt-pocket EFEM consistently registered lower exposures than measurements made with the EFEM at other locations, and lower than measurements made with a conducting vest or those predicted from electric-field measurements. Furthermore, electric fields at work locations in high-voltage facilities, e.g., under de-energized equipment and near grounded structures, may be substantially less than the maximum levels commonly reported and may then fall below the EFEM threshold. Shielding of the shirt-pocket EFEM during normal activities might also be a factor in the difference between measured and reported exposures.

A lack of measured exposure for the nonexposed category is also indicated in Table 4. The nonexposed group was composed of system dispatchers and data system maintenance personnel, who work indoors.

Although the actual amount of time spent above the threshold field is uncertain, the measured values are considered a valid relative indicator of cumulative exposure above threshold.

Time Histograms

Time histograms of electric-field exposure describe actual exposure quite well. Time histograms of daily exposures, by bin, are shown in Figure 1. Median and 90% levels are shown for various reported voltage levels and for occupational categories within the 230- and 500-kV voltage levels. The EF of 2.5 used here results in a threshold of 0.4 kV/m. Another EF would change the absolute values for the field ranges in Figure 1 but would not change the conclusions regarding relative exposure.

From Figure 1A it is seen that activities near 500-kV energized equipment resulted in more exposure time at higher field levels than did activities near 230-kV equipment. This is especially pronounced for the 90% levels in higher bins. A similar comparison can be made between 230-kV and 115-kV exposures.

Exposure time histograms for 500-kV job categories are also shown in Figure 1B. At this voltage level, the substation operators appeared to be exposed to high fields about as often as electricians and line crews. However, the sample sizes for the electricians and line crews are too small to allow any generalization. Data also indicate that the 230-kV line crews' exposure tended to be greater than that for the 500-kV line crews.

All the median and 90% level exposures in Figure 1 represent less than 10% of total exposure time while wearing the EFEM. Exposures above bin 3 ($>$ 4 kV/m) represent only minutes during the course of an 8-hr workday, even for the most frequently exposed personnel.

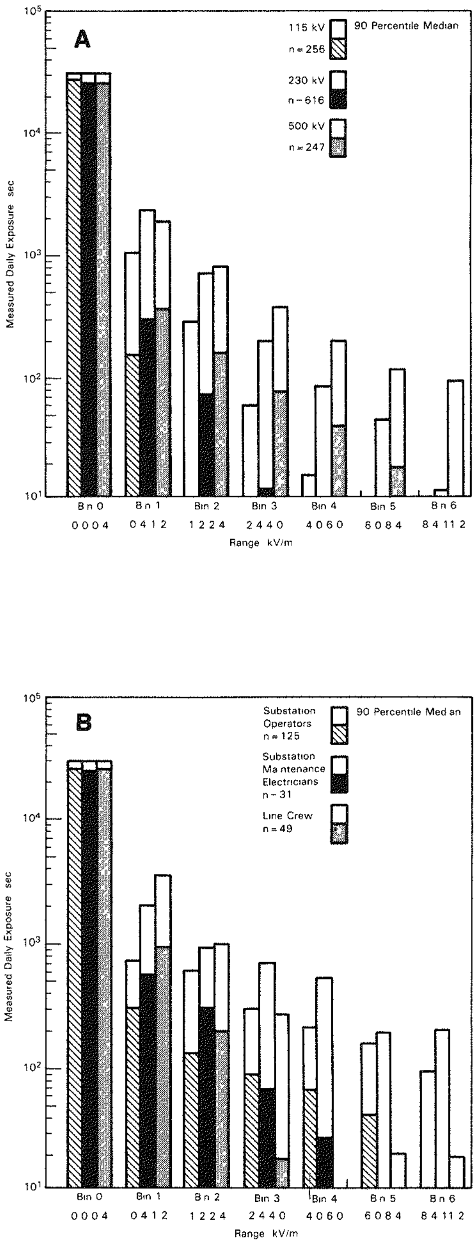

Figure 1. Measured Time Histograms of Electric-Field Exposure of BPA Personnel as a Function of A) Voltage and B) Job Category. Field ranges based on enhancement factor (EF) of 2.5.

Analysis of data from other job categories resulted in median and 90th percentile exposures that were considerably below those of Figure 1. The power system control and system protection maintenance crafts group (all voltages, n = 348) recorded exposures longer than 1 min only at the 90% level in bin 1 (244 sec) and bin 2 (64 sec). The nonexposed group showed essentially no median exposures above bin 0. The 90% level of exposure for the nonexposed group in bin 1 was 28 sec, with essentially no exposure in higher bins at the 90% level.

Because of the nonlinear bin widths, interpretation of these histograms should be made cautiously. In terms of time per unit field interval the exposures actually decline more rapidly than shown in Figure 1. The distribution of times within bins probably follows the same pattern as the overall distribution; i.e., much more exposure at the lower edge than at the higher edge of the bin.

Accumulated Exposure

Accumulated exposure was computed from the EFEM data by summing the product of field and time over all bins to yield a single estimate of exposure in (kV/m)h. Minimum and maximum accumulated exposures above threshold were estimated, using the lowest and highest fields for each bin, respectively.

The ranges for median and 90th percentile accumulated exposures above bin 0 (> 0.4 kV/m) for various occupations and voltages are shown in Figure 2. Actual exposures were probably near the minimum values because, as indicated previously, most of the exposure time was likely to be in the lower portions of the bins. Estimated median exposures ranged from about 0.001 (kV/m)h per day for nonexposed workers to about 0.5 (kV/m)h per day for 500-kV workers. Estimated 90th percentile exposures ranged from about 0.02 (kV/m)h per day for nonexposed workers to about 4 (kV/m)h per day for the 230-kV linemen and 500-kV electricians in this sample.

Even with the large spread of estimated accumulated exposures for each group, several conclusions can be made regarding the accumulated exposures. 1) Exposures were higher as the reported voltage increased. 2) The estimated median exposure for all job categories that reported time spent near 230-kV energized equipment was about a factor of three higher than the estimated exposure for those near 115-kV energized equipment. 3) At the 90% level, the ratio of 230-kV exposure to 115-kV exposure was approximately 2.5 to 1. 4) For 500 kV, median accumulated exposures were three to four times those at 230 kV. 5) At the 90% level, the difference was less than 2 to 1 for 500-kV over 230-kV exposure. 6) The occupational exposures above 0.4 kV/m, associated with work near high-voltage facilities, were two to three orders of magnitude greater than exposures in the nonexposed group.

The line crew category included linemen and ground personnel. Exposures for the specific job classification "linemen" actually showed the highest exposures. With this particular sample, the estimated exposures for 230-kV linemen (n = 97) were 0.8 to 1.8 and 3.4 to 6.1 (kV/m)h for the median and 90% levels, respectively.

Stopps and Janischewskyj (1979) estimated average daily exposures of 6.9 and 12.7 (kV/m)h for Canadian linemen and substation workers, respectively. These estimates were computed from measured exposures for individual tasks and estimates of frequency of tasks. The median values in Figure 2 are 10 to 20 times lower than the Canadian estimates.

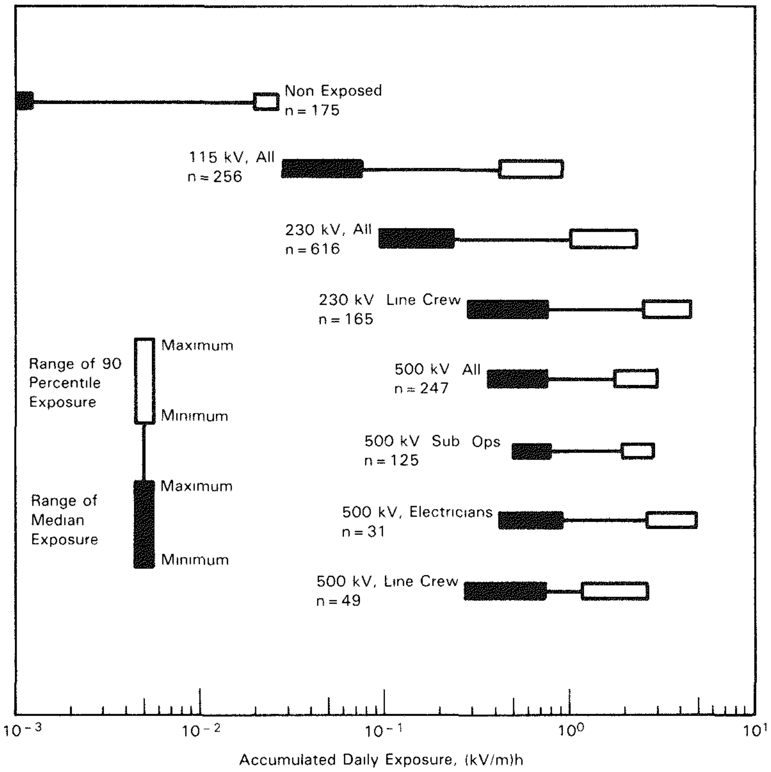

Figure 2. Estimated Accumulated Daily Electric-Field Exposure of BPA Personnel as a Function of Voltage and Job Category. Exposure was measured by an exposure meter carried in the shirt pocket; threshold of meter, 0.4 kV/m.

There are several possible factors in the two studies that may have contributed to the differences in exposures. Both studies represent small numbers of workers and exposure days in a particular occupation. The Canadian study sampled a highly exposed group, while our study included all members of a job category. Furthermore, an EF of 2.5 may not be enough to account for the shielding in the shirt-pocket location compared to the hard-hat dosimeter used in the Canadian work. Considering the differences between the study populations and study methodology, the discrepancy between the two values for daily exposure is not unexpected and may indicate the degree of uncertainty that can be expected in estimating or measuring exposure.

CONCLUSIONS

Measurements were made of electric-field exposure for 135 BPA employees over 1861 exposure days. Analyses of the data collected by EFEM worn in the shirt pocket were made in terms of three exposure variables: 1) measured time spent in fields greater than approximately 0.4 kV/m; 2) distribution of time spent in various field ranges above the threshold of 0.4 kV/m, and; 3) accumulated exposure in (kV/m)h above threshold. Exposures were characterized with respect to job category and facility voltage class.

There is a strong relationship between measured exposure time above threshold and whether time was spent near energized high-voltage facilities. However, measured exposure time is much less ($\leq 10\%$), quantitatively, than reported time near energized facilities. Contributors to the large discrepancies between measured and reported exposures are: shielding of the EFEM in the shirt-pocket location, low levels of field exposure experienced near energized equipment, and over-reporting of time near energized equipment.

Time histograms of daily electric-field exposure indicate that time was spent in higher fields as the equipment voltage increased. However, measured time of exposure, above an equivalent unperturbed field of 4 kV/m, represented only minutes per day even for the most frequently exposed personnel.

Estimates of accumulated exposure in (kV/m)h above threshold indicate that the median daily exposure for 500-kV workers and frequently exposed 230-kV workers was roughly 0.5 (kV/m)h. The 90% levels for these groups were roughly 2 (kV/m)h. The accumulated daily exposures above threshold for high-voltage workers were two to three orders of magnitude greater than for a nonexposed group of system dispatchers and data equipment maintenance personnel.

Based on the quantitative measures of exposure, job categories with the highest measured exposures were: 230- and 500-kV line crews, with linemen receiving the most exposure; 230- and 500-kV substation maintenance electricians; and 500-kV substation operators.

The nature of occupational electric-field exposure makes any method or parameter used to characterize exposure of a large group approximate and subject to large variability. This study has demonstrated that even with this variability, it is possible to quantify exposures of an occupational group and to identify individuals and groups with relatively high electric-field exposure.

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EXPOSURE OF PEOPLE TO POWER-FREQUENCY ELECTRIC AND MAGNETIC FIELDS

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ABSTRACT

Two types of personal exposure monitors, worn on the upper arm have been used in separate surveys of occupational exposure to 50-Hz electric fields Two hundred eighty-seven transmission and distribution workers were monitored over a 2-week period with a single-band integrating monitor and 47 workers over an average of 6 days with a four-band time-histogram monitor Average daily exposures for transmission workers in both surveys were less than 1 kV m^{-1}hr, with very little time (average 1 2 min per day) recorded in fields above 4 5 kV m^{-1} Instruments have been developed for monitoring exposure to 50-Hz magnetic fields in terms of time spent in five field-strength bands a static unit, which records the three spatial components separately, and a personal monitor, which averages overall spatial directions A limited survey has shown that background domestic field strengths are typically 1 mG or less, they are very variable over time and, in many cases, apparently dominated by out-of-balance currents in (underground) street distribution cables

Electric-field strengths in the vicinity of high voltage ac power-transmission plant are generally well characterized However, the extent to which people may be occupationally or otherwise exposed to them is less well defined and is not easy to estimate Measurements using personal-exposure dosimeters have generally yielded appreciably smaller exposure values than estimates based on measured field strengths and the times spent by individuals in those fields (Stopps and Janischewskj, 1979, Deno, 1977, Lovstrand et al , 1979, Deno and Silva 1984, Chartier, Bracken, and Capon 1984) The reason probably lies partly in the difficulty of making estimates which adequately allow for screening of the electric fields by objects such as trees, fences, buildings, etc Individual measurements appear to be essential if realistic exposure values are to be obtained

With magnetic-field exposure, the problems are different Interest here has centered not so much on the relatively intense and well-characterized magnetic fields near high-voltage transmission plants as on the much weaker and less predictable fields characteristic of many domestic and urban environments Wertheimer and Leeper (1979, 1982) have suggested that these fields may be linked with increased incidence of cancer Environmental 50-Hz magnetic fields tend to be very variable over both time and space Reliable personal-exposure estimates would require a detailed knowledge of the field characteristics as well as of the movements of the individual concerned

In this paper, we present the results of limited surveys of occupational exposure to electric fields and describe instruments for the characterization of domestic magnetic fields and the assessment of personal magnetic-field exposure

OCCUPATIONAL EXPOSURE TO 50-HZ ELECTRIC FIELDS

Measurements of personal exposure to 50-Hz electric fields have been made in conjunction with a recent health-questionnaire survey of electric-power transmission and distribution workers in southwest Britain (Broadbent et al., 1985). This study, carried out during 1980 and 1981, found no correlations between exposure to electric fields and a number of aspects of general health.

Exposure measurements were made with a miniature version of the simple electrochemical dosimeter described by Deno (1979). It was worn in an armband sleeve on the upper arm and yielded a single reading of exposure in kV $m^{-1}hr$ for all field strengths greater than about 60 V m^{-1} (unperturbed vertical field strength, subject standing upright). The effective "dead-band" resulting from polarization effects in the charge-storage cells extended up to 6.6 kV $m^{-1}hr$, so that meaningful measurements were possible only above this level.

Results were obtained for 287 workers, each of whom wore a dosimeter during working hours for a 2-week period. One hundred sixty-six were transmission workers, dealing with plant at 132 kV, 275 kV and 400 kV. The remaining 121 were distribution workers dealing with plant at 132 kV and below.

Only two of the distribution workers and 26 of the transmission workers received measurable exposures over the 10 working days. Figure 1 shows the distribution of these "exposed" individuals among five main job categories for the transmission group. The highest proportion of exposures was registered by linemen and the lowest by engineers. Numbers are, however, too small for general conclusions to be drawn. The median exposure for these 26 individuals was 1.5 kV $m^{-1}hr$ per day; the maximum, 24.3 kV $m^{-1}hr$ per day.

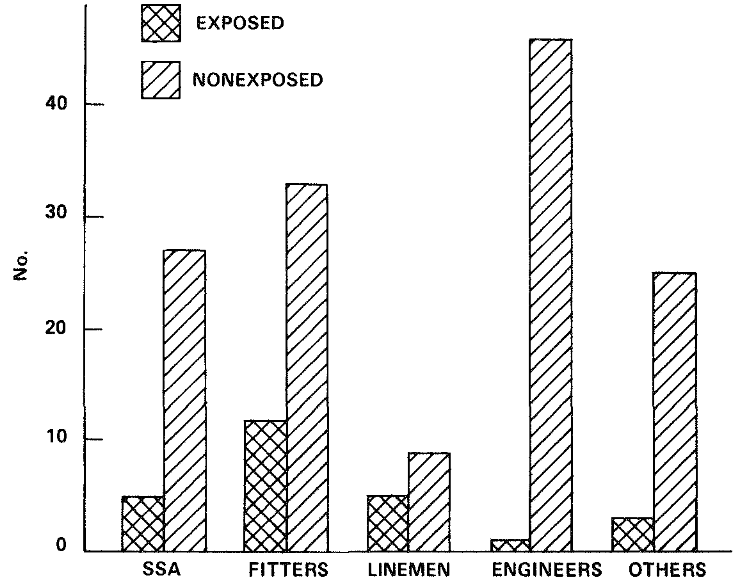

Figure 1. Results of Single-Band Electric-Field Exposure Measurements for 166 Transmission Workers (Systems at 132 kV and Above) in Five Job Categories. "Exposed" individuals received more than 6.6 kV $m^{-1}hr$ over the 2-week measurement period (i.e., an average of >0.66 kV $m^{-1}hr$ per day). SSA = substation attendants

The rarity of appreciable exposure in this study was surprising. Further measurements have been carried out more recently to gain a better idea of the actual distribution of occupational exposure at the lower end of the range. These have been made with a dosimeter of the time-histogram type, in which electrochemical cells are used to register the time spent in each of four bands of electric-field strength. The bands are 0.4 - 1.5, 1.5 - 4.5, 4.5 - 9.5 and >9.5 kV m^{-1} (unperturbed vertical field strength for subject standing upright). Time resolution for the instrument is 0.01 hr. It is also worn on the upper arm.

Forty-seven transmission workers have been monitored on a daily basis to yield a total of 319 exposure days of data. Most of the data were obtained during a 3-week period in September and October 1983. Subjects were classified into the same five main job categories and also according to the highest voltage rating of the plant near which they worked each day. The dosimeters were worn for a minimum of 3 hr and a maximum of 13.75 hr, the average being 7.9 (SD 1.5) hr per day.

Figure 2 shows time histograms derived from the averaged data obtained for each job category. Conversion of the exposures to kV m^{-1}hr is subject to some uncertainty because time spent at the top or the bottom of a band registers equally. The exposure values given assume that the whole time was spent, on average, midway in each of the three lower bands. The "error" represents the possibility that it was spent instead at the upper or lower extremities. Time in band 4 was assumed to be spent only at 9.5 kV m^{-1}.

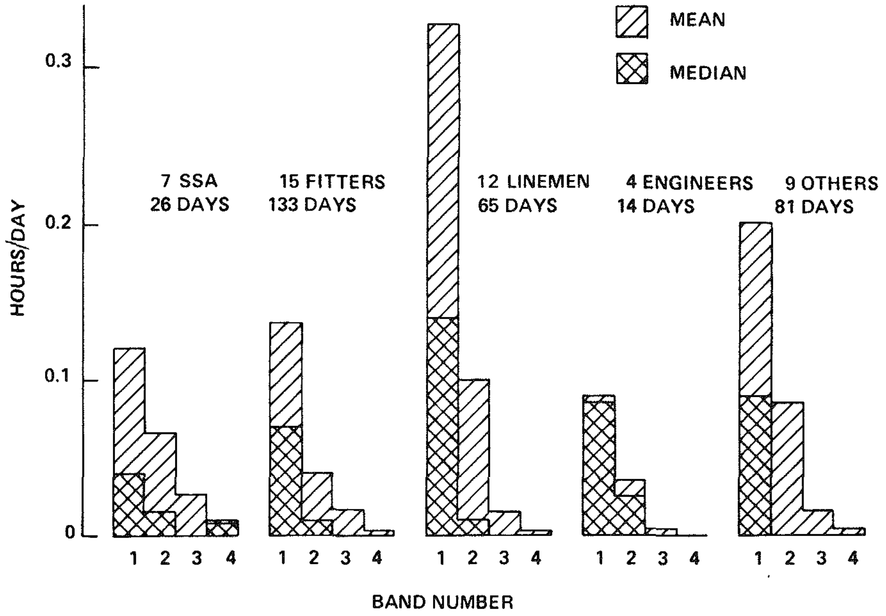

Figure 2. Daily Time-Histogram Electric-Field Exposure Measurements for 47 Transmission Workers. Bands 1, 2, 3 and 4 correspond to field ranges 0.4 - 1.5, 1.5 - 4.5, 4.5 - 9.5 and > 9.5kV m^{-1}, respectively. Mean and median times are shown for the five job categories. Corresponding integrated exposures in kV m^{-1}hr are: SSA: 0.58 ± 0.24, fitters: 0.40 ± 0.17, linemen: 0.75 ± 0.38, engineers: 0.2 ± 0.11, and others: 0.60 ± 0.26. SAA = substation attendants.

On this basis, average exposures are modest, being greatest for linemen, at 0.75 $kVm^{-1}hr$ per day, and least for engineers, at 0.22 kV m^{-1} per 8-hr day. Very little time (on average, 2.1 min or less) was spent by any group in fields greater than 4.5 kV m^{-1}. Band times classified according to plant voltage, given in Figure 3, show a clear trend towards longer exposure times for the higher voltages.

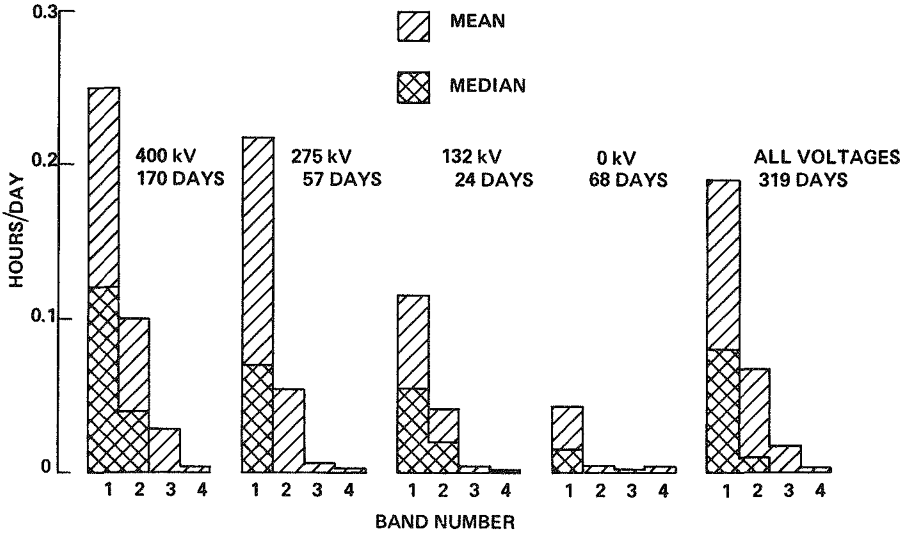

Figure 3. Mean and Median Times in the Four Field-Strength Bands for Daily Exposures of Transmission Workers to Electric Fields, Classified According to the Highest Voltage of Nearby Transmission Plant on that Day.

Occasional readings in bands 3 and 4 were unsupported by finite readings in the adjacent lower band, and no steps have been taken to eliminate these possibly spurious contributions. In only four cases did such readings exceed 0.01 hr. Nevertheless, in view of the generally very low level of exposures in these bands, especially band 4, the averages shown may include an appreciable spurious component.

Figure 4 is a cumulative histogram of all the individual exposures, converted to average kV $m^{-1}hr$ values as outlined above. The overall mean exposure is 0.53 kV $m^{-1}hr$, with a median of 0.17 and a maximum of 9.98 (recorded by a fitter working in a 400-kV compound).

The results of the two surveys are difficult to compare exactly, but a rough indication of their degree of similarity is given by the proportions of exposures registered above 0.66 kV $m^{-1}hr$ per day by transmission workers in each case. Figure 5 shows the proportions for each job category and suggests that the two surveys are in reasonable agreement.

In summary, it appears that the transmission workers studied spend very little time (on average, 1.2 min per day) in fields greater than 4.5 kV m^{-1} and that fewer than 15% of their daily exposures exceeded 1 kV $m^{-1}hr$. It can confidently be assumed that distribution workers, dealing with plant voltages of 132 kV and below, have less exposure than this. The survey using four-band dosimeters was originally envisaged as a pilot for a more extensive study, but the low level of exposures encountered probably renders further work unnecessary.

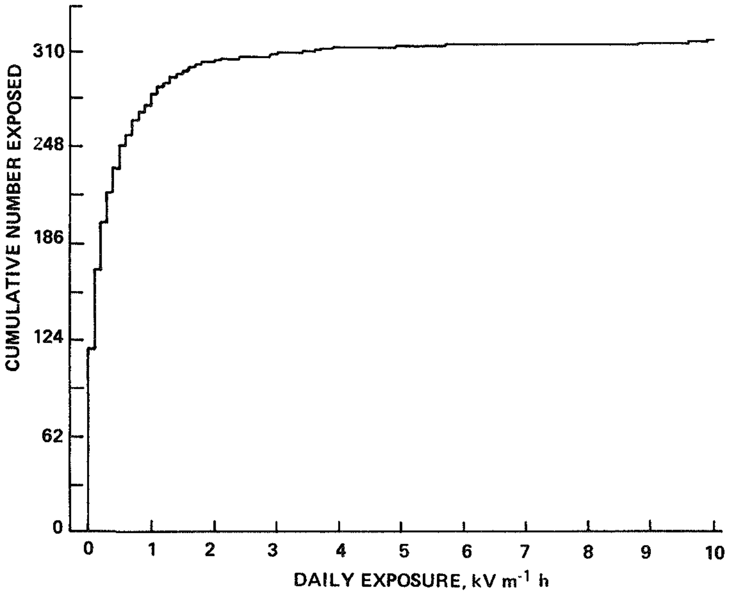

Figure 4. Cumulative Histogram of Integrated Daily Exposures to Electric Fields for Transmission Workers over 319 Exposure Days. Over 85% of the exposures were less than 1 kV m^{-1}hr.

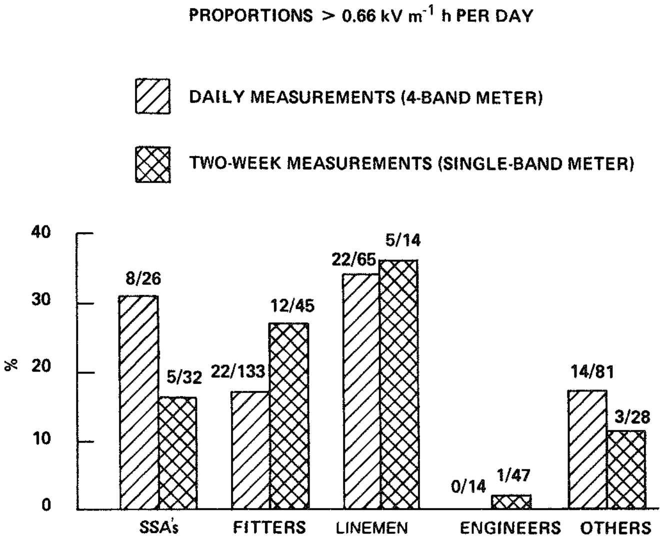

Figure 5. Comparison of Results Obtained for Electric-Field Exposure of Transmission Workers in the Two Independent Surveys, Using the Four-Band Time-Histogram Dosimeter and the Simple Integrating Dosimeter, Respectively. The proportion of workers who received more than an average of 0.66 kV m^{-1}hr per day is shown for each of the five job categories.

INSTRUMENTS FOR MONITORING EXPOSURE TO DOMESTIC MAGNETIC FIELDS

Domestic 50-Hz magnetic fields may have a large harmonic content, and a decision must be made as to whether the important feature to measure is the magnetic-field strength *per se*, or its time-derivative. The time-derivative is a technically simpler proposition and is directly proportional to the electric fields which will be induced in living tissue. We have therefore taken this route, but for present purposes have neglected harmonics when deriving field strengths in milligauss.

A compact and unobtrusive instrument has been developed for static measurements. It is based on three mutually orthogonal pick-up coils, each feeding a four-band, time-histogram recorder similar in principle to those used for personal electric-field exposure monitoring (Figure 6). The band threshold levels are normally set at 0.1, 0.6, 2.3 and 4.0 mG (equivalent rms 50-Hz magnetic-field strength), and the time-resolution is 0.01 hr. The instrument is deployed for a measured period (normally, ~24 hr), and time spent in fields less than 0.1 mG is obtained by difference, thus yielding information on five field-strength bands for each spatial component.

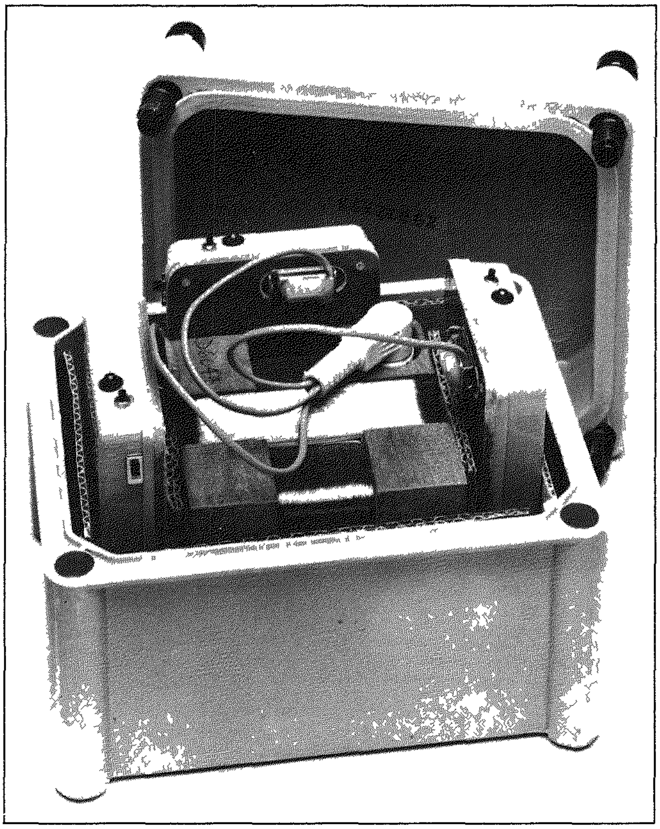

Figure 6. Time-Histogram Recorder for Measuring Magnetic-Field Exposure is Based on Three Mutually Orthogonal Pick-Up Coils, Each Feeding a Four-Band Electrochemical Integrating Module. The unit is housed in a weatherproof, glass-fiber-reinforced case.

The addition of a compact digital data logger (Grant Instruments, Cambridge, UK) makes it possible to record details of the time variations of the three spatial components, together with their instantaneous vector sum, directly in computer-compatible form. The package illustrated in Figure 7 takes a reading of each of these four quantities on a 256-point scale once per second. It averages the data once per minute and accumulates the averages for periods up to 33 hours.

Figure 7. Digital Magnetic-Field Logger Uses the Same Pick-up Coil System as Described in Figure 6, with a Preamplifier Incorporating an Rms Module, Which Allows the Vector Sum to be Recorded in Parallel with the Three Spatial Components.

For monitoring personal exposure to alternating magnetic fields, the problem is to devise a pick-up-coil system which is large enough to give an adequate output in fields as low as 0.1 mG and yet not too heavy or cumbersome to wear. The system we have developed uses a single coil, incorporated in a shoulder strap, which supports a four-band time-histogram module in a pouch at waist level (Figure 8). The plane of the coil lies at an angle of approximately 30° to the vertical.

Figure 8. Personal Magnetic-Field Exposure Meter Incorporates a 180-Turn Pick-up Coil in the Supporting Strap. The pouch houses a four-band electrochemical time-histogram module.

Assuming that, when worn over an appreciable time, the coil will randomly adopt all possible orientations relative to the magnetic-field direction, it may be shown that the average measured field amplitude is one-half the true average value. Even if the dominant field component is vertical, as may be the case if its source is an underground distribution cable, the same factor of one-half applies. Thus, with the sensitivity of the preamplifier doubled, the effective band-threshold levels are, to a first approximation, the same as those of the static instrument and may be used to derive meaningful integrated exposures (in mG hr). Capacitive coupling of the pick-up coil eliminates response to all but the most violent movements by the wearer relative to the earth's magnetic field, and the instrument is insensitive to 50-Hz electric fields up to 8 kV m^{-1}.

SOME CHARACTERISTICS OF DOMESTIC 50-HZ MAGNETIC FIELDS IN THE UK

Spot measurements have been made in about 50 houses in the vicinity of Leeds and London. Close to operating electrical equipment, field strengths may reach several hundred milligauss, but "background" levels have been found to be generally low — typically, less than 1 mG — and very variable over time. Figure 9 shows a continuous record over several days of the vector sum of the three spatial components, measured in the front room of a house at a point 20 m from underground distribution cables. As is often the case, very little of the activity is related to identifiable power consumption in the house itself. The component parallel to the roadway (and hence parallel to the distribution cable[s]) is generally the weakest, sometimes effectively zero (Figure 10). Figure 11 shows simultaneous recordings made at different distances from the roadway which, in this case, had distribution cables along both sides. Much of the detail is common to all three traces, but because the contributions from the two cables are presumably independent, the amplitudes are not related simply to distance from either cable.

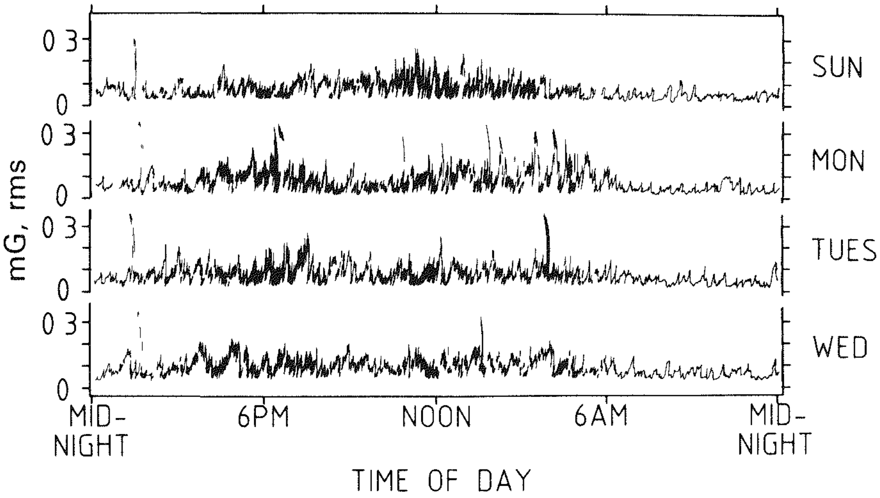

Figure 9. **50-Hz Magnetic-Field Amplitude Recorded through Four Successive Days in a Suburban House. Recorder sited 20 m from street distribution cables.**

Distribution cables in the UK normally have three closely spaced phase conductors, with a neutral conductor or an earth/neutral sheath. At more than a few diameters from the cable, the residual magnetic field is due mainly to unbalanced currents which do not return via the earth or neutral conductors. The field is therefore difficult to predict from the cable loading.

In many cases, there is a distribution cable on only one side of the street, and a spot measurement of magnetic field strength made close to the cable can be used to predict the "background" field strength within the adjacent house, according to an inverse-distance relationship.

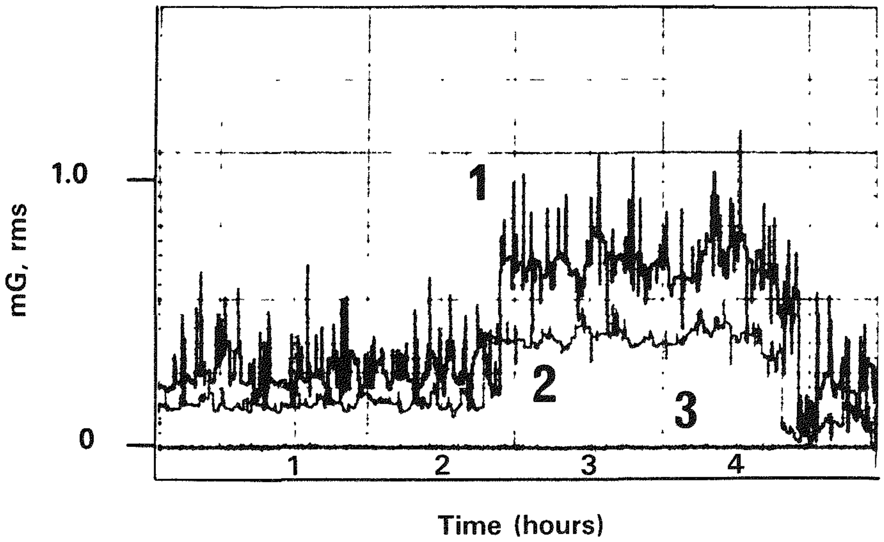

Figure 10. The Three Spatial Components of a 50-Hz Magnetic Field Measured in a Suburban House. Recorder sited 8.5 m and 20.5 m, respectively, from distribution cables on both sides of the street. (1) Vertical, (2) horizontal, perpendicular to street, (3) horizontal, parallel to street.

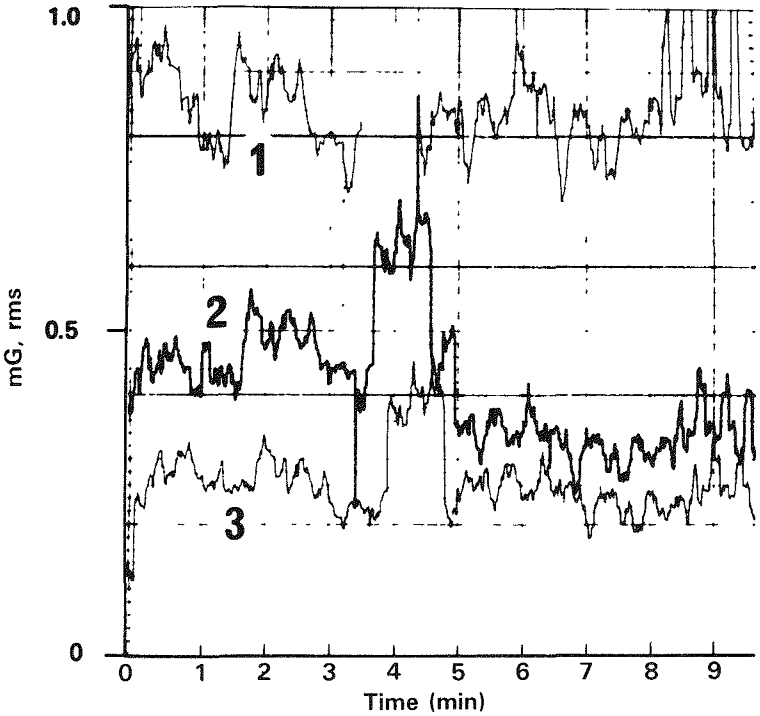

Figure 11. Simultaneous Records of 50-Hz Magnetic Field Strength (Vertical Component) in a Suburban House, Measured at Three Distances from Distribution Cables on Both Sides of the Street: (1) 8.5 and 20.5 m, (2) 17 and 29 m, (3) 23 and 35 m.

Figure 12 shows a plot of fields calculated in this way against measurements made inside the house within a few minutes of the "cable" measurement. The correlation coefficient is ~0.8. This observation suggests the possibility that background domestic field strengths may be correlated with side of the street in the UK and that this may provide a means of broadly classifying houses in case/control studies. While subject to considerable random error, such an approach appears to be largely free of systematic bias.

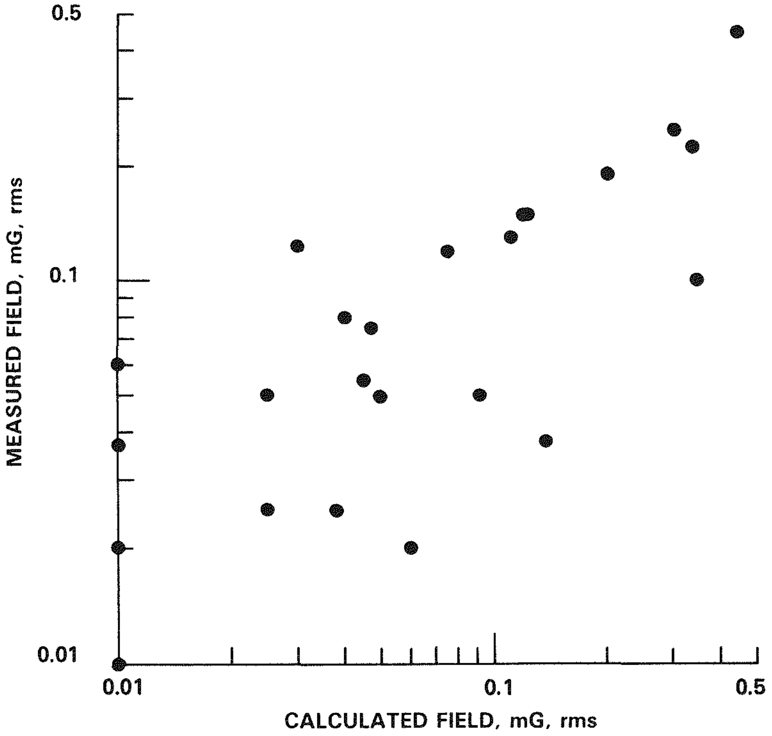

Figure12. Background 50-Hz Magnetic-field Strengths Measured in 24 Houses Plotted Against Fields Calculated on the Basis of a Measurement Made ~2 m Directly above the Adjacent Street Distribution Cable. The correlation coefficient is ~0.8.

ACKNOWLEDGMENTS

We thank Dr. A. Myers and Mrs. C. Startin of Leeds University for carrying out many of the magnetic-field measurements and for providing the data for Figure 12. We are grateful to Dr. J. C. Kinlen of Oxford University for discussion of the ideas outlined in the final paragraph. Most of this work was done at the Central Electricity Research Laboratories of the Central Electricity Generating Board and is published with the permission of the Board.

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ESTIMATING PUBLIC EXPOSURE TO POWER-FREQUENCY ELECTRIC FIELDS

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ABSTRACT

A method has been implemented to estimate public exposure to power-frequency electric fields for a variety of activities. Such estimates are critical to assessing potential risks from exposure to electric fields. The method uses an activity systems model to characterize human activities in situations where exposure to electric fields is possible. This approach provides the framework that combines electric field maps, activity (time budget) maps, and experimentally determined "activity factors" to produce histograms of time spent in various levels of electric field intensity. This paper explains how these estimates can be related to the actual electrical quantities that are applied to the human body during exposure through the use of "equivalent electric fields." The exposure-measuring system uses an electric field sensor vest and data collection instrumentation. The vest can measure human exposure (and activity factors) for a wide range of electric field intensities (1 V/m to over 10,000 V/m). This system was used to collect experimental data near 115- to 1200-kV transmission lines. Examples of annual exposure estimates (time histograms) are presented for transmission lines (farming operations and outdoor recreational activity) and for indoor domestic fields. The data strongly suggest that public exposure to electric fields of the magnitude found on the right-of-way of high voltage powerlines is infrequent, even for suspected high exposure groups. The utility of the exposure estimates is demonstrated by a sample comparison with the exposure parameters of a typical laboratory animal experiment.

Interest in the potential effects of exposure to extremely low-frequency (ELF) electric and magnetic fields has been demonstrated by the government, the scientific community, the electric utility industry, and the public. All recognize that ongoing ELF-field health research produces information necessary for risk assessment.

The criteria for information essential to risk assessment has recently been outlined in *Risk Assessment in the Federal Government: Managing the Process,* prepared by a committee of the National Research Council (NRC) Commission on Life Sciences (National Research Council, 1983). The four essential steps, diagrammed in Figure 1, include:

1. Hazard identification: establishing whether causal links exist between environmental agents and biological or health endpoints.

2. Dose-response assessment: determining the functional relationship between biological response and magnitude, duration, or frequency of exposure. This step often involves extrapolation from high to low dose and from animals to humans.

3. Exposure assessment: characterizing the magnitude and duration of human exposure to the agent(s) in question.

4. Risk characterization: estimating the fraction of a population likely to be affected under ambient conditions.

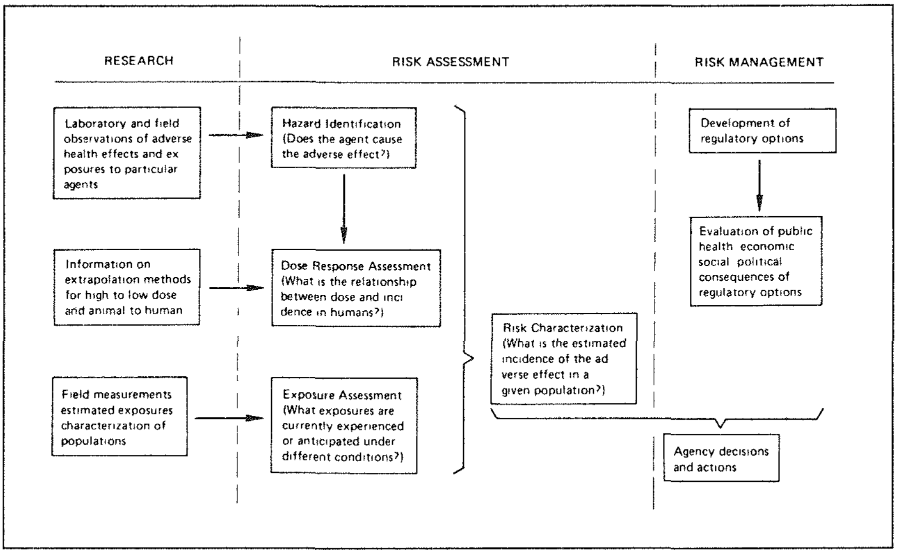

Figure 1. Elements of Risk Assessment and Risk Management.

The methodologies and data presented in this paper apply to the third step, exposure assessment. A more complete definition of exposure assessment is found in the NRC document: "...the process of measuring or estimating the intensity, frequency, and duration of human exposure to an agent currently present in the environment or of estimating hypothetical exposures that might arise from the release of new chemicals into the environment. In its most complete form, it describes the magnitude, duration, schedule, and route of exposure; the size, nature, and classes of the human populations exposed; and the uncertainties in all estimates. Exposure assessment is often used to identify feasible prospective control options and to predict the effects of available control technologies on exposure." (National Research Council, 1983).

Although the issue has been in the public domain for at least a decade, only recently have efforts been launched to characterize the public's field exposure. Three major factors have contributed to this development:

1. **Emerging Research.** The literature now contains some publications which report biological responses to electric and magnetic fields by laboratory subjects (animals and cells) and others that speculate on associations between putative exposure and increased cancer rates in humans. While it is difficult to extrapolate from the laboratory studies to human risks, and the epidemiological findings are tentative, it is clear that both classes of research require the perspective provided by exposure assessment.

2. **Growing Acknowledgment of the Value of Exposure Assessment.** It is now well appreciated that, by themselves, ambient levels of environmental agents are not adequate predictors of exposure. Equally important are the spatial and temporal descriptions of human activities. Perhaps nowhere is this so striking as in the field of air quality. Exposure assessments show that air quality indoors, where most of us spend over three-fourths of our time, is markedly different from the quality predicted by outdoor measurements. Indoor combustion (e.g., cooking, wood burning), ventilation, and composition of building materials all influence indoor air quality. In a similar fashion, appliance usage and household wiring patterns are important determinants of electric and magnetic field exposure profiles. Exposure assessments must also include the workplace where, depending on the job, exposure may considerably exceed nonoccupational levels.

3. **State of Measurement Technology.** The preferred way to gather data on personal field exposure is to outfit individuals with devices which directly record the electric and/or magnetic field and store collected data. If the data analyses reveal trends that can be extrapolated from the measurement sample to larger populations, then mathematical modeling techniques can be incorporated in the assessment.

Devices that record personal exposure to electric fields have become available only recently, and supplies are still limited; magnetic field devices are now in early stages of development.

The research presented in the following sections demonstrates how spatial maps of field strengths are integrated with human activity and time-budget data to yield realistic exposure information. We also describe the measurement system used in this project to collect personal electric field exposure data. The issue that initially gave rise to the project concerned exposure to 60-Hz electric fields from overhead transmission lines. Farmers with cropland traversed by transmission lines and recreational users of rights-of-way were selected for study as models of high exposure groups. Estimates of exposure unrelated to transmission lines ("domestic exposure") are also included to provide a perspective on background exposure.

The selection of the appropriate units to express levels of exposure should be based on an understanding of the exposure process. However, effects of electric fields on humans, other than from perception at higher intensities or, secondarily, from spark discharges, are unknown. We present exposure estimates as annual time spent in discrete ranges of electric fields. Despite the uncertainty concerning effects and exposure processes, these estimates should have general applicability.

The activity systems model approach taken in this project for 60-Hz electric fields can be adapted to structure risk assessments for electric and magnetic fields across the ELF spectrum. The information gathered in such assessments can be used, for example, to extrapolate exposure estimates to larger populations or to those suspected to be sensitive (e.g., pregnant women). They can also be used to help in assigning appropriate units of exposure and to contribute to a better understanding of the relevance of animal experiments to people. Recently, the importance of exposure assessment was aptly stated by the Office of Science and Technology (May 22, 1984): "An estimate of cancer risk for humans exposed to an agent can be no more accurate than an exposure assessment that it utilizes. Lack of adequate exposure data is frequently a major limiting factor in evaluation of carcinogenic risks for humans." (Office of Science and Technology, 1984).

ACTIVITY SYSTEMS MODEL

Activity systems models are used to study the relations between the activities of human populations and their physical environments. Activities are characterized in terms of their space and time patterns, and these patterns are related to environmental conditions.

Activity systems models have been used for more than a decade to study human activity patterns and their results. Models of this type have been used to study human activity patterns in urban areas (Chapin, 1974). Other models have been used to analyze automobile transportation behavior (Hummon, Baker, and Zemotel, 1979; Hummon and Burns, 1981) and exposure to indoor and outdoor air pollution (Moshcandreas, Zabransky, and Pelton, 1981). A key feature of all these studies is that peoples' activities place them in physical locations for certain periods of time, and these locations are associated with social or physical conditions of interest.

For estimating electric field exposure, a similar approach has been outlined in detail for a variety of public activities (Silva, Zaffanella, and Hummon, 1984). The model involves the creation of an electric field map for the study area. Time budget or labor analysis data are used to prepare an activity map for the study area. The electric field and activity maps are then combined to produce an estimate of time spent in unperturbed electric fields at various levels; these values are modified through the use of activity factors. An activity factor describes the electrical relation between a reference condition (standing erect, with arms at side, perfectly grounded) and a specific activity, which may involve movement, use of equipment, and varying degrees of grounding. For example, the activity factor could be the total body current to ground, expressed as a percentage of the theoretical, reference body current. The final results of the activity systems model are estimates of time spent in electric fields based on integration of the field strength, time, and activity factors throughout a study area. This methodology is being adapted into EXPOCALC, a computer program for exposure assessment modeling.

The activity systems approach is more efficient than distributing instrumentation to a large population and collecting data for an extended period. However, an exposure measurement system is needed to 1) empirically determine activity factors, especially for complex activities, and 2) validate the accuracy of exposure predictions generated by the activity systems model.

EXPOSURE MEASURING SYSTEM

A new measuring system has been developed (Deno and Silva, 1984) that is suitable for most outdoor and indoor exposure measurements. The system consists of a "sensor vest" and pocket-size data collection instrumentation (Figure 2). The sensor is made of conductive material and intercepts the current which, in the sensor's absence, would enter the part of the body it covers. The current (I_v) flows through the data collection instrumentation before entering the body through a medical electrode. The sensor is otherwise electrically insulated from the body. The data collection instrumentation contains ion transfer integrators which accumulate electrical charge proportional to the exposure. The ion transfer integrators are discharged by a separate readout device, which records the accumulated charge that is proportional to exposure. Exposure is measured in five contiguous "bins" of equivalent electric field intensity. The exposure measuring system is shown in use in Figures 3 and 4.

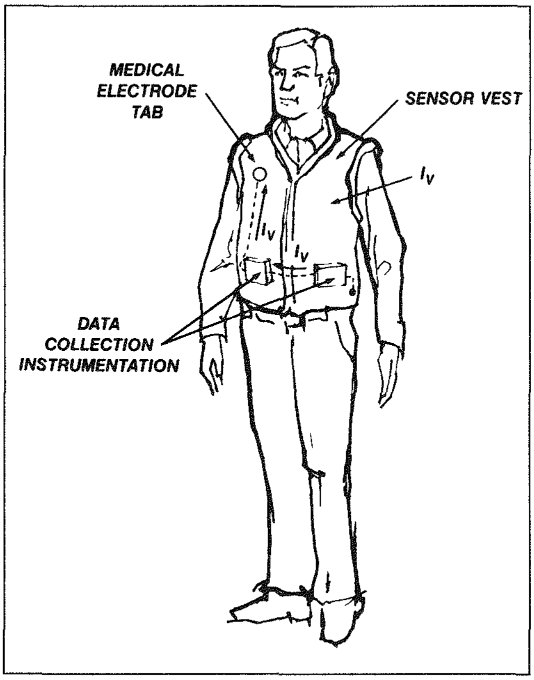

Figure 2. Electric Field Exposure Measurement System.

The choice of a vest or a jacket as a sensor for exposure measurements was dictated by a number of practical reasons:

- convenient to wear,
- insensitive to small changes in body position,
- does not disturb induced currents entering the body,
- relates well with upper-body exposure (an area of biological significance).

Figure 3 Exposure Measuring System in Use under 500-kV Line

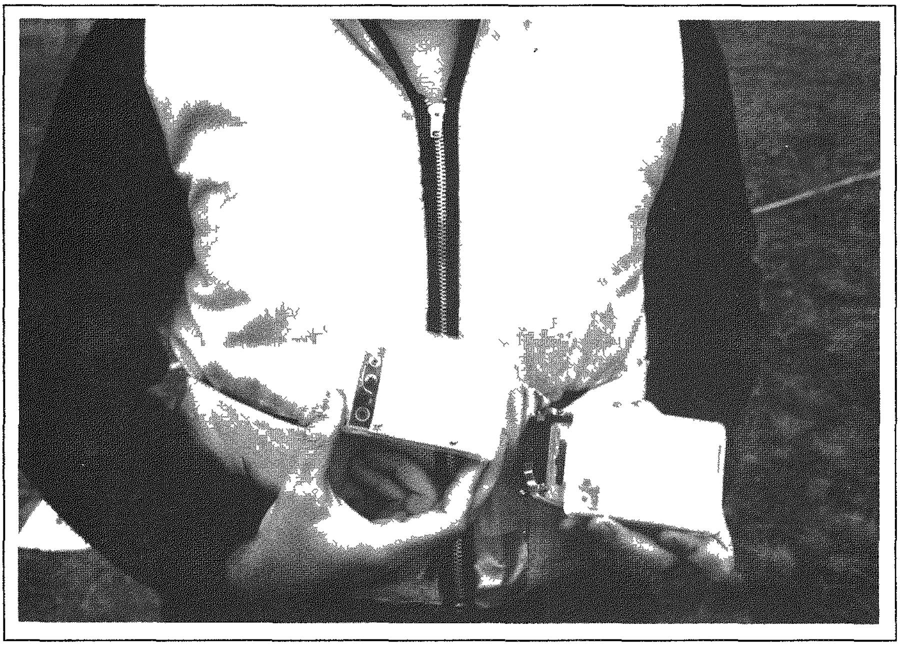

Figure 4. Instrumentation for Data Collection in Exposure Measurement System.

ACTIVITY FACTORS

Investigators have found that actual measured exposure to electric fields may be considerably lower than that predicted by estimating time in unperturbed fields (Stopps and Janischewskyj, 1979). Many factors combine to produce lower exposures; some of the most important are: the effect of body position, relative grounding during an activity, and shielding caused by objects or equipment that may be used in that activity. To illustrate the effect of grounding, consider a person standing in an unperturbed, 10-kV/m electric field. If the person wears ordinary shoes on dry pavement, the electric fields on the surface of the body and the body currents induced by the external electric field are lower than the surface fields and body currents induced when the person is electrically grounded (i.e., standing with wet shoes on wet grass). The differences between these two situations are shown in Figure 5. When the person is insulated, each index of exposure is reduced to that experienced if the unperturbed electric field were less than 10 kV/m (i.e., the body does not "experience" the 10-kV/m field but, instead, experiences an "equivalent" electric field which is significantly lower). This effect is described by the activity factor (shown in parentheses in Figure 5).

From Figure 5 we see that the vest measurement system is, in general, a good indicator of upper-body exposure indices. Therefore, the unperturbed field is multiplied by the appropriate activity factor to produce an equivalent field to which a person is exposed.

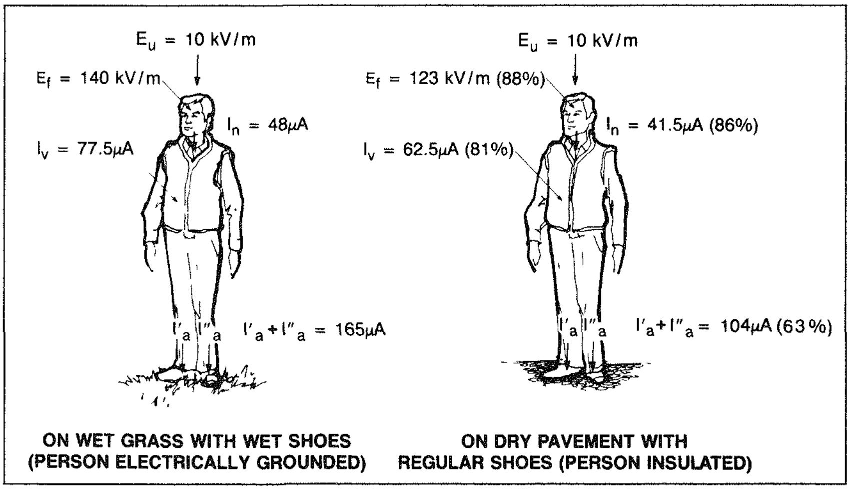

Figure 5. Electric Field on Forehead (E_f), Current in Neck (I_n), Vest Current (I_v), and in Ankles (I_a) for a Grounded Person and an Insulated Person. The activity factor for each quantity is shown in parentheses.

EXPOSURE MEASUREMENT PROGRAM

The vest measurement system was used across the United States for a number of measurements during typical farming and recreational activities near operating transmission lines (Figure 6). Farmers and other individuals participated in the program, and measurements were conducted during farming and other tasks.

The program had two main goals:

- To collect electric field exposure data and measure activity factors under realistic conditions near transmission lines.
- To validate the exposure methodology, which was based on activity systems modeling.

RESULTS

Table 1 lists selected activity factors determined by measurements during the test program (see Silva, Zaffanella, and Hummon, 1984 for a more complete listing).

Farm exposure

Farm exposure estimates were developed using measured activity factors and time-budget data provided by the U.S. Department of Agriculture (USDA). The USDA has compiled time data for farming activities and has also identified 18 farms (Hatch, 1982) that provide statistical composites which are representative of various geographical regions.

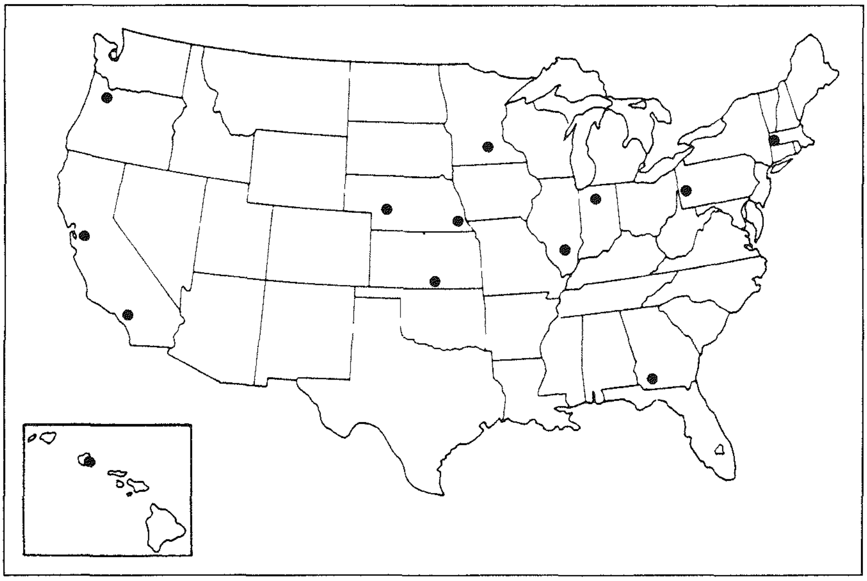

Figure 6 Exposure Measurement Program Sites

TABLE 1 Selected Activity Factors Determined by Exposure Measurement Program

Activity Description	Number Measurements	Activity Factor, (%)	
		Range	Average
Standing in work boots	20	68 - 96	89
Standing in various shoes	36	60 - 96	79
Standing barefoot on rocky soil	1	---	95
Standing in jogging shoes	5	67 - 79	73
Working bent over	3	52 - 76	65
Moving through heavy brush/saplings	1	---	21
Inside jeep (fiberglass top)	3	2 - 4	3
Inside pick-up truck	2	---	0.7
Driving farm tractor (open top)	25	11 - 63	42
Driving farm tractor (closed cab)	5	1 - 5	2
Driving combine with cab	5	0.3 - 0.4	0.4
Riding trail motorcycle	2	---	59
Riding horseback	4	80 - 87	84
Sitting in lawn chair	2	43 - 53	48
Swinging on swingset	2	57 - 63	60
Cross-country skiing	1	---	78
Snowshoeing	1	---	86
Sitting in aluminum boat	3	28 - 33	30
Hiking with backpack	13	73 - 104	90
Riding bicycle	2	78 - 86	81
Playing tennis	13	50 - 72	64

Table 2 summarizes the results of an analysis of the Illinois typical USDA farm for three different transmission line designs. The data in this table are presented for an individual person working on the farm and reflect only time performing outdoor work.

TABLE 2 Equivalent Electric Field Exposure Estimates for Illinois Farm

Electric Field Eeq (V/m)	Annual Time in Electric Field (Hr) 115 kV	 345 kV	 765 kV
0 - 1	1295	1087	605
1 - 2	37	77	280
2 - 4	34	71	152
4 - 8	26	56	101
8 - 16	23	43	76
16 - 32	20	34	58
32 - 64	12	29	46
64 - 125	7	22	39
125 - 250	9	15	34
250 - 500	13	15	21
500 - 1000	3	14	19
1000 - 2000	1	14	21
2000 - 4000	0	2	21
4000 - 8000	0	1	6
> 8000	0	0	1
Maximum Eeq (kV/m)	1 5	4 5	10 5

Even when a high-voltage line crosses a farm, about 90 to 98% of a farmer's time is spent in electric fields below 60 V/m (the approximate range of equivalent electric fields from domestic sources). The remaining 2 to 10% of the time is spent in equivalent electric fields ranging up to several thousand V/m, depending on line design.

One final consideration is the temporal aspect of exposure. Besides daily variations, one might consider exposure accumulated by month during a year of farm work. Such a histogram is shown in Figure 7. This graph depicts the accumulated exposure, by month, for the USDA typical Georgia farm crossed by a 500-kV line. The exposure totals increase in the spring months with ground preparation and planting, decrease in midsummer, and peak in the fall during harvest. This comparison demonstrates an important aspect of time spent in the higher levels of an electric field: exposure occurs sporadically throughout the year; it does not occur all at once.

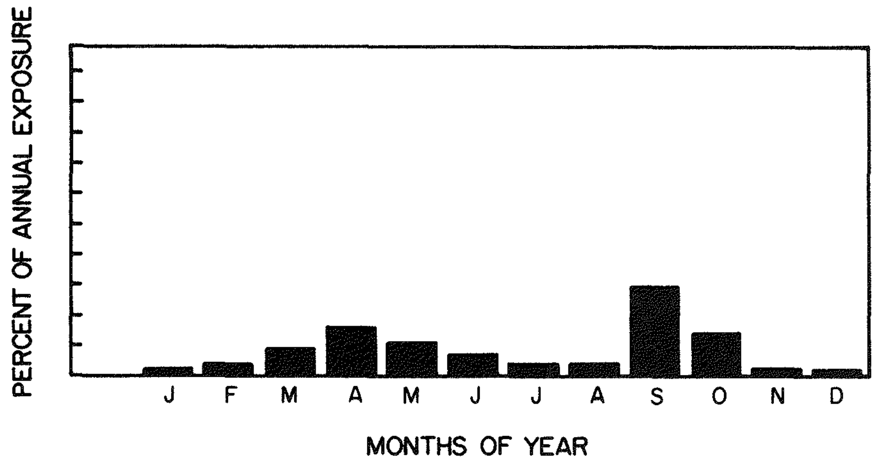

Figure 7. Example of Exposure, by Month, for a Farm with a 500-kV Line.

Recreational exposure

Recreational activities were evaluated along existing paths on the right-of-way of a 230-kV line in California and a 345-kV line in Michigan. For the estimates, all recreational activity was assumed to take place on the transmission line right-of-way. Participants are assumed to go back and forth at this location (with some random rest stops) until a distance is covered that is appropriate for the activity duration. No shielding by vegetation, shrubbery, small trees, outdoor light standards, or buildings was considered. A summary of the activity details is provided in Table 3; the results are shown in Table 4.

The estimates reveal that, for the situations modeled, most exposure occurs in equivalent electric fields above 60 V/m. Estimates were higher for the skiing situation due to increased line voltage and activity path location. If cumulative exposures are considered as an index, then the annual recreational exposure estimates shown in Table 4 are about 10 to 20% of the estimated annual domestic exposure level presented in the next section (about 70 kV/m · h).

TABLE 3. Summary of Activity Details Used to Estimate Electric Field Exposure

Activity	Speed (mph)	Annual Distance Traveled at Site (mi)	Average Activity Factor (%)
Jogging	7	85	80
Bicycling	12	125	82
Skiing	4	45	78

TABLE 4. Summary of Sample Electric Field Exposure Calculations

Exposure Bins Eeq (V/m)	Annual Exposure, (kV/m · h) Jogging 230 kV	Bycycling 230 kV	Skiing 345 kV
0 - 50	0	0	0
50 - 25	0.42	0.48	0
250 - 1000	4.33	3.84	4.80
1000 - 3000	1.37	1.20	5.92
3000 - 6000	0	0	4.68
ANNUAL TOTAL	6.12	5.52	15.40

Domestic exposure

The study of exposure to electric fields from high-voltage transmission lines would not be complete without evaluating exposure to power-frequency electric fields present in domestic environments. In a house, an office, or a commercial building electric fields are generated by the power supply wires and by the devices attached to them. These fields are much lower than peak transmission line fields, but they are encountered for much longer periods of time. Therefore, using an index of field exposure expressed by the product of field and exposure time (V/m) · h, domestic fields could be comparatively significant. Domestic exposures can be considered background or ambient exposure levels for most of the population.

Electric field exposure from domestic sources was evaluated with the vest measurement system. A series of about 70 measurements were made at two homes in California; one home in Kansas; one commercial building in Hawaii; one home and office in Massachusetts; and three homes, a grocery store, and a large shopping mall in Pennsylvania (Silva et al., 1985). The measurements included a wide variety of exposure situations, carpet types, shoes, and body positions. The results were combined with human domestic time budget data (University of Michigan, 1977) to produce annual estimates of household exposure.

A typical annual distribution of the estimated time spent in domestic electric fields is provided in Figure 8. The graph is derived from the values recorded in the domestic measurement program previously mentioned, but it is qualitatively representative of general domestic exposure. A broad peak encompasses the most common sources of exposure, such as lamps and appliances. The second peak is caused by appliances such as electric blankets, phonographic/recording equipment, and electric tools.

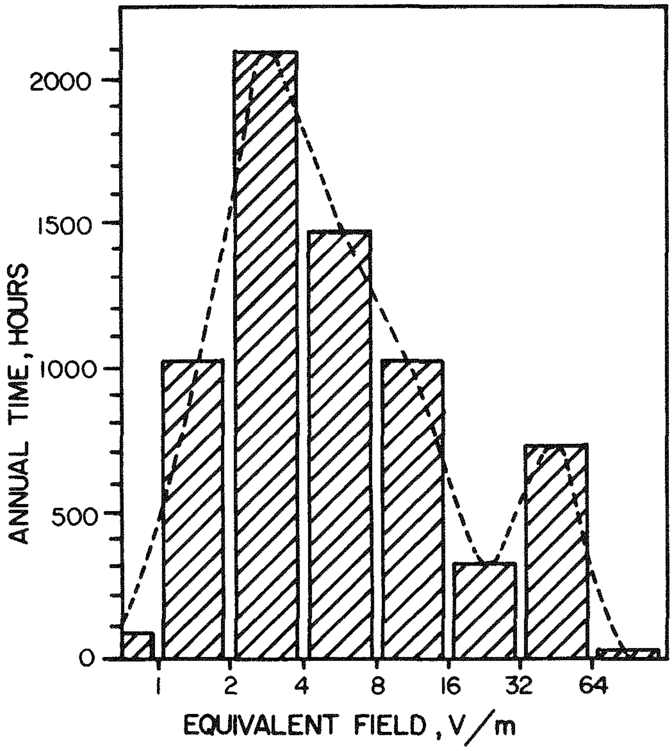

Figure 8. Typical Distribution of Annual Domestic Electric Field Exposure.

USE OF EXPOSURE ESTIMATES

The results of the activity systems model lend themselves to three broad applications: 1) exposure information can be incorporated into risk assessments, 2) exposure of a general population or subpopulation (farmers, for example) can be compared with that in laboratory studies, and 3) exposure estimates can be used in the design and planning of future research projects. The results can help investigators more accurately model the magnitude and temporal aspects of actual human exposure. A sample comparison with the exposure parameters of a typical laboratory-animal experiment demonstrates the utility of the exposure estimates.

Consider a sample comparison of the farm exposure estimates of Table 2 with some typical laboratory animal exposures (Phillips, Anderson, and Kaune, 1980). Suppose that the method of comparison is based on current density in the thorax. The farm exposure data of Table 2 are now converted to histograms of time spent at various levels of current density (using the values in Kaune and Phillips, 1980). These comparison histograms are presented in Figures 9 and 10 for the 345-kV and 765-kV cases, respectively. No attempt was made in the analysis to deal with any of the physiological considerations that are necessary for comparisons between laboratory animals and humans. The data in Figures 9 and 10 are provided to demonstrate the utility of the exposure estimates.

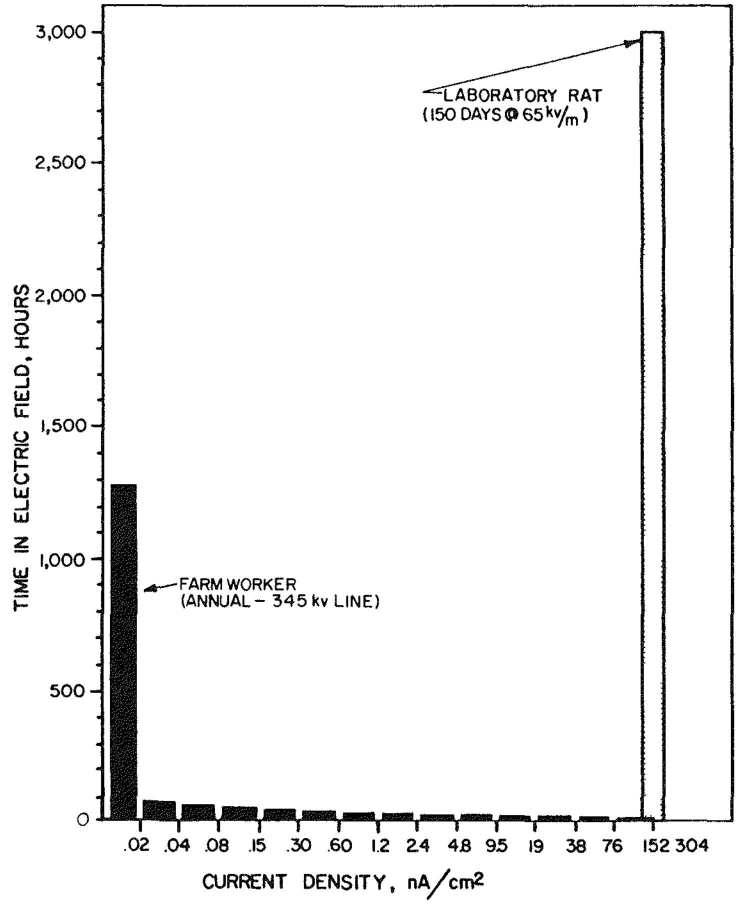

Figure 9. Example Comparison of Current Density (345-kV Case).

Another comparison with typical laboratory data could be based on an evaluation of time spent above a threshold of perception of the electric field. To perform this comparison, we need a value for the threshold of perception for humans and for laboratory rats. A median threshold for perception of 6- to 7-kV/m has been reported for humans (Electric Power Research Institute, 1982). Rats have reportedly been able to detect electric fields in the 4- to 8-kV/m range (Stern et al., 1983). The results, presented in Table 5, have been refined for the electric field values of interest. (Also, additional line designs have been added.) Other values might be used for the animal and human perception thresholds, but the comparison provides an example of another use of the human exposure estimates.

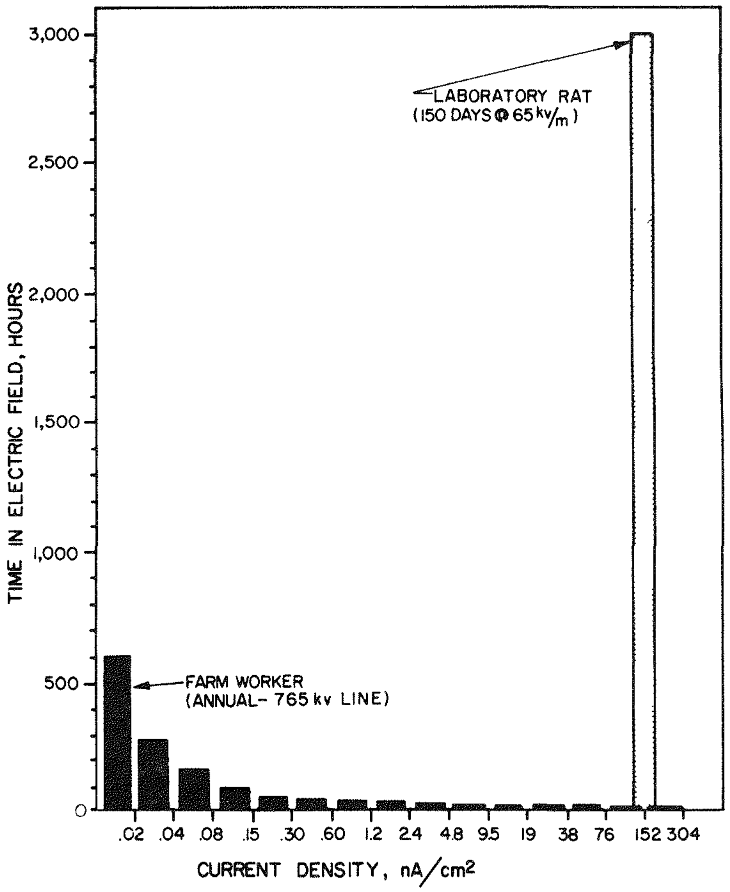

Figure 10. Example Comparison of Current Density (765-kV Case).

TABLE 5. Time Spent in Electric Field Above Threshold of Perception[a]

Subject	Electric Field Range (kV/m)	Time at Eeq Threshold
Farmer (115 kV)	≦2	0
Farmer (230 kV)	≦3	0
Farmer (345 kV)	≦5	0
Farmer (500 kV)	≦9	1/2 hour/yr
Farmer (765 kV)	≦12	3 hours/yr
Laboratory Rat	65 - 130	1200 - 3000 hr

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[a] Humans: 6-7 kV/m; Laboratory Rats: 4-8 kV/m

CONCLUSIONS

- An activity systems model can be used to develop estimates of public exposure to power-frequency electric fields for a variety of human activities. The model provides the framework that combines electric field maps, activity maps, and experimentally determined activity factors to produce histograms of time spent in various levels of electric field strength.

- Human exposure to electric fields cannot be evaluated using the unperturbed electric field alone. Rather, it is necessary to introduce the concepts of equivalent fields and activity factors. Equivalent field is the unperturbed uniform field which would cause the same electrical quantities applied to the body as those in a well-defined reference situation. Activity factor is the ratio between exposure during an activity and the theoretical exposure which would occur in the reference situation for the same unperturbed field. Equivalent field is the product of unperturbed electric field and the appropriate activity factor.

- For the farmers studied, a large amount of the outdoor work time (90 to 98%) was spent in equivalent electric fields below about 60 V/m. For the recreational exposure examples, most of the time was spent in fields above 60 V/m.

- As more data become available, a broader range of applications will be possible. Public exposure estimates can be used to compare human exposure with that in laboratory studies, for risk assessment, and in the design and planning of future research projects.

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A UK PROGRAM TO STUDY THE RESPONSE OF PEOPLE TO 50-Hz ELECTRIC AND MAGNETIC FIELDS NEAR AN ELECTRIC POWER PLANT

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ABSTRACT

The program consisted of: 1) a health-questionnaire investigation of electricity transmission and distribution staff in one part of the UK; 2) a case control study of all childhood cancers in the Yorkshire Regional Health Authority area and their relationship to a variety of environmental factors, including the proximity of high-voltage transmission lines; 3) measurement, in strong electric fields, of the performance of cardiac pacemakers fitted to patients suffering from a variety of cardiac infirmities; 4) studies of attention and verbal reasoning skills in volunteers during the passage of a 500-μA, 50-Hz current through the body. The studies are now largely completed, and the results are discussed. They do not indicate any general need to restrict access to places where there are electric and magnetic fields arising from electric power equipment beyond the long-standing precautions to prevent electric shock and annoyance from small discharges.

The Central Electricity Generating Board (CEGB) program of research into the possibly health-related effects of electric and magnetic fields has involved the study of human exposure under differing conditions:

a) men occupationally exposed to electric fields from high-voltage transmission systems in South-West Britain,

b) volunteers subjected to the passage of electric currents under controlled laboratory conditions, using psychometric tests,

c) victims of childhood cancer in one region of the UK, using a case control (case referent) study, and

d) patients suffering from a variety of cardiac diseases, in whom the response to electric fields of cardiac pacemakers of different designs was evaluated.

In summary, the findings confirmed that power-frequency electric fields at strengths encountered in the occupational and general environment do not have deleterious effects on the health of persons exposed at work or in the community.

The strongest ground-level field to which the public are exposed in the UK is about 11 kV/m under the lowest span of 400-kV lines. This condition is rarely found; lines rarely run at maximum load and most spans have more than the minimum clearance (Scherer, Ware and Marsico, 1984 make the same point for the American Electric Power Co. system). An average value under the conductors is probably less than 5 kV/m; it is lower still under lower-voltage lines. There is no specified width of right-of-way in the

UK. Land is not usually bought by the CEGB for transmission lines; an easement to erect and use a line is obtained, and payments are made for the disturbance caused and for loss of facility, e.g., having to plow around a transmission tower. Providing that safety clearances are maintained, buildings and houses are erected beneath lines.

The electricity supply industry has had experience since at least the 1930s in dealing with directly perceived effects of capacitive induction (e.g., Barber et al., 1974). In practice, difficulties are few and are readily overcome by screening or earthing. Such difficulties do not call for a comprehensive ruling on electric-field strength designed to cover all contingencies on what may or may not be done with any "right-of-way boundaries"; in a densely populated country like the UK, at least, that would be a profligate policy.

Within 400-kV substations the ground-level fields are about 5 kV/m, although close to metal structures, such as instrument kiosks, the fields are lower; much of the work is done in such low-field areas. The maximum ground-level field rises to 22 kV/m.

Magnetic fields near 400-kV lines fluctuate widely, both during the day and between seasons, as the power flow rises and falls; an average value beneath a 400-kV line is about 250 mG but at peak load, 1000 mG may be found. In houses, magnetic fields resulting from distribution cables are only a few mG, but higher values can occur in flats (apartment blocks). Near domestic equipment one may find fields up to about 1 G. These magnetic fields are not directly perceived by people.

We have also considered the possibility that air-ions produced in the corona discharges near the live conductor might be significant, but few air-ions escape from ac corona. We have developed instrumentation (Houlgate and Wilson, personal communication) to measure air-ions under wet weather conditions. Below 400-kV lines there are rarely excesses of air-ions, but we have observed bursts at ground level of a few thousand excess ions per cm^3, lasting 20 to 100 seconds. Negative ions often predominate; positive ions do so rarely (Houlgate and Wilson, personal communication).

We know of no effect of excess ions on health except, possibly, those resulting from precipitation of smoke and other small particles in the air.

EPIDEMIOLOGY

South-West Britain Survey

Broadbent et al. (in press) describe the survey and its results in detail. A health questionnaire was administered by specially trained nurses in an interview comprising 150 or so questions, which lasted about an hour. Exposure to electric fields was measured during the fortnight before the interview, and estimates were made by supervisory engineers of the time spent by the men in low-, medium- and high-strength fields during the previous 6 mo and during the previous 15 yr.

Perhaps because of inexperience in making such estimates, and also lacking exposure measurements to guide them, the engineers' estimations far exceeded the measured values. This has been noted by others (see Male, Norris, and Watts, this volume). Exposure measurements were available for 287 subjects, of whom 28 had a measurable exposure (in this case greater than 6.6 kV/m hr for the 2 wk). The average exposure of this group was about 30 kV/m hr for the 2 wk. Although the estimates exceeded the measurements, the higher measurements were correlated to a degree with the higher estimates.

Those studied included people working on the distribution system (voltages up to 132 kV only). This group was rarely exposed and was chosen with that expectation. The fact that those working on plant at 275 kV and 400 kV were not more often exposed is perhaps explained partly by the fact that they do much of their work away from energized equipment and partly by the fact that work is often done close to earthed objects which provide screening. Another factor might be that the current flow in the body is reduced to some extent by high earth resistances. More details on exposure measurement are given by Male, Norris, and Watts (this volume).

Health measures recorded in the questionnaire included visits to the doctor, use of medicines (both prescribed and unprescribed), headaches, anxiety, obsessional symptoms, somatic symptoms, depression, job dissatisfaction and cognitive failure. Job factors were also included: amount of physical work, shift changes, time spent traveling, overtime, discretion exercised on the job, variety of things to be remembered.

The general level of health was higher than in manual workers in other industries, assessed by the same technique (Broadbent et al., 1985). There were significant differences in health measures between different categories of job, different parts of the country, and in association with factors such as overtime, working alone, working long hours or frequently changing shift. After allowing for the effects of job and location, however, there was no association between either estimated or measured electric-field exposure and health.

Environmental Factors Influencing the Incidence of Childhood Cancer

This case control study, which is not yet complete, is based at Cookridge Hospital in Yorkshire and uses childhood cancer records. Controls were selected from birth registers, using the nearest births matched for maternal parity, social class, urban versus rural gradients and other factors. The addresses of cases and controls were listed, and the list was mixed up so that the various environmental factors of the houses occupied during the 6 mo around birth were assessed blind. Factors included are gas and electricity accounts, family history, type of house, population density structure in the neighborhood, proximity of main roads, railways and industrial activity, proximity of overhead lines and estimates of magnetic fields. Other factors to be considered are the use of drugs and X-rays, and other events in pregnancy.

The code can be broken "in the computer" and only summary data extracted so as to preserve the blindness of the data, so that if further environmental data become available they can be used.

The chief difficulty has been in estimating exposure to magnetic fields, even in simply knowing the level of magnetic field at the house concerned. This difficulty arises mainly from the fact that the magnetic-field levels fluctuate during the day by orders of magnitude. Spot measurements are useless. (See Male, Norris, and Watts, this volume.) Furthermore, we have not yet been able to find ways of knowing clearly what is the main source of the magnetic field at a house. In some cases, domestic equipment can be the dominating source; in other cases, currents in cables in the road are more important. For average fields, from below 1 to 3 mG, we have not yet formulated a good way of estimating the magnetic fields at an address occupied by the patient 5 to 15 yr earlier, to take account of the latent period for cancer production.

If field strengths higher than 3 mG are considered, then overhead transmission lines are the only identifiable source. We are analyzing the possible influence of fields arising from these, but we will likely have to depend on judgments of (average) current flows at the time of interest. The number of addresses involved is much lower than if we had been able to include distribution lines. Of the 1054 addresses (417 cases, 637 controls) considered, only 81 lie within 100 m of power lines; beyond that distance, even for lines of the highest power, we may expect magnetic fields to be small.

Work is currently directed towards assessing magnetic fields at the addresses concerned. The importance of negative-sequence currents is being assessed. Some of the factors we have identified are discussed by Male and Norris (1982).

Laboratory Study of Memory, Vigilance and Verbal Reasoning

This study has been reported by Stollery (this volume) at this conference and will be published in full elsewhere. No specific illness was suspected to result from exposure to electric fields near transmission plants. However, some studies (see Male and Norris, 1982 for references) had suggested that nonspecific responses might result from or be expressed as changes in the action of the central nervous system. Our review of the literature suggests that the only described effects that resulted from electric-field exposure are those associated with perception of the field through small discharges, or from hair and clothing movement.

To cover a point not previously examined we have studied the passage of electric currents via electrodes which were attached to the body and designed to bypass perception of the field. In these laboratory studies, currents of 500 mA at 50 Hz were passed via 10 electrodes on the upper body (including four on the head) to the feet.

As a way of searching for effects on the central nervous system, each of 76 subjects undertook a sequence of tests to examine memory, vigilance and verbal reasoning four times during each of two 5.5-hr days; electric current flowed on only one day. Stress and arousal were self-reported, using a mood-adjective checklist at the start and end of each day. The subjects were volunteers with no known history of previous exposure to strong electric fields.

To seek for effects of current, some 150 interactions were examined in an analysis of variance of the parameters of the psychometric tests: most, but not all of these interactions were independent. (A significance criterion of $P < 0.05$ was used.) The main factor emerging from the psychometric tests is that the ability to determine the truth of passive sentences was affected by the passage of current ($P < 0.03$). In subjects treated with current flow, the average response time increased from 3.3 sec by about 260 msec. The experiment could not distinguish whether current flow improved the learning procedure, impaired repetition of the learned task or impaired performance generally.

Performance in tests of serial reaction time and semantic reasoning, and in other aspects of syntactic reasoning, did not appear to be related to current flow.

Self-reported arousal, on average, fell during the day, but it fell less on the second day in the group through which current had passed that day ($P < 0.013$). Self-reported stress was not affected by the passage of current.

Other factors that affected performance in tests were practice, sleep, and the use of alcohol and perception of "tingling" at the electrodes, which was experienced for a few minutes by 63% of the subjects. (In one aspect of the visual search test, a current-related interaction of perception appeared to be statistically significant.)

The results show a statistical association with much variability. Some analysis remains to be done.

The currents used were higher than those normally induced in people living and working near electrical power plants. The 500 μA used is equivalent to a field of about 35 kV/m; occupational exposures for transmission workers, however, average about 0.5 kV/m hr (Male, Norris, and Watts, this volume). This difference in exposure level, together with the mildness of the apparent effects, leads us to conclude that no effect on health would result from body currents induced by living near power lines. We are considering what further specific experimental work, if any, is merited with regard to the passage of the lower currents experienced in practice.

CARDIAC PACEMAKER PERFORMANCE

Bridges, Frazier, and Hauser (1978) reported electronic tests on cardiac pacemakers, both on the bench and implanted in baboons, which showed that the action of some designs of pacemaker could be altered by electrical interference if the wearer of a pacemaker were to encounter a strong electric field or otherwise have electric currents induced in his body. Butrous et al. (1983) carried out a series of measurements of pacemaker performance in which wearers stood in electric fields in the laboratory and others in which currents were introduced into the body through electrodes (Butrous et al., 1984). Pacemaker performance was monitored by continuous electrocardiography.

The results showed that some designs of pacemaker were insensitive to interference from body currents induced by fields even as high as 20 kV/m, which is about the highest field likely to be experienced in practice. The most sensitive pacemaker was affected by a field of only about 2 kV/m. No pacemaker was found to be permanently affected by electrical interference: all recovered virtually instantaneously when the interference source was removed. In many cases the interference resulted in the pacemaker providing sustained regular stimulation to the heart. This is not believed to be harmful but in one case caused discomfort.

Under circumstances of a kind which might be found in practice, some sensitive pacemakers may either stimulate irregularly or fail to stimulate at all. Under these circumstances it is conceivable that there may be a transient loss of consciousness, but consequent change in body position might be expected to change internal current paths and induced voltages so that the pacemaker would again begin stimulation. We know of no incident of this extreme interference, either in a member of the general public or in a person exposed occupationally.

Two people who, from time to time, work in substations and who use sensitive pacemakers have been provided with conducting suits to prevent current being induced in the body. Such suits are used by some utilities in live-line working to reduce annoyance from discharges when working in strong fields. These suits need to be designed with very good electrical contact between the parts of the suit, including the boots, if pacemaker interference is to be reliably and adequately suppressed.

Exposure to strong electric fields is not the only source of electrical interference that may affect an implanted pacemaker. Leakage currents from electrical equipment can be sufficiently strong to induce maloperation, even when the leakage currents are below levels specified in National Standards for new equipment.

For these reasons it seems appropriate that cardiologists use pacemakers which are insensitive to electrical interference and advise those already fitted with pacemakers to approach unfamiliar electrical equipment carefully, perhaps in the company of others. To this end the work has been widely published.

CONCLUSIONS

From these studies we note that:

- in those occupationally exposed to electric fields in the UK we found no effect on health;
- passage of body currents of 500 μA (equivalent to fields of 35 kV/m) revealed three statistically significant but equivocal associations between current flow and psychological measures. There was no association with stress or with any of a large number of other performance measures. The positive findings were of modest statistical significance and occurred at currents much higher than would be normally experienced. They have no implications for people living or working near high-voltage equipment.
- some designs of cardiac pacemaker may suffer from electrical interference when the wearer is near an electric plant, but pacemakers of insensitive design are available.

An epidemiological survey of environmental factors associated with cancer induction remains to be completed.

We are now considering whether and in what way further helpful information might be derived from additional work.

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HUMAN EXPOSURE TO 50-Hz ELECTRIC CURRENTS

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ABSTRACT

The biological effects associated with exposure to low-frequency electromagnetic fields have previously been investigated by applying an external field to test subjects Consequently, a major difficulty has been to separate those effects produced by the induced body currents from those produced by sensory, field-induced, phenomena (e g , microshocks) Our study avoided the sensory phenomena associated with external fields by applying electric currents directly to human volunteers via body-contact electrodes A 500-μA current was applied so that 40% entered the head and 30% entered the upper part of each arm, simulating exposure to a vertical electric field of about 36 kV/m Seventy-six male volunteers were studied, in a double-blind trial, in sessions lasting about 5 5 hr Each subject participated in both an exposure and a sham-exposure session, the exposure/sham-exposure order was counterbalanced across subjects A mood-adjective checklist (examining self-reports of stress and arousal) was administered immediately before and after each session, and a 1-hr sequence of four cognitive tests was repeated four times during each session This paper is restricted to discussion of the results from the mood-adjective checklist and a questionnaire examining reports of sensations at electrode sites

Research into the relationship between power-frequency electromagnetic fields and human health has adopted a multidisciplinary approach and now seeks to provide converging evidence from a variety of perspectives. In early investigations, the initial concern was with evaluating survey data from occupationally exposed individuals in an attempt to establish whether a hazard to health existed (Asanova and Rakov, 1972; Roberge, 1976; Knave et al., 1979; Broadbent et al., 1985). Recent approaches have included: (a) more accurate measurements of the electromagnetic environment under power lines and calculations of current distribution and dose (Barnes, McElroy, and Charkow, 1967; Deno and Zaffanella, 1975; Schneider et al., 1974), (b) attempts to extrapolate data from nonhuman species and in vitro studies to implications for human exposure (Marino et al., 1977; Lymangrover, Ketu, and Soto, 1983), and (c) theoretically oriented work directed toward understanding the response of cellular systems to internal fields and currents (Adey, 1981).

At the same time, occupational physicians have become interested in applying psychological and behavioral techniques to assess the effects of exposure to a range of potentially toxic substances (Johnson and Anger, 1983). Psychological techniques represent a physically noninvasive method for examining central nervous system functioning and are thought to be particularly useful when the status of any underlying biochemical reactions is unclear. Furthermore, these techniques directly assess the functional sensitivity of the human central nervous system under in vivo conditions, avoiding the difficulties of extrapolating from animal and in vitro studies.

Our experiment examined whether a relatively short-term exposure to a strong 50-Hz electric field influenced human psychological functioning. One of the main objectives was to isolate possible effects due to induced body currents from peripheral field-induced phenomena such as hair vibration and microshocks. To achieve this, currents were applied directly to the body via contact electrodes, and no high-voltage fields were actually present. Central nervous system functioning was examined by means of five psychological tests that measured performance of memory, attention, verbal skills and self-reports of mood.

DESIGN AND PROTOCOL

Seventy-six male volunteers, with no previous history of occupational exposure to high-voltage electric fields, were recruited from the electricity supply industry in the North-Western region of the UK. Each subject attended on four occasions. The first session served to acquaint subjects with the purpose of the study (familiarization) and ensured that they were healthy (initial medical examination). The second and third sessions, designated experimental, each lasted a full day. The fourth session was a final medical examination.

Subjects attended the two experimental sessions in exposed/sham-exposed pairs, with their respective roles assigned at random on the first day and reversed for the second day, in a double-blind design. Subjects exposed on the first day and sham-exposed on the second day were designated group A, and those meeting the two experimental conditions in the reverse order were designated group B. A between-subject factor, called current-group, was used to represent the two orders of presenting the exposure condition in this counterbalanced design.

Exposure System

Four standard EEG electrodes were fitted to the scalp; two were placed in anterior-posterior positions and two on the left-right axis above the ears. Three self-adhesive EEG electrodes (each having a steel disc 2.5 cm in diameter) were placed on the upper part of each arm, and return electrodes were placed under the instep of the foot. The electrode leads terminated at a junction box (worn on a waist belt), which was in turn connected to the current-supply equipment by a single cable (Figure 1). Schneider et al. (1974) have estimated approximately 14-μ A flows for each kV/m of electric field at 50 Hz. Accordingly, a 500-μA, 50-Hz current was used to simulate exposure to a 36-kV/m electric field. Currents of 50 μA were passed at the 10 upper electrode sites, with 40% of the total current entering through the head and neck, above the shoulders. This distribution of current is similar to that found by Deno (1977) for a man standing upright in a vertical electric field. During sham-exposure, subjects were electrically isolated from the current source.

Experimental Sessions

The schedule for each experimental day is shown in Figure 2. At 0920 hr, electrodes were fitted to both subjects, and a perception test was then given. This test measured the lowest current (in μA) which could be perceived at a standardized arm electrode site. Perception usually took the form of slight tingling, itching or prickling sensations. The 10 upper-body electrodes were adjusted to carry 50 μA each, and the current was switched off. The perception test and electrode adjustments were then repeated for the other subject.

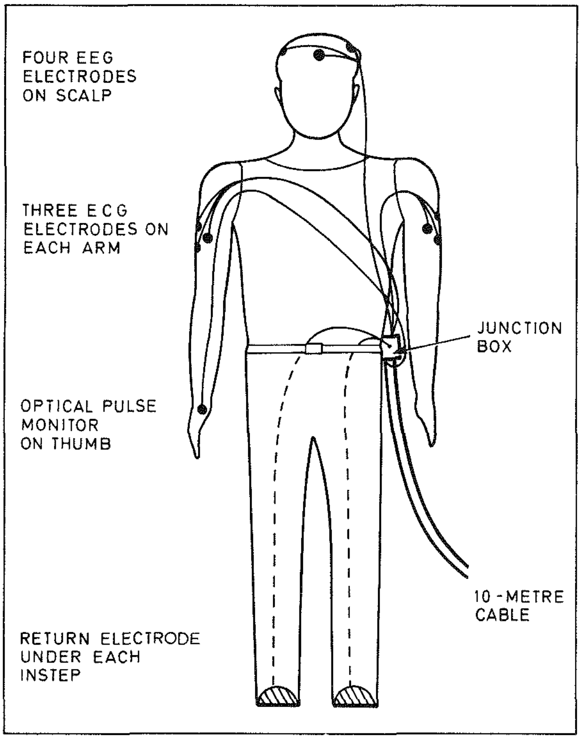

Figure 1. Distribution of Surface Electrodes Used to Apply 50-Hz Electric Currents to Human Subjects.

Both subjects were then given a perception questionnaire and completed a before-session mood-adjective checklist. Subjects retained the perception questionnaire throughout the session and used it to note the presence and duration of any sensations which occurred during that day.

Current was switched on at 1030 hr and flowed almost continuously until 1600 hr (approximately 5.5 hr). A 1-hr sequence of four psychological tests was repeated four times during the day, the first sequence starting a few minutes after the current had been switched on. This was followed by a short break, then the second sequence of tests. After lunch, the third sequence of tests was given, followed by a short break, then the final sequence of tests. Interruptions of current (disconnections) occurred only during the break between testing periods and, only then, when a subject needed to leave the testing laboratory.

The current was switched off at 1600 hr, and an after-session mood-adjective checklist was completed. All electrodes were disconnected, and the contact surfaces were cleaned. Subjects normally left the laboratory by 1630 hr. Both experimental sessions followed the same procedure.

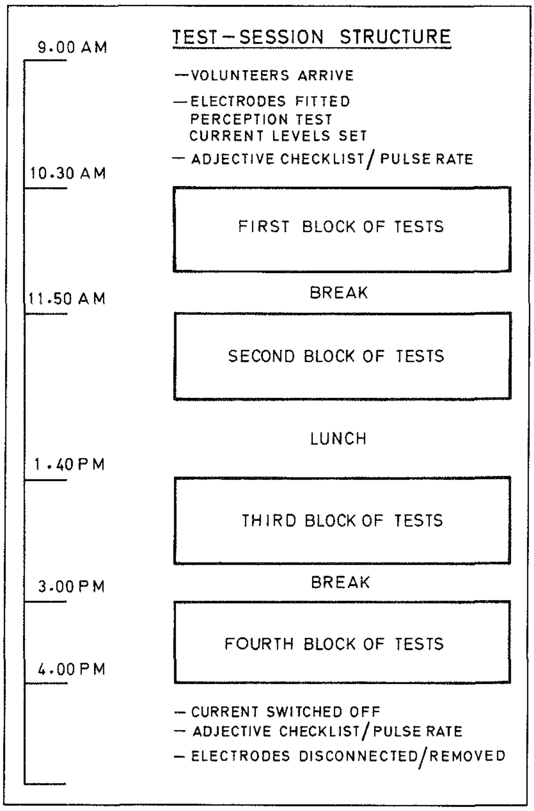

Figure 2. The Schedule for Experimental Sessions in which Human Subjects were Exposed or Sham-Exposed to 50-Hz Electric Current.

Psychological Tests

A total of five tests was administered during the course of each experimental day: a mood-adjective checklist and four tests of cognitive performance. The mood-adjective checklist, assessing self-reports of both stress and arousal (MacKay et al., 1978), was given in a pencil-and-paper version, but the four performance tests were administered and controlled by microcomputer.

Two of the performance tests probed verbal reasoning skills. The first examined linguistic/syntactic reasoning (Baddeley, 1968; Baddeley and Hitch, 1974). The second examined semantic reasoning or retrieval from semantic memory (Baddeley, 1981; Tulving, 1972).

The other two performance tests probed attentional skills. One was a cognitive vigilance task (Broadbent and Heron, 1962). The other assessed sustained concentration in a continuous, five-choice, reaction-time test (Broadbent, 1971; Poulton, 1970).

RESULTS

The results from the four performance tests administered will be reported elsewhere. This paper is limited to a discussion of the extent to which "perception" at electrode sites compromised the double-blind nature of the study, and the findings from the mood-adjective checklists administered before and after each session. Because of equipment malfunctions, the results for this part of the study were lost for one subject, leaving 75 for analysis. Table 1 shows the group-matching achieved from the double-blind allocation of conditions.

TABLE 1. Group-Matching Variables for Human Subjects Exposed or Sham-Exposed to 50-Hz Electric Fields (Group A, N = 38; Group B, N = 37)

Variable	Group A		Group B	
Age (years)	36.7		35.5	
Duration of exposure (minutes)	317.6		321.0	
Perception level (μA)	334.8		315.1	
Number of disconnections	1.7		1.9	
Duration of sensations (minutes)	5.1		12.0	
	Group A		Group B	
	Day 1 Exposure	Day 2 Sham-Exposure	Day 1 Sham-Exposure	Day 2 Exposure
Before-session stress	2.1	1.5	1.8	1.4
Before-session arousal	7.5	6.8	7.8	7.9
Before-session pulse (bpm)	63.3	62.9	62.7	63.4
Duration of sleep (hours)	7.0	7.1	6.9	7.1
Duration of extra sleep (hours)	-0.1	-0.1	-0.5	-0.3
Morning caffeine intake (cups)	0.8	0.8	0.7	0.7
Recent alcohol intake (ml)	20.0	28.0	16.0	11.0

Perception Questionnaire

Although electrode currents were always nominally well below the perception level determined before exposure, 63% of the subjects reported itching or prickling sensations (mainly at arm electrode sites) at some time during the two experimental days. Initially, a subject was classified according to whether he reported any sensations (the SOME perception group) or not (the NONE perception group). Table 2 shows that within the SOME group, 37% reported sensations on both days (the BOTH group), 48% only on the exposure day (the RIGHT group), and 15% only on the sham-exposure day (the WRONG group). Nonparametric tests (Siegel, 1956) showed that subjects were more likely to report sensations during exposure sessions (McNemar test, $Z = 2.56$, $P = 0.012$), and these sensations were reported to last longer on the exposure day

(Wilcoxon $Z = 4.07$, $P < 0.001$). Averaged over all subjects, the reported duration of sensations was 8.4 min on an exposure day and 2.6 min on a sham-exposure day. The mean duration of exposure was 319 min, with an average of 1.8 disconnections being made during each 330-min experimental session. There was no significant correlation between the duration of sensations on the exposure day and the perception levels determined before exposure ($R = 0.04$, $P > 0.25$).

TABLE 2. Mean Duration of Sensations (in Minutes) During Exposure and Sham-Exposure of Humans to 50-Hz Electric Current

	Current Group A[a]		Current Group B[a]	
Perception Group[a]	Day 1 Exposure	Day 2 Sham-Exposure	Day 1 Sham-Exposure	Day 2 Exposure
NONE[b] (28)	0.0	0.0 (17)	0.0	0.0 (11)
SOME[c] (48)	9.6	3.8 (21)	4.4	16.2 (27)
BOTH[d] (18)	12.4	10.0 (8)	7.5	28.9 (10)
RIGHT[e] (23)	7.8	0.0 (13)	0.0	14.9 (10)
WRONG[f] (7)	--[g]	--[g] (0)	6.3	0.0 (7)

[a] The number of subjects is shown in parentheses.
[b] NONE = no perception reported
[c] SOME = perception reported at some time
[d] BOTH = perception reported during both experimental days
[e] RIGHT = perception reported on exposure days only
[f] WRONG = perception reported on sham-exposure day only
[g] Not applicable

Because the reported sensations lasted longer when the current was on, the double-blind nature of the experiment was clearly compromised to some extent. However, it is perhaps not justifiable to omit those subjects who reported sensations because of the short average duration of these sensations in relation to the total exposure time, coupled with the presence of sensations during sham-exposure periods. Of more importance and interest, however, is that a study of those reporting sensations might reveal whether or not exposure effects are dependent on sensations. The analysis strategy was therefore to consider "perception" as a second grouping factor crossed with the current-group allocation (see Table 2).

The Mood-Adjective Checklist

The mood-adjective checklist provides a measure of self-reported feelings of both stress and arousal. The stress score (max = 18) is thought to represent an internal response to the perceived favorability of the external and internal environment. The arousal score (max = 12) corresponds to a sleep-wakefulness dimension (MacKay et al., 1978). The stress and arousal adjectives were in a random order on each checklist, but the scores for each measure were analyzed separately. Test scores were examined by an analysis of variance with covariance, using the variables shown in Table 1 as covariates. Before- and after-session scores were classified as two levels of a within-subject time-of-day factor.

No exposure effects were apparent in the analysis of stress scores; on both days, subjects felt equally stressed before and after the session (mean score = 1.86). Two covariates correlated with between-subject stress scores: before-session arousal and the duration of sensations on the exposure day. Before-session arousal was negatively correlated [F(1,69) = 5.59, P = 0.02], indicating that the more aroused subjects also felt less stressed. Of more interest, however, was the positive correlation with the duration of sensations [F(1,69) = 12.4, $P < 0.001$]. Omitting the duration-of-sensations covariate yields an identical pattern of results, thus there was no evidence that the SOME group rated themselves as more stressed than the NONE group. This indicates that when subjects reported sensations, those feeling more stressed reported that the sensations lasted longer.

In contrast, analysis of arousal scores showed a day x current-group x time-of-day interaction [F(1,71) = 6.41, P = 0.013]; that is, the effect of exposure was independent of perception. Later exploration of this interaction, using a Newman-Keuls analysis (Winer, 1973), revealed that the before-session arousal scores, on each day, were equivalent for group A and group B. Furthermore, subjects always felt less aroused at the end of the session ($P < 0.01$). However, while after-session scores were lower following exposure than following sham-exposure (Figure 3), the between-subject differences were not significant, and the interaction was localized to group A. After-session arousal was higher on the second day for group A ($P < 0.01$) and equivalent on each day for group B.

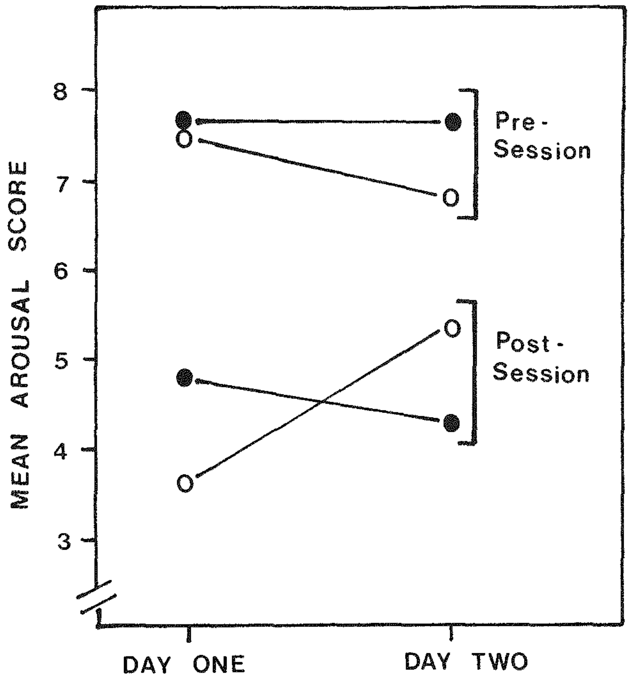

Figure 3. The Effect of Exposure to 50-Hz Currents on Arousal Scores (0 - - -0, Group A; ● - - - ●, Group B).

In addition to this effect of exposure, two covariates correlated with within-subject arousal scores: before-session pulse rates and recent alcohol consumption. Pulse rates were positively correlated [F(l,69) = 9.17, P = 0.004], while the amount of alcohol consumed the preceding night was negatively correlated [F(l,69) = 13.7, P = 0.001]. Thus, a subject felt more aroused on the day he had a higher pulse rate and had drunk less alcohol the night before.

DISCUSSION AND CONCLUSIONS

In this experiment of human exposure to 50-Hz electric currents, self-reported feelings of stress and of arousal were differentially sensitive to the exposure conditions.

Stress scores remained low and constant over both experimental sessions, and no effects of exposure were apparent. However, while current did not influence feelings of stress, stress was strongly correlated with the duration of reported sensations (although not with their incidence). This finding, coupled with the absence of an exposure effect on stress, lends support to the argument that the physiological and biochemical stress responses reported in earlier studies of electric-field exposure may relate to perceived effects, such as hair vibration or microshocks, rather than to effects of the associated induced body currents.

Unlike stress scores, arousal scores were lower at the end of each day, and a current-related interaction was observed. The magnitude of the exposure effect was independent of perception and, therefore, not compromised by the pattern of perception found. Although the postexposure pattern on both days was consistent with the hypothesis that current made subjects feel less aroused, the later significance test localized the source of the current-related interaction to group A, that is, those exposed on the first day and sham-exposed on the second day. Thus, in addition to the simple hypothesis that current reduces arousal, four separate explanations may be applicable to the pattern of significance observed in the study.

The first possible explanation assumes that there is an intrinsic difference between the two randomly allocated groups of subjects (group A and group B). Specifically, if group A were better able to sustain arousal over the day than group B (compare the relatively small decline on the sham-exposure day), then current on the first day makes them feel less aroused. To explain why current does not influence arousal in group B (there was an equivalent fall in arousal on both days), it must be assumed that (a) after-session arousal scores must be above some minimum to observe an exposure effect and (b) the after-session scores had fallen close to this level even on the sham-exposure day. That is, the exposure effect in group B was obscured by the low levels of arousal reported at the end of the day (i.e., "floor" effect).

The second explanation would assume that all subjects are better able to sustain arousal on the second day, perhaps because the whole testing procedure was then familiar and generally experienced as less tiring. This hypothesis receives some support from the significant day x time-of-day interaction found in the analysis of arousal scores [F(1,71) = 4.84, P = 0.031]. Thus, subjects in group A were feeling significantly more aroused at the end of the second day because they benefited (a) from the increased familiarity with the testing procedures on the second day and (b) from being in the sham-exposure condition. Similarly, for subjects in group B, it must be assumed that the benefit derived from the increased familiarity with the testing procedure on the second day was offset by the counteracting tendency for arousal to fall more on an exposure day. The failure to find a significant difference between groups A and B on either day alone could again be attributed to a "floor" effect.

The other two suggested explanations are based on the notion of state-dependent transfer: the exposed and sham-exposed conditions are assumed to represent two distinct "pharmacological" or "psychological" states. Because group A and group B differ only in the direction of the transfer (i.e., the order of testing the two conditions), the effect can only be explained in terms of the direction of the transfer. First, using group B as the base line, it could be postulated that subjects trained in the presence of current (group A) were more able to sustain arousal when subsequently retested without current. Second, using group A as the base line, it could be postulated that training without current (group B) predisposes subjects to feel less aroused after being retested with current.

In summary, the simplest explanation of the findings is that subjects felt less aroused after 319 min of fairly continuous exposure to 50-Hz electric currents. However, this explanation is qualified by the apparent lack of an effect in those sham-exposed on the first day (group B). The experimental design does not, however, allow a choice to be made between the alternative hypotheses outlined above. If either of the first two hypotheses is correct, then the implication is that arousal would be lower following exposure to electric current, but that it may be subject to a "floor effect." The implications of the two state-dependent transfer hypotheses are more complex because they assume that the order of exposure is the important variable.

In addition to sensitivity to the exposure conditions, arousal scores were significantly correlated with presession pulse rates and recent alcohol consumption. In general, a subject felt more aroused when his pulse was higher and when he had drunk less alcohol the previous night. Although these observations were not completely unexpected, they are useful because they provide internal evidence of the sensitivity of the checklist in the circumstances of this study.

Clearly, further work is required both to provide confirmation for an effect of 50-Hz currents on feelings of arousal (but not on feelings of stress) and to explore the alternative hypotheses suggested above. If, for example, the influence of current is subject to a "floor effect," then less-demanding testing procedures should lead to generally higher after-session arousal scores, thus avoiding an after-session "floor effect." Alternatively, more regular measurements of arousal during the day (e.g., before each test sequence) would help to clarify whether or not a "floor effect" was present. For example, the exposed group might reach the "floor" level earlier during the day than the sham-exposed group. An examination of the two state-dependent explanations requires a more complex design because, in our design, both group A and group B change state from the first day to the second day. The inclusion of two groups of subjects who are tested in the same state on both days (i.e., one group that is sham-exposed on both days and another group exposed on both days) would help clarify whether or not state-dependent transfer effects were occurring (see Eich, 1980 for further discussion of state-dependent transfer designs).

Finally, before concluding that occupational exposure to electric fields leads to reports of lower arousal, it should be recalled that a 5.5-hr exposure to a nominal field of 36 kV/m is not typical of normal working conditions in the U.K. (Broadbent et al., 1985). Whether or not effects are produced by fields which are encountered in practice remains unknown.

ACKNOWLEDGMENTS

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60-Hz FIELD EFFECTS ON HUMAN NEURO-REGULATORY, IMMUNOLOGIC, HEMATOLOGIC AND TARGET ORGAN ACTIVITY

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ABSTRACT

This study was part of a comprehensive investigation of the effects on humans of exposure to 60-Hz electric and magnetic fields Taking into account previous research, the battery of biochemical tests chosen was theoretically based, recognizing the complex interaction of brain regulatory mechanisms, endocrine, and lymphocytic and immune suppression functions, including T-cell destruction and enhancement Numerous hematologic, chemistry, and immunologic variables were examined Prior to exposure, male volunteers (N = 12) provided extensive baseline data Subjects then participated in four experimental sessions, spaced 1 wk apart Two sessions involved exposure to uniform, 60-Hz fields (6 hr at 9 kV/m, 16 A/m), the remaining two sessions were identical to the previous ones except that no field was presented Order of field presentation was counter-balanced under double-blind conditions, and each subject served as his own control During each session, data were collected on biochemical variables, as well as on performance, physiology and subjective state Total urine output was collected from 1800 hr the night before through the morning after each session Blood was drawn immediately before and after the 6-hr exposure periods Subjects ate a restricted diet for 48 hr prior to each session and ate standard meals during each session Additional data were collected on activity and dietary intake for the period surrounding each session LDH levels were significantly higher in the pre-exposure compared to postexposure periods (P = 0 004), and this difference was greater on the first day under real-field exposure conditions than on all other days (P = 0 015) Differential leukocyte analysis showed a significant increase in lymphocytes only on day 2 of the real-field exposure Pre-exposure levels of T-helper cells (%) were higher than postexposure (P = 0 033) levels, and this phenomenon was significant on exposure days but not on sham-exposure days (P = 0 016) *During exposure conditions there was a trend for T-helper cell* levels to be higher (P = 0 099) overall than under sham-exposure conditions

INTRODUCTION

The effects of 60-Hz electric and magnetic fields on human health and function have not been clearly established. Difficulties in experimentation and interpretation of results are due to a variety of factors: the complex interaction of such fields with physical and biological parameters (Figure 1), conflicting findings; lack of replication, variation in experimental conditions; possible secondary effects (e.g., ozone, noise); and species differences. Recent research, however, suggests that the brain and certain other neurophysiological and neuroregulatory responses in the mammalian nervous and immunologic systems may be more sensitive to exposure to electric and magnetic fields than other systems (Adey, 1977, 1978, Gibson and Moroney, 1974; Dumansky, Popovich, and Prokhvatilo, 1976; Taylor and Cheung, 1977; Wiktor-Jedrzejczak et al., 1977; Cerretelli et al., 1979; Jaffe et al., 1980; Fam, 1980, Tuchackova and Cenkova, 1982; and Winters, 1984).

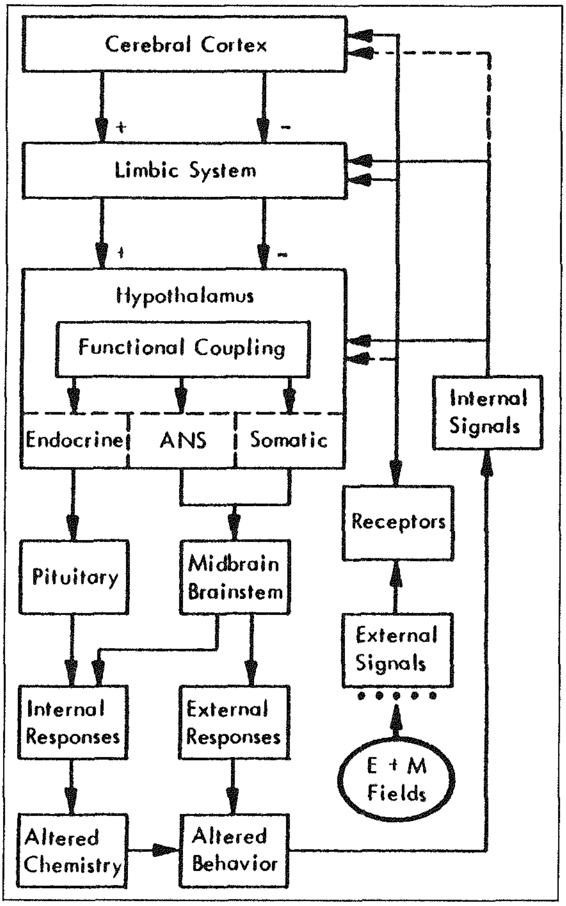

Figure 1. Interactive Biological Processes of Interest to Studies of Human Exposure to Electric and Magnetic Fields.

Ragan et al. (1983) have summarized blood and serum chemistry laboratory studies on animals exposed to electric-field strengths of 10 to 100 kV/m. Changes (increases and decreases) have been reported in serum proteins, lymphocytes, and constituents such as glucose, calcium, urea nitrogen and lactic dehydrogenase. Species differences and exposure to different field strengths may play a role in these discrepant findings.

Contradictory findings have also been reported in studies evaluating various hormonal variables. Free et al. (1981) reported that exposure reduced testosterone but did not affect corticosterone levels, and other researchers have reported variable changes in corticosterone (e.g., reductions, Marino et al., 1977 and Phillips, Anderson, and Kaune, 1979; increases, Oumansky, Popovich, and Prokhovatilo, 1976 and Tuchackova and Cenkova, 1982).

The study to be described was designed to evaluate the effects of exposure to 60-Hz electric and magnetic fields on a comprehensive battery of biochemical variables, selected to parallel and complement previous research findings (Table 1), as well as data obtained simultaneously on individual performance, physiology, and subjective state. The study was conducted under known exposure conditions, and, for the first time, employed double-blind experimental control procedures on humans.

TABLE 1 Biochemical Variables and Methods of Analysis for Evaluating Effects of Exposure to Electric and Magnetic Fields

Variable	Method	Instrument	*Concentration* Units
Blood Chemistries			
Albumin	Spectrophotometry	Analyzer 500	g/dl
Blood glucose	Spectrophotometry	Analyzer 500	mg/dl
Calcium	Spectrophotometry	Analyzer 500	mg/dl
Sodium	Ion electrode	Nova I	mM/L
Potassium	Ion electrode	Nova I	mM/L
Uric Acid	Spectrophotometry	Analyzer 500	mg/dl
Lactic acid dehydrogenase	Spectrophotometry	Analyzer 500	
Specific Proteins			
IgG	Spectrophotometry	Analyzer 500	mg/dl
IgA	Spectrophotometry	Analyzer 500	mg/dl
IgM	Spectrophotometry	Analyzer 500	mg/dl
Complement C_3	Spectrophotometry	Analyzer 500	mg/dl
Complement C_4	Spectrophotometry	Analyzer 500	mg/dl
Alpha-1-antitrypsin	Spectrophotometry	Analyzer 500	mg/dl
Alpha-2-macroglobulin	Spectrophotometry	Analyzer 500	mg/dl
Hematologic Analyses			
Packed cell volume (PCV or hematocrit)	Counting/sizing	Coulter S Plus IV	Percent
Hemoglobin (HGB)	Counting/sizing	Coulter S Plus IV	g/dl
Erythrocyte count	Counting/sizing	Coulter S Plus IV	μm^3
Leukocyte count	Counting/sizing	Coulter S Plus IV	μm^3
Mean corpuscular volume (MCV)	Counting/sizing	Coulter S Plus IV	μm^3
Mean corpuscular hemoglobin (MCH)	Counting/sizing	Coulter S Plus IV	pg
Mean corpuscular hemoglobin concentration (MCHC)	Counting/sizing	Coulter S Plus IV	Percent
Platelet count			
Immunologic Analysis			
Lymphocyte population	Flow cytometry	Ortho 50H Cytofluorograph	Percent
T-Cells	Flow cytometry	Ortho 50H Cytofluorograph	Percent
B-Cells	Flow cytometry	Ortho 50H Cytofluorograph	Percent

TABLE 1. Continued

Variable	Method	Instrument	Concentration Units
Natural killer cells	Flow cytometry	Ortho 50H Cytofluorograph	Percent
Helper cells	Flow cytometry	Ortho 50H Cytofluorograph	Percent
Supressor cells	Flow cytometry	Ortho 50H Cytofluorograph	Percent

This paper presents the results for three important classes of biological parameters: blood chemistry, hematology and immunological factors. Analysis of data on hormones, neurotransmitters and metabolites, and catecholamines has not yet been completed, and results for those variables will be reported separately.

METHODS

The study approach incorporated well-known, valid and reliable physiological, biochemical and performance measures. This multidisciplinary approach was necessary to better understand the complex interactive biophysical problem of effects of electric and magnetic fields on human function. This section presents details of the data-collection procedures, and the laboratory methods and determinations developed and used during the study.

Experimental Design

Twelve subjects participated in four experimental sessions, spaced 1 wk apart: two sessions involved 6 hr of exposure to a 60-Hz, 9-kV/m, 16-A/m electric and magnetic field, and two identical sessions involved exposure to a sham field. Order of field presentation was counterbalanced, and the experiment was conducted under double-blind conditions.

Within each session, a multi-task performance battery was presented five times: immediately prior to activation of the field, three times during exposure to either real or sham fields, and immediately after exposure. Physiological recordings were obtained during the first and last performance batteries (See Graham et al., 1984, for specific procedures.) Blood samples for each session were collected just before and immediately after exposure to the real or sham field. All urine voided from 1800 hr the night before each session through the waking urination the morning after the session was collected.

Exposure System and Dosimetry

Description of the human exposure facility, the double-blind control system, and the dosimetry studies performed are reported in Cohen, Graham, and Cook (this volume). Procedures for presentation of the fields under double-blind conditions and other subject experimental methods and procedures are described in Graham et al. (this volume).

Subjects

Subjects were 12 male adults between the ages of 21 and 35. Selection criteria ensured that subjects were in good health, drug-free, had the verbal and arithmetic skills necessary to perform the experimental tasks, and were able to understand the study and the risks and benefits involved. All subjects gave written informed consent prior to their participation.

Procedures

Baseline Sample Collection. Baseline blood samples for each subject were obtained on two separate days prior to field exposure, at the same times of day as those scheduled during the experimental sessions. Blood (22 ml) was drawn by venipuncture from the nondominant arm in the morning and from the dominant arm in the late afternoon. Baseline urine samples were also collected prior to field exposure at three times of day: (a) on first awakening, (b) between 1200 and 1230 hr, and (c) between 1600 and 1700 hr. Containers with the necessary acidification agent were provided for the purpose of collecting samples. Subjects were asked to keep the at-home samples refrigerated until returned to the laboratory. Baseline information on diet, sleep, exercise, etc., was also collected.

Experimental Sample Collection. Biochemical parameters can be affected by dietary habits, drug intake, exercise patterns, sleep habits, and stressful events occurring outside the experiment. If unusual variation occurs in these extra-experimental influences just prior to field exposure, they can introduce ambiguity into the analysis and confound interpretation of the findings. For this reason, during the experimental sessions subjects provided information on these variables for the 24-hr period prior to each experimental session and, after each session, until the morning of the next day. Subjects were also on a restricted diet for 48 hr prior to each session and ate a standard breakfast and lunch the day of the session. The amount of sodium and caffeine ingested was also controlled during the experimental period.

All experimental sessions followed the same schedule of activities. At the start of each session, subjects had their vital signs monitored, changed into the standard clothing to be worn during the session, had physiological recording sensors attached, and performed the 1-hr task battery. The recording sensors were then removed, a urine sample was obtained, and the first blood sample was taken. The field was activated immediately after sample collection, and a second performance battery was presented. At 1200 hr, the subject left the exposure chamber to provide another urine sample and to eat lunch. Additional performance batteries were presented after 3 and 5 hr of exposure. The second blood sample and a urine sample were collected after 6 hr of exposure. All subjects performed the test battery just prior to and following sample collection in both the morning and the afternoon.

Total urine was collected from each subject from 1800 hr the night before each experimental session through the waking urination of the morning after the session. Urine samples were pooled except for the two waking collections and the pre- and postexposure collection. On the morning following the session, the subject returned the samples collected outside the laboratory, had vital signs monitored, and provided information concerning mood, diet and activity over the previous 24-hr period.

METHODS OF ANALYSIS

Standard clinical laboratory procedures were used wherever possible for analysis of body fluids. If an analysis procedure was unavailable or not sensitive enough for the study, the procedure was modified, or a new procedure was developed. Summaries of the assays performed, methods, sample handling and storage requirements used are presented in Tables 1 and 2.

TABLE 2. Sample Handling and Storage Requirements for Evaluating Effects of Exposure to Electric and Magnetic Fields

Aliquot Number	Analytes	Sample Analysis Period	Sample Type	Storage Conditions	Volume (ml)
	Hematology				
	Lymphocyte population	24 hr	EDTA whole blood	50-70°F	7
	Complete blood count with platelets and indices	4 hr	EDTA whole blood	Room temperature	0.3
	Chemistry				
1	Lactic acid dehydrogenase (LDH)	48-72 hr	Serum	Room temperature	0.2
2	Specific proteins: IgG, IgA, IgM Complement C_3, C_4 Transferrin Alpha-1-antitrypsin Alpha-2-macroglobulin	6 mo	Serum	-40°C	1
3	Albumin Uric acid Calcium Sodium Potassium	6 mo	Serum	-40°C	1
4	Aldosterone Cortisol	6 mo	Serum	-40°C	0.5
5	FSH LH	6 mo	Serum	-40°C	0.5
6	Testosterone Growth hormone	6 mo	Serum	-40°C	0.5
7	Thyroxin (T_4) Thyroxin binding globin (TBG)	6 mo	Serum	-40°C	1.0
	Immunologic Analysis				
	Lymphocyte population	12 hr	EDTA whole blood	50-70°F	50
	T-Cells	12 hr	EDTA whole blood	50-70°F	50
	B-Cells	12 hr	EDTA whole blood	50-70°F	50
	Natural killer cells	12 hr	EDTA whole blood	50-70°F	50

TABLE 2. Continued

Aliquot Number	Analytes	Sample Analysis Deadline	Sample Type	Storage Conditions	Volume (ml)
	Helper cells	12 hr	EDTA whole blood	50-70°F	50
	Suppressor cells	12 hr	EDTA whole blood	50-70°F	50

Blood Chemistry

The specific chemistries for albumin, blood glucose, calcium, uric acid, lactic acid dehydrogenase (LDH), specific proteins, sodium and potassium were analyzed. The Centrifichem® Analyzer System 500 (Baker Instruments, Allentown, PA), a batch analyzer, requires samples of 5 to 50 μl per analysis, which allows the system to perform multiple analyses of blood variables required for the study. The automated centrifugal rotor provides for spectrophotometric readout of blanks, standards, controls and samples, processes the data, and prints out results. This analyzer system was used in all evaluations except sodium and potassium, using detailed methods described in Baker Centrifichem Reagent Reports (1980 a, b; 1981).

To assay specific proteins (Table 1) on the Analyzer 500, microsamples of prediluted protein calibrators and control serum were mixed with antiserum to the specific protein of interest in the presence of a buffer-containing polymer. The absorbance of the turbidity generated as a result of the antigen-antibody complexes formed during the reaction was measured, then converted to concentration units by mathematical comparison to the absorbances of the calibrators. The following specific proteins, which have varying immune functions, were evaluated: IgG, IgA, IgM, Complement C3, Complement C4, alpha-1-antitrypsin and alpha-2-macroglobulin.

Sodium and potassium were analyzed using a Nova analyzer, (Nova Biomedical, Waltham, MA; Nova, 1978). This system utilizes ion-selective electrodes and 0.5 ml of undiluted serum to provide simultaneous measurements of both sodium and potassium. The system incorporates internal calibration every 2 hr as well as a 1-point calibration against buffer for each specimen analysis. Electrode stability is verified with low-, normal-, and high-range external standards before every run.

Hematologic Measurements

The Coulter S-plus IV (Coulter Electronics, Hialeah, FL) hematology analyzer was used for hematologic measurements. Details of methods for each parameter of interest can be found in Coulter (1982). The total volume used for each assay was 0.1 ml, which yielded a 12-parameter profile of each specimen. The variables measured were: packed cell volume (PCV or hematocrit), hemoglobin (HGB), erythrocyte count, leukocyte count, mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH), mean corpuscular hemoglobin concentration (MCHC), and platelet count. Particles in the red-cell bath with a volume between 2 and 20 μm^3 were counted as platelets. To quantify differential leukocyte (white blood cell) count, smears of whole blood were treated with Wright's stain, using a Hematek (AIMS, Elkhart, IN) automatic slide stainer.

One-hundred white blood cells (WBC) were counted and identified using Leitz (Leitz, Rockleigh, NJ) microscope AFM 160-51 (Davidson and Henry, 1974). The white-cell population was enumerated as to lymphocytes, monocytes, granulocytes, eosinophils, and basophils. Transferrin, a specific protein related primarily to iron transport and other hematologic factors, was quantified using the protein method previously described.

Immunologic Measurements

The lymphocyte population was identified as total T-cells, B-cells, and natural killer, helper and suppressor cells, using monoclonal antibodies. Monoclonal staining of peripheral white cells was used, and cells were analyzed using a fluorescent-labeled antibody flow-cytometry method. An Ortho 50 H Cytofluorograph (Ortho, Westwood, MA) with 2150 data acquisition system was used for analysis. (See Table 1).

A lymphocyte blastogenesis assay was used to measure cell-mediated immunity by stimulating lymphocytes with T- and B-cell-specific mitogens: concanavalin A (Con A) and phytohemagglutinin (PHA), plant lectins that stimulate T-cell populations; and pokeweed mitogen (PWM), a plant lectin that is primarily B-cell specific.

RESULTS

Baseline Data

Baseline data were taken in the morning and afternoon on two different days, prior to the start of the experimental sessions. Overall results indicate that baseline data are within the "normal" ranges for the parameters of interest. No significant differences were found between the two baseline days. As expected, however, baseline values differed somewhat in the morning versus afternoon assessments.

Blood Chemistry

There were no significant differences between field-exposed and sham-exposed conditions for calcium, glucose, uric acid, albumin, potassium, or sodium.

Analysis of variance of data from the experimental period revealed two significant effects for lactic acid dehydrogenase (LDH). Levels were significantly higher in the morning than in the afternoon (F - 13.26, df 1, 11, P = 0.004) and, as shown in Table 3 and Figure 2, there was a significant interaction between field, day, and period (F = 8.38, df 1, 11, P = 0.015). Two other types of analysis were performed to gain a better understanding of the interaction. First, separate analyses for Day 1 and Day 2 were performed. On Day 1, LDH levels were higher in the morning than in the afternoon (F = 12.28, df 1, 11, P = 0.005), and this effect was greater under real-field than under sham-field conditions (F - 15.28, df 1, 11, P = 0.002). On Day 2, LDH was again higher in the morning (F = 7.50, df 1, 11, P = 0.02), but no difference in this effect was found as a function of field conditions.

The second set of analyses examined the sham- and real-field data separately. During exposure to the sham fields, LDH values were somewhat higher in the pre- versus postexposure periods (F = 3.77, df 1, 11, P = 0.078). When data from the real-field condition were examined, LDH levels were higher in the morning, prior to field exposure, compared with the postexposure levels (F = 33.56, df 1, 11, P = 0.0001). This effect was greater for the first day of exposure than for the second day (F = 7.18, df 1, 11, P = 0.02).

TABLE 3. Field x Day x Period Interaction Effects on Lactic Acid Dehydrogenase (LDH) and Lymphocytes from Human Subjects Exposed to Electric Fields

Variable	F	MSe	df	P =
LDH	8.38	18.87	1,11	0.015
Lymphocytes	5.24	18.71	1,11	0.043

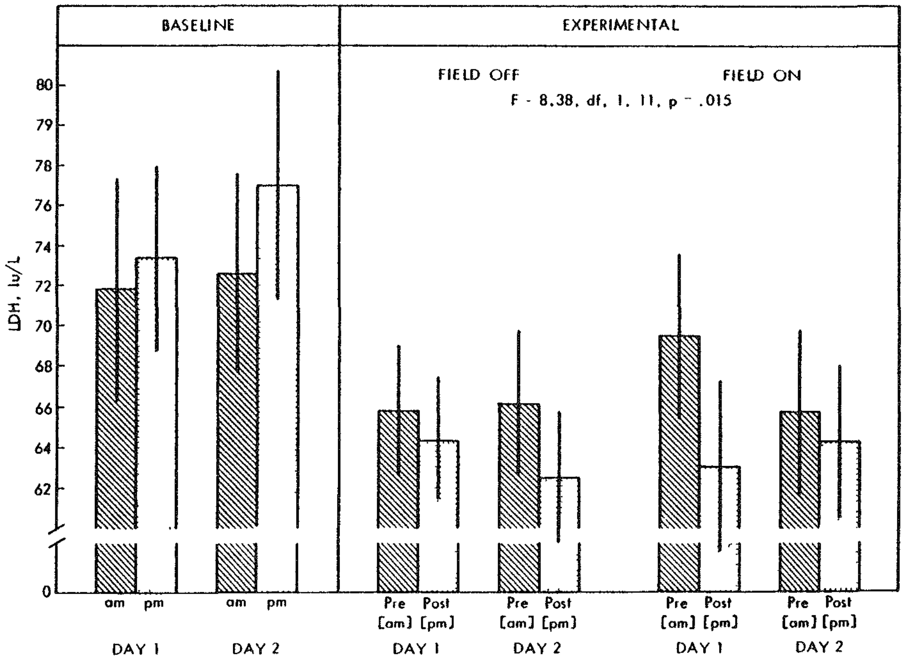

Figure 2. Lactic Acid Dehydrogenase Concentrations in Humans as a Function of 60-Hz Real Versus Sham Exposure: Field x Day x Period Effects.

Hematology

No differences associated with field exposure were found for WBC, red blood count (RBC), HGB, PCV, MCV, MCH, MCHC, or platelets. The differential leukocyte count revealed that changes in percent lymphocytes was the only significant hematological effect. During experimental sessions, there was a significant interaction (F = 5.24, df 1, 11, P = 0.043) between field condition, day, and time of day (shown in Table 3 and Figure 3). When Day 1 and Day 2 were analyzed separately, no significant effects were found (within either day). Thus, the significant interaction effect can be attributed entirely to the different patterns found on the first and second days of exposure. To further elucidate this effect, analyses of real- and sham-field conditions were performed separately. The data indicated no significant differences within real or sham conditions. Using paired *t*-tests, additional analysis revealed a significant difference ($t = 2.36$, df 11, $P = 0.038$) between the pre-exposure and postexposure lymphocyte values on Day 2 of exposure to the real field. This one difference appears to account for the complex interaction effect observed.

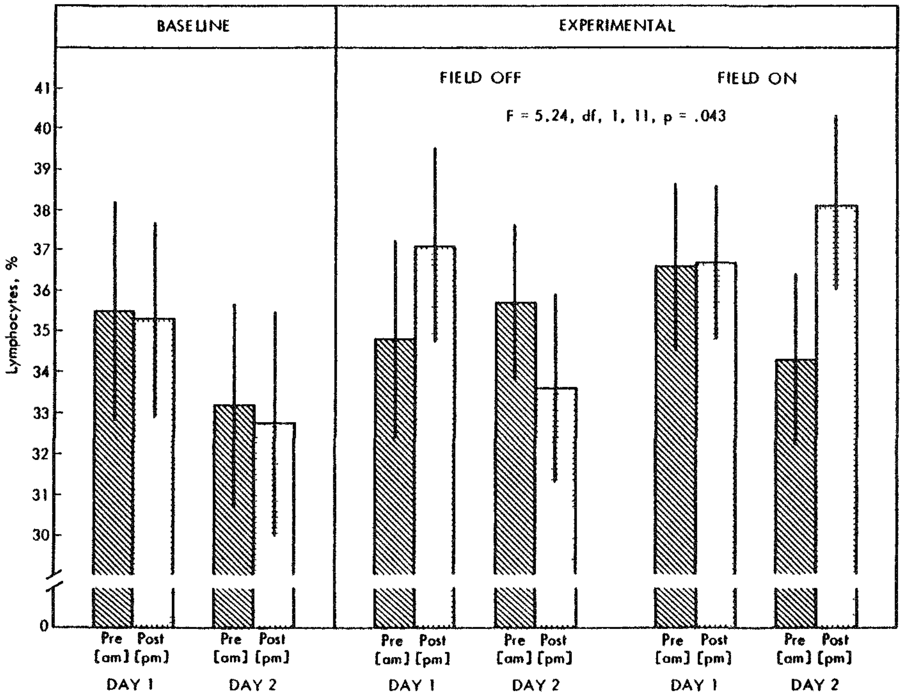

Figure 3. Lymphocyte Values in Humans as a Function of 60-Hz Real Versus Sham Exposure: Field x Day x Period Effects.

Immunology

Of the immunological variables other than lymphocytes, only T-helper cells showed any changes in levels which might have been attributed to field conditions (Table 4). First, there was a trend for T-helper cells to be higher under real- than under sham-exposure conditions ($F = 3.24$, df 1, 11, $P = 0.099$). T-helper cell levels were also higher in the morning than in the afternoon ($F = 5.95$, df 1, 11, $P = 0.033$), and this phenomenon was greater on field-exposed days than on sham-exposed days ($F = 8.00$, df 1, 11, $P = 0.016$). A trend was observed for an interaction between field conditions, day of exposure and time of day ($F = 3.83$, df 1, 11, $P = 0.076$) and is shown in the right-hand panel of Figure 4.

TABLE 4. Changes in Immunologic T-Helper Cells from Human Subjects Exposed to Electric Fields: Period and Field x Day x Period Interactions

Factor	F	MSe	df	P =
Field	3.24	19.54	1,11	0.999
Period	5.95	4.88	1,11	0.033
Field x Period	8.00	2.04	1,11	0.016
Field x Day x Period	3.83	5.17	1,11	0.076

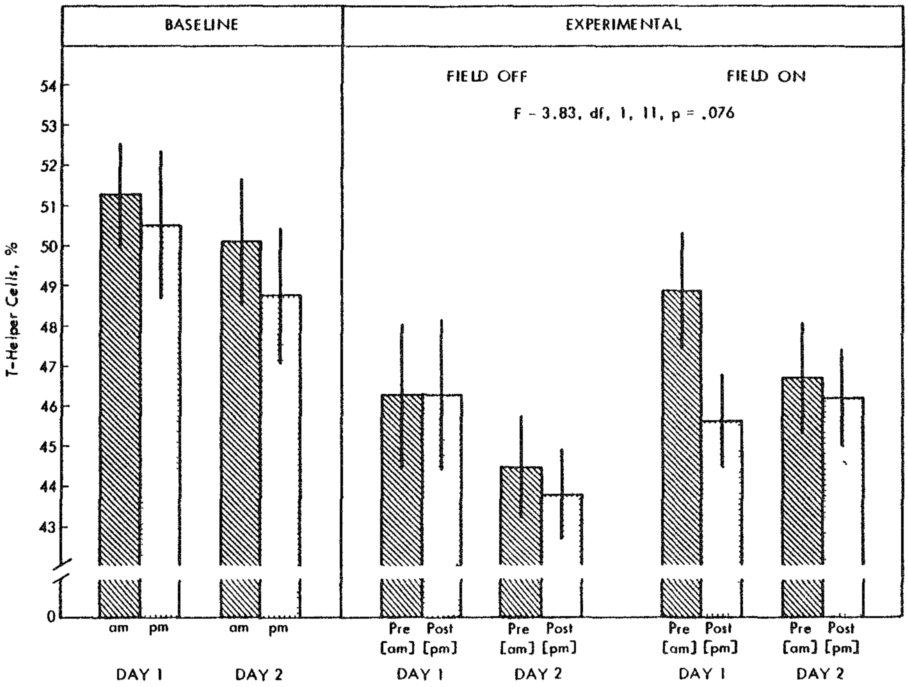

Figure 4. T-Helper-Cell Values in Humans as a Function of 60-Hz Versus Sham Exposure: Field x Period and Field x Day x Period Effects.

Because of the importance of T-helper cells in the body's immunological response, the overall effects described above were examined in detail. First, the three-way interaction was examined for each day separately. On Day 1, T-helper cells were more numerous in the morning (F = 5.53, df 1, 11, P = 0.038), and this effect was attributable entirely to the real-field condition. On Day 2, no significant differences, were found between pre- and postexposure measures, although there was a trend for higher concentrations of T-helper cells under real-field conditions (F - 3.76, df 1, 11, P = 0.078). Under real-field exposure, T-helper cell concentration was significantly higher in pre- versus postexposure periods (P = 0.01); no such difference was found during sham-field exposure. Thus, the three-way interaction appears to arise from the higher pre-exposure levels under Day 1 of real-field conditions.

DISCUSSION

Because of the complexity of this study, caution is advised in interpreting results. Experimental design and other factors to be considered in the interpretation of these results include: 1) exposure to the real field was for two 6-hr periods, each interrupted by a 15- to 30-min nonexposure food break; 2) the order of presentation of field exposure versus sham exposure was counterbalanced, so that although each person was exposed to the real field twice, the time between exposures varied from a minimum of 1 wk to a maximum of 3 wk; 3) because of within-subject design, the sham exposure is not a pure no-exposure condition; and 4) serum samples were only taken immediately prior to field exposure and immediately following exposure. Additional factors which should be taken into consideration include: circadian rhythms; dynamic-versus static-activity effects on biochemical changes; "normal" biochemical ranges; and adaptation or unknown effects related to human physiological responses to 60-Hz fields.

Previous studies on 60-Hz electric and/or magnetic field effects have shown alterations in blood and serum constituents. The greater decrease in LDH concentrations under real-field postexposure conditions on Day 1 are contradictory to the findings of Dumansky, Popovich and Prokhvatilo (1976) and Udintsev and Morog (1976), who reported increases in cardiac and skeletal LDH activity after exposure to 50-Hz fields of 0.1 to 5 kV/m electrical and 200 gauss magnetic flux density. However, these were unreplicated animal studies at different exposure levels and duration, and did not include sham-exposed control groups.

Our findings are well within the normal range of LDH values for our subjects and for the general population (49-110 IU/L). Of interest, however, is the degree of change from pre- to postexposure on Day 1 of the real-field condition. This difference could be attributed simply to the higher pre-exposure levels on that day; however, tissue LDH consists of five isoenzymes, in varying proportions, with the LDH activity in each characterized by a certain isoenzyme composition. Changes in these specific isoenzymes are widely distributed in tissue related to various aspects of hematologic, cardiac and hepatic functioning. Interpretation related to specific mechanisms involved cannot be made without further study. There are some factors which could explain the decreased LDH levels in the afternoon versus the morning samples. For example, it has been found that less exhausting work at low levels of intensity is associated with lower LDH concentrations (Astrand, 1960; Astrand and Rodahl, 1970). It is also well documented that concentrations of lactate in skeletal muscle and blood are lower in the trained than in the untrained state during submaximal exercise (Mole et al., 1973); and decreased cardiac or hepatic activity has been correlated with lower LDH values. In addition, it is well known that with increased exertion there are, typically, concomitant increases in LDH levels. As expected, LDH values are higher on the baseline days (Figure 2) than during the experimental periods. This is probably because the subjects are going about their daily lives, exerting themselves more than in the experimental sessions, where they were not physically active. This inactive state, in addition to the higher pre-exposure levels, may have influenced the results obtained.

Some studies have found influences of 60-Hz electric fields on major humoral and cellular components of the immune system. Decreases in lymphocytes and leukocytes and changes in serum globulin concentrations have been reported (Bianchi et al., 1973;

Marino, Becker, and Allrich, 1976; Cerretelli et al., 1979; and Fam, 1980). Other studies have not found any consistent effects of field exposure on cellular or humoral immune-system components (Morris and Ragan, 1979).

In contrast to previous findings on effects of electric and/or electric and magnetic fields, our study showed an increase in lymphocyte percent, rather than a decrease, under real-field exposure conditions. No significant changes in leukocytes or in humoral aspects (immunoglobulins) of the immune response system were found as a function of real-field exposure.

Kuhl, Wilson, and Ralli (1952) found that young men adapting to acute stress showed increased lymphocytes and uric acid levels and decreased heart rate. However, immunosuppresive effects, as exhibited by decreased lymphocyte blood levels, following exposure to major environmental stressors have also been well established (Selye, 1983). Data from our study indicate either that there was no change after real- or sham-field exposure, or increased lymphocytic activity. This finding is contradictory to a maladaptive stress hypothesis but concordant with a positive-effects adaptive model of responsivity to a moderate environmental stressor. Previous research indicates that environmental stressors can depress as well as enhance immune responsiveness (Monjan and Collector, 1977). Dean (1966) found that, at certain levels, reactions to stressors are necessary and may be beneficial in improving performance. Lymphocyte values are all within normal ranges for these subjects and for males in general.

T-cells are those lymphocytes influenced by the thymus and highly involved in cell-mediated immunity functions of surveillance and protection against intracellular organisms and neoplasms. Of all the other immunologic variables assayed (Table 1), only lymphocyte and T-helper-cell levels appeared to change significantly as a function of real-field exposure, but only on Day 1. Although T-helper cells decreased, indicating immunosuppression, there were neither increases in T-suppressor cells nor changes in any other immune parameters during the same periods of exposure. Similarly, measurement of cell-mediated immunity by mitogen blast transformation showed that the functional activity of T- and B-cell-specific mitogens (Con A, PHA and PWM) did not differ after real-field exposure. These results are similar to results of Morris and Phillips (1982), who reported no differences in functional activity in the response of spleen cells to mitogens in exposed versus sham-exposed animals.

Circadian variation has been observed in the response of human lymphocytes to mitogen stimulation, but the results are conflicting. There is little controlled in vivo experimental information available. T-helper-cell levels are generally higher in the morning than in the afternoon (Cove-Smith et al., 1978), as exhibited in our study. The higher pre-exposure levels on Day 1 as well as other T-helper-cell values are within normal limits.

In summary, expected circadian variations were observed, and many of the variables studied did not exhibit significant changes in concentration under real-field exposure conditions. The significant changes in LDH and T-helper cells occurred on Day 1 and, in lymphocytes, on Day 2 of real-field exposure. Additional work needs to be performed before definitive interpretation can be made of these results. The findings reported here should be considered preliminary; statistical evaluation of the impact of exposure on the other variables collected in the study is currently in progress. Future research should focus on the in-depth evaluation of biochemical and physiological parameters, using larger populations and incorporating appropriate baseline measures and multiple experimental control procedures.

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A DOUBLE-BLIND EVALUATION OF 60-Hz FIELD EFFECTS ON HUMAN PERFORMANCE, PHYSIOLOGY AND SUBJECTIVE STATE

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ABSTRACT

A comprehensive, double-blind investigation of the effects of exposure to 60-Hz electric and magnetic fields on the performance, physiology and subjective state of 12 men was conducted. Subjects participated in four sessions spaced 1 week apart. Two included exposure to a uniform, 60-Hz field (6 hr at 9 kV/m, 16 A/m); the remaining two were identical, except that a sham field was presented. Order of field presentation was counterbalanced, and each subject served as his own control. In each session, physiological data (electroencephalogram, electrocardiogram, skin conductance level and response, and respiration rate) were collected before and after exposure, and performance measures (13 sensory, motor, perceptual, and cognitive tasks) were obtained before, during, and after exposure. Data were obtained on exposure history, vital signs, mood, diet, sleep and activity patterns, and physical symptoms. Subjects wore standardized clothing, ambient conditions were controlled, and continuous measures of short circuit current were obtained during exposure. Major findings include: 1) neither subjects nor experimenters could detect exposure conditions at better than chance levels; 2) field exposure had no differential effect on vital signs, symptoms, mood, daily life activities, or on most performance measures; 3) critical flicker threshold showed a field-related interaction ($P = 0.004$); however, additional analyses indicated that the interaction was due to differences between the two sham exposure days; 4) cardiac interbeat interval was longer ($P = 0.02$) after real compared to sham field exposure; and 5) significant field-related alterations were found for several components of the auditory and visual evoked response; a number of them indicated reversals of effect over exposure days. Caution is advised in interpreting these data, and directions for future research are indicated.

In order to meet rising energy demands, electric power is being transmitted via overhead transmission lines at increasingly higher voltages. Since these lines cross populated areas, there is a need to determine if the electric (E) and magnetic (H) fields associated with high-voltage power lines present any risk to human health and function. This project was part of a larger research effort sponsored by the New York State Department of Health (NYSDH). Our goal was to conduct a comprehensive, double-blind investigation of the effects of exposure to a combined, 60-Hz field (6 hr at 9 kV/m, 16 A/m) on multiple measures of human performance, physiology and subjective state. In addition, through a cooperative agreement with NYSDH, the U.S. Department of Energy (DOE) sponsored the collection of human biochemical, immunological and histological data as part of the double-blind investigation. Findings and methods from the DOE portion of this project are reported separately (Fotopoulos et al.) in this volume.

METHODS

Apparatus

The 60-Hz Human Exposure Facility. Performance of the double-blind study required that we first construct a 60-Hz exposure facility, specifically designed for human testing and capable of presenting E and H fields of known characteristics in a controlled laboratory environment. A detailed description of the characteristics, control systems and dosimetry measurements made in the facility is presented in Cohen, Graham, and Cook, this volume. From the subject's point of view, the facility appears to resemble a small office. It has panelled walls with pictures on them, a carpeted floor and indirect overhead lighting. In the center of the room, there is a comfortable chair and footrest constructed of PVC pipe and vinyl fabric. All electrically dangerous, field-generating equipment is located out of sight above the ceiling and behind the walls, at distances more than adequate to prevent flashover. In addition, the facility is equipped with five independent electric safety systems. One safety system allows the subject to stop exposure at any time for any reason.

The exposure room is positioned inside a parallel-plate system, and capacitively coupled, copper gradient rings are located behind the room walls to increase field uniformity. The H field is generated by six Helmholtz coils that surround the room in both the vertical and horizontal axes. Dedicated equipment is used to maintain ambient temperature and relative humidity at controlled levels, and the exposure area is continuously monitored from two adjacent control rooms via closed-circuit television and audio intercommunication equipment. Uniform E and H fields can be generated in the subject test area (0 - 16 kV/m, ± 5.6%; 0 - 32 A/m, ± 4.8%). Additional equipment provides continuous monitoring of E and H field strength and individual short circuit current (I_{SC}) throughout the exposure period.

The 60-Hz Double-Blind Control System. The facility also has a system to present real and sham E and H fields under double-blind control conditions (for details, see Cohen, Graham, and Cook, this volume). Experimenters are kept unaware of exposure conditions through a system of hardware/software interlocks under the control of a master computer program. The interlocks blank, mask or disguise all field-related cues in the control room equipment. The experimenters operate a master computer program, which assigns subjects to exposure conditions, verifies that the assigned and actual conditions match, sets the interlocks, and controls the presentation of real and sham fields.

In order to develop the subject portion of the double-blind system, we first conducted a study of human perception over the range 0 - 15 kV/m and 0 - 32 A/m on 10 men and 10 women (Graham, Cook, and Cohen, 1983). They did not perceive the H fields; in fact, 90% of the subjects could not perceive a 9-kV/m E field when seated in the chair in the center of the facility. However, if their hands were raised above ear level, 17 of the 20 subjects could immediately perceive the E field when seated. Continuous measures of I_{SC} also increased significantly when subjects raised their hands, and this movement could be detected while it was still in progress.

The ability of the continuous I_{SC} monitoring circuit to detect limb movement in progress provided the basis of the subject double-blind system. This system operates as follows. Individual I_{SC} is continuously monitored and compared to a reference I_{SC} value (the value for a particular individual when the hands are raised to ear level in a

9-kV/m field). If continuous I_{SC} should exceed the reference value, the strength of the E field is automatically decreased by 75% for 30 sec, then returns gradually to the original 9-kV/m level. On return, the I_{SC} comparison is again made; if the hands are still raised, field strength again decreases; if I_{SC} is below the reference value, field strength continues at 9 kV/m.

Thus, the system uses the moment-to-moment response of the subject's body to the E field as a dynamic sensor/controller to mask field perception. The system allows the subject complete freedom to raise his limbs; however, when he does, his hands enter an E field reduced below the threshold of perception, and no cues to the presence of the real versus the sham field are provided.

The Multi-Task Battery (MTB). A computerized, MTB was developed to interface with the facility and to provide automated collection of multiple measures of human performance and physiology. MTB tasks and measures are summarized in Table 1, together with the other measures obtained in the study. Subjects performed the 13 tasks in the MTB in fixed order during every session; however, individual task stimuli were randomized during each presentation of the MTB.

Each subject performed the MTB while seated in the chair in the center of the facility, facing the closed door of the facility. During exposure testing, each subject wore a sweatsuit (50% cotton, 50% acrylic), cotton socks, and a set of stereo headphones, and held the three-button MTB response device on two polyurethane pillows placed in his lap. The response device was shielded and optically isolated from the field. Prior to the study, dosimetry tests of a 6-ft male mannequin were conducted to determine if the standardized clothing and stimulus response devices described above significantly shielded subjects from the field, or whether they distorted I_{SC} in nine separate body segments. These tests indicated that only minimal shielding occurred (5.9%), and no marked distortion of segmental I_{SC} was observed (Cohen, Graham, and Cook, this volume).

Directly ahead of the subject, at a distance of 1.0 m, was a black horizontal bar with three light-emitting diode (LED) stimuli positioned at eye level. A Grass photostimulator (Grass Instruments, Quincy, MA) was attached to the outside of the exposure room door and was visible to the subject through a 13-mm-diameter hole in the door. The inner side of the door was covered with black cloth. Ambient light was always set at a constant moderate level. The photostimulator served as the stimulus for the critical flicker fusion (CFF) task, and a computerized speech generator was used to present numbers under controlled conditions in the digit span and paced serial addition tasks. Tasks involving the collection of evoked response data used, as a visual stimulus, either the red/green middle LED or tone bursts through the headphones. Standard psychophysiological techniques were used to record and analyze brain-wave activity, heart rate, respiration rate, and electrical activity of the skin.

Subject Population

Announcements describing the study were posted at local universities and colleges, and volunteers were asked to telephone if interested. Prior to participation, each volunteer was given a complete and accurate description of the purpose, procedures, risks and benefits associated with the study, and signed the statement of informed consent approved by the cognizant Institutional Review Board. Twelve male subjects met the screening criteria shown in Table 2 and completed all study requirements. Subjects were paid for their participation, and for providing blood and urine samples.

TABLE 1. Summary Table of Tasks Presented and Measures Obtained

Tasks Presented	Measures Obtained
Physiology	
Collected on each experimental and postexperimental day	Pulse rate Oral temperature Blood pressure (systolic and diastolic)
Collected during task battery presentation before and after field exposure	Heart rate Skin conductance level Skin conductance response Respiration EEG amplitude and latency (N100, P200, N200, P300)
Performance	
Visual oddball task	Visual evoked response, number correct
Auditory oddball task	Auditory evoked response, number correct
Selective attention task (simple and complex decision-making)	Percent correct-matching condition Percent correct-mismatching condition EEG averages for above Mean reaction time, match Mean reaction time, mismatch
Signal detection task	Reaction time and number correct (hits, misses, false alarms, correct rejections) EEG averages for above
Digit span task (memory span)	Number digits forward Number digits backward
Simple reaction time task	Mean and standard deviation (SD) Number anticipatory responses Adjusted mean and SD
Critical flicker fusion task	Ascending mean and SD Descending mean and SD
Paced serial addition task (dynamic memory test)	Percent correct and number misses (three separate error scores)
Reverse tapping task (attentional perseveration)	Percent correct Number misses
Interval production task (internal timing generation task)	Score Mean and SD of interval production
Time perception task (5- and 10-sec time estimation task)	Percent correct Mean time estimated Mean absolute deviation
Wilkinson addition task (speeded addition task)	Number attempted Number correct

TABLE 1. Continued

Tasks Presented	Measures Obtained
Subjective Effects	
Profile of Mood States	Tension/anxiety Depression/dejection Anger/hostility Vigor/activity Fatigue/inertia Confusion/bewilderment
Symptom questionnaire	Total score
Double-blind ratings	Experimenter ratings (a.m. and p.m.) Subject ratings (a.m. and p.m.)
Dosimetry	
Short circuit current	Minute mean and SD for total exposure period Total cumulative exposure
Electric field strength	Minute means/total exposure
Magnetic field strength	Minute means/total exposure
Ambient temperature	Strip chart/total exposure
Relative humidity	Strip chart/total exposure

TABLE 2. Criteria for Participation in the Double-Blind Study

- Male between 21 and 35 year of age
- High school education plus 2 years of additional educational/technical training
- No chronic health problems
- No illness which resulted in bed confinement for more than 3 days in the past 3 months
- No history of brain or nervous system damage or disorder
- Not currently in psychotherapy or contemplating such treatment
- No metal prostheses (contact lenses acceptable)
- Not taking medication; willing to provide a urine sample for analysis of licit and illicit drugs
- Willing to eliminate certain foods from diet and not use alcohol or drugs for 48 hr before each experimental session and until the morning after each session

Procedures

Training and Baseline. Each subject was trained for approximately 12 hr to reach criteria on the various tasks. During training, subjects were also familiarized with the various subjective scales and physiological recording procedures, and provided baseline vital-sign data, urine and blood samples.

Experimental Sessions. Each subject participated in four 10-hr experimental sessions spaced 1 week apart. Two of the experimental sessions involved 6 hr of total exposure to a 60-Hz, 9-kV/m, 16-A/m combined field; the remaining two sessions were identical except that no field was presented. Order of field presentation was counterbalanced under double-blind conditions, and each subject served as his own control. During all 6-hr exposure periods, a 15- to 30-min break out of the field was provided for lunch and urine collection.

Within each experimental session, the MTB was presented five times: once before exposure, three times during exposure, and once after exposure. Physiological measures were collected during the pre- and post-exposure MTB presentations. In addition, subjective measures and vital-sign data were obtained at the beginning and end of each session, and again the next morning.

RESULTS

The double-blind procedures used in this study were successful. Analysis of daily ratings indicated that neither subjects ($\chi^2 = 1.09$, df 1, n.s.) nor experimenters ($\chi^2 = 1.76$, df 1, n.s.) were able to judge at better than chance levels when the real or sham fields were being presented.

Vital Signs, Physical Symptoms and Subjective Measures

Analysis of variance revealed no effects due to field exposure on oral temperature, pulse rate or blood pressure, although the expected effects due to time of day were observed. Similarly, exposure to the real versus the sham field was not associated with significant alterations in mood, increased reports of physical symptoms, or changes in daily life activities.

Performance Measures

Analysis of variance was also used to analyze performance data. The expected effects of time of day, task demands and task repetition on performance were observed. The strongest indication of a valid field effect would be a field-by-period interaction (i.e., no differences observed in MTB-1, the first test battery prior to field exposure, followed by significant field-related performance changes at subsequent measurement points), or a significant field main effect. Neither significant field-by-period interactions nor significant main effects related to field exposure were found for any of the performance measures evaluated except, initially, for CFF. A complex interaction for the descending frequency component of the CFF test is shown in Figure 1. A significant field-by-day-by-period interaction was found ($F = 5.57$; mean square error [MSe], 0.94; df 4, 44; adjusted $P = 0.004$); the direction of the field effect reversed over the two exposure days.

We performed additional analyses to clarify the interaction. These indicated that: 1) performance was not different on day 1 of exposure to either the real or sham field; 2) performance was not different on the 2 days of exposure to the real field, but was different between the 2 days of exposure to the sham field; and 3) on the second exposure day, the only difference between the two field conditions occurred at test battery 4. Thus, the interaction was due to the differences between sham conditions plus the difference at one test battery point on the second day of exposure. It is obvious, however, that threshold variability was excessive, and that this finding should be replicated using more accurate procedures.

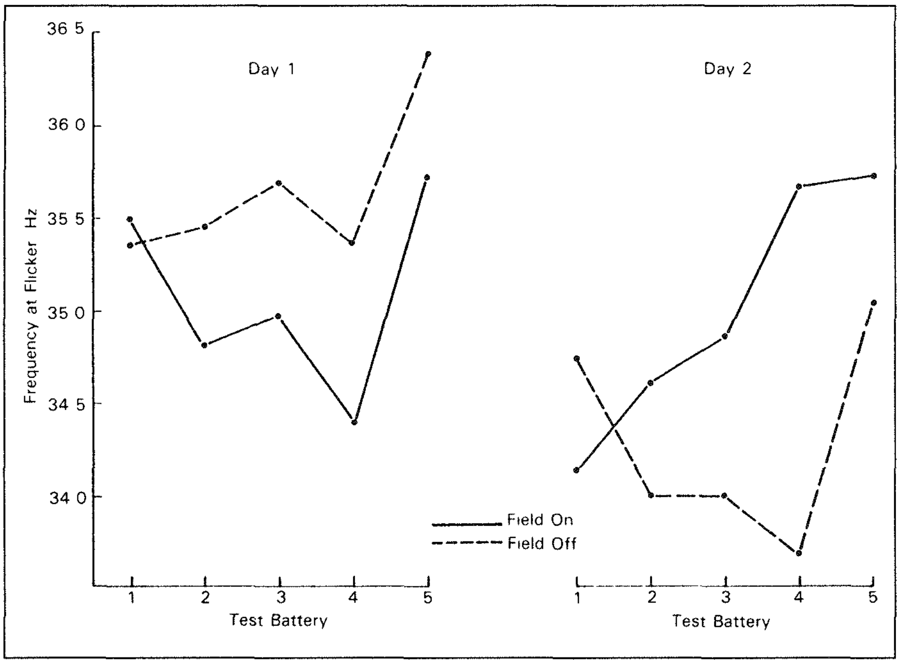

Figure 1. The Descending Threshold for Critical Flicker/Fusion: Field-Related Interaction (P = 0.004).

Physiological Measures

Data were obtained immediately before and after the exposure period during the 5-min resting baseline portion of the battery, and also during performance of the auditory and visual oddball tasks, the selective attention task, and the signal detection task. The relationships between physiological measures and time of day, task demands, and task repetition were as expected.

A significant interaction involving field exposure was found for Cardiac Interbeat Interval (IBI) (F = 4.98, mSe 567, df 2.22. P = 0.022). Further analysis revealed that the primary effect occurred during the resting baseline period of the battery, not during subsequent task performance. The IBI did not differ between field conditions prior to exposure; however, IBI was longer after exposure to the real than to the sham field (slower heart rate). The effect was most apparent during the first minute compared to the last minute of the 5-min baseline period. The magnitude of the difference in IBI as a function of exposure to the real versus the sham field was approximately 3 beats per minute.

Evoked Response Measures. Measures of brain-wave activity were obtained during the performance of four tasks in order to gain additional information about possible field-related effects on neural function during task performance. Brain-wave activity was recorded from the scalp of every subject each time a stimulus was presented in the various tasks. The recorded activity was then averaged to reduce random brain wave-activity and to enhance activity related to task performance; artifacts were then deleted.

By examining the relationships between different components of the averaged evoked response, we hoped to learn more about possible field effects on the underlying neural functions involved in task performance. For example, in one of the tasks used in this study (auditory oddball), subjects were presented with a small number of high-pitched tones interspersed randomly in a long series of low tones. The subject had to push his button each time he detected a rare high tone, and keep track of how many were presented. This is a relatively simple task; however, its very simplicity allows a good deal to be learned about cognitive and neural function. The mental activity involved in this task can be thought of as a number of important subactivities, each of which contributes to the whole, and each of which takes time to perform. For example, subjects performing this task had to: 1) voluntarily direct attention to the task and away from other things; 2) maintain a stimulus set to detect rare or unusual events; 3) when an event was detected, determine whether it was rare and required action to be taken; and 4) take action, once the decision was made.

The major components observed in the evoked response are usually identified sequentially by the time of their typical peak occurrence, in milliseconds, and whether they are positive or negative. These include N100, P200, N200, and P300. A large body of research has attempted to relate changes in the amplitude or latency of these components to cognitive activities such as those described above. The relationships found are not always perfect, and a good deal of controversy exists concerning the meaning or functional significance of alterations in particular components. However, there is relative consensus at the present time that the major components described below are related to various cognitive activities involved in stimulus selection, information processing and decision-making (Sutton and Ruchkin, 1984).

The N100 component of the evoked response is generally thought to index the initial, voluntary selection of specific classes of incoming information for subsequent analysis (e.g., a conscious decision to pay attention only to stimuli coming from a specific location, or only to stimuli of a certain pitch). Once attention is directed to a particular sensory channel, N100 amplitude is typically enhanced to stimuli in that channel compared to stimuli in nonselected or ignored channels. This enhancement, however, generally occurs to all stimuli in the selected channel, regardless of any differences that might exist in the significance or meaningfulness of the incoming stimuli. Thus, the initial selection process indexed by N100 is a volitional one that appears to be based primarily on perception of the simple physical attributes of a stimulus which distinguish it from other stimuli (Picton et al., 1978).

In contrast, the N200 component is generally thought to have a more involuntary nature, and to index the later process of stimulus classification. It is typically obtained as a response to rare or infrequent stimuli when they are randomly embedded in a series of common stimuli. This component is involuntary in the sense that any rare event, regardless of its significance, and regardless of whether it occurs in a selected or unselected channel, will evoke it. In addition, the amplitude of N200 will vary inversely with the probability of occurrence of the rare event (e.g., N200 amplitude will be greater to stimuli with a 20% versus a 70% probability of occurrence), and N200 latency will vary with the complexity of the classification process involved. Thus, this component is similar to a general "mismatch" detector, and may represent the initiation of the actual cognitive decision process. In other words, detecting that a rare event has occurred is the initial step in deciding if the event detected is also the particular significant event the individual is looking for.

The P200 component is not as well understood as the others; the available literature suggests that P200 is involved in the stimulus evaluation process, and sensitive to the probability of occurrence of stimuli which are relevant to task performance (Picton et al., 1978). Although P200 bears some functional resemblance to P300, its morphology is different and, therefore, appears to reflect somewhat different neural processes.

The P300 component is, by far, the most widely studied component of the evoked response. Numerous studies have indicated that this component is intimately related to higher cognitive stimulus-processing and evaluation. The amplitude of P300 has been shown to vary consistently with the subjective probability and sequencing of stimulus occurrence (Duncan-Johnson and Donchin, 1977). P300 amplitude is also affected by the amount of task-relevant information provided by the stimulus, the subject's confidence in his/her response, and the difficulty of discrimination between relevant and irrelevant stimuli. The latency of P300 varies systematically with the discriminability of the stimulus, and is usually highly correlated with reaction time (Duncan-Johnson, 1981; Magliero et al., 1984).

Analysis of the evoked response data from this experiment indicated that the effects of the various tasks on evoked response components were as expected. Our discussion will therefore focus on the effects of 60-Hz fields on these phenomena. The data are of two types: the absolute amplitude and latency of the various evoked response components, compared to the values prior to stimulus onset, and the amplitude and latency compared to the previous peak or trough. The latter analyses are indicated by the terminology N100-P200, P200-N200, and N200-P300. All data were recorded from the vertex site.

Auditory Oddball Task. This task is designed to evaluate the response of the brain to the detection of rare or infrequent auditory events. Both the amplitude and latency of the P300 component were affected by field exposure. Contrary to expections, the decrease in P300 amplitude was significantly less after exposure to the real field than after exposure to the sham field (field-by-period interaction; F = 5.66, MSe 5.64, df 1,9, P = 0.04). This interaction is shown in the left section of Figure 2; the middle and right sections of Figure 2 further explore this relationship. No effects of the field on P300 amplitude were apparent on the first day of exposure. On Day 2, however, P300 amplitude did not decrease as expected after exposure to the real field (F = 7.17, MSe 6.79, df 1,9, P = 0.025). P300 latency showed similar results (F = 5.76, MSe 260, df 1,9 P = 0.04).

We also examined the effects of the field on the peak-to-trough relationships between the components of the evoked response; these analyses reflect the particular aspects of the evoked response affected by field condition. A significant main effect for field was found for N200-P300 latency. The difference in latency between N200 and P300 (i.e., the time from the N200 peak to the P300 trough) was greater for exposure to the real than to the sham field (71 versus 62 msec; F = 10.67, MSe 348, df 1,9, P = 0.01). Similarly, there was a significant field-by-period interaction for N100-P200 amplitude (F = 6.25, MSe 3.76, df 1,9, P = 0.03), indicating that the amplitude difference did not decrease from MTB-1 to MTB-5 after real field exposure but did decrease after sham exposure.

Visual Oddball Task. This task was identical to the auditory oddball, except that red and green visual stimuli were substituted for high and low pitched tones. The N100 and N200 amplitudes were less for real than sham field conditions (+ 0.14 versus - 0.81 μV; F = 8.98, MSe 3.6, df 1,8, P = 0.02; and - 0.68 versus - 1.83 μV; F = 6.43, MSe 7.3, df 1,8, P =

0.03, respectively). P200-N200 latency was also less for the real than for the sham field condition (72.4 versus 78.8 msec; F = 9.36, MSe 157, df 1,8, P = 0.02).

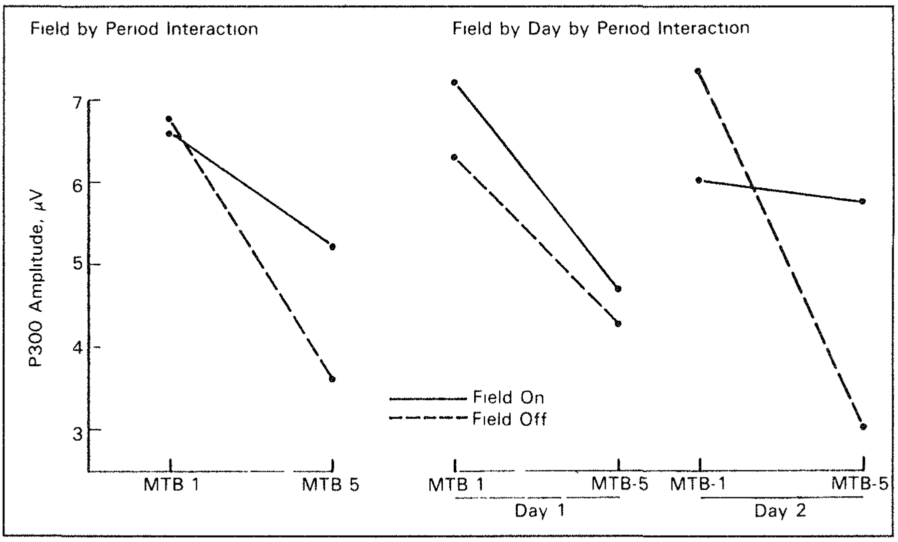

Figure 2. Effects of 60-Hz Fields on P300 Amplitude During the Auditory Oddball Task.

In addition, two significant interactions involving field condition were found: 1) N200-P300 latency differentiated between targets and nontargets more during MTB-1 than during MTB-5. 2) This effect was greater when subjects were exposed to the real field than to the sham field (F = 7.76, MSe 157.8, df 1,8, P = 0.02). P200 latency did not differentiate between targets and nontargets on sham-exposure days. On real-field-exposure days, however, P200 latency was shorter to target stimuli in the morning (MTB-1), then reversed and was shorter to nontarget stimuli during MTB-5 (F = 5.72, MSe 235, df 1,8, P = 0.04).

Selective Attention Task. In this task, the subject responded to each of 160 rapidly presented stimuli. Of these, 120 were called mismatch stimuli, and required only simple categorization. The remaining 40 stimuli (match stimuli) were randomly interspersed, and each required a more complex decision concerning the information available within a particular stimulus category.

No main effects or interactions involving the field were found for the majority of component analyses conducted. However, the analyses revealed several puzzling interactions with field condition for N100 amplitude (P = 0.01), N200 latency (P = 0.03), and P200-N200 latency (P = 0.02). These interactions indicated that a reversal of field effects occurred over exposure days or test periods. The components that showed reversal effects appeared primarily in association with stimuli involved in the simple decision-making aspects of the task. No reversal effects were observed for the amplitude and latency of P300, or for the N200-P300 complex components associated with complex decision-making.

Signal Detection Task. Two hundred visual discrimination trials were presented in this task. On each trial, the subject had to decide whether the second of two light flashes was longer or shorter than the first. One hundred long flashes (targets) were randomly interspersed with 100 short flashes (nontargets). Visual evoked-response data associated with the correct detection of targets ("hits") were compared with similar data obtained for the correct detection of nontargets ("correct rejections").

Both N100 latency and N200 amplitude were significantly increased under real compared to sham conditions (F = 5.58, MSe 364.0, df 1,9, P = 0.04 and F = 5.07, MSe 2.9, df 1,9, P = 0.05, respectively). In addition, peak to trough analyses indicated a strong field-by-period interaction for N200-P300 amplitude (F = 28.22, MSe 0.4, df I,9, P = 0.0005), which is shown in Figure 3. At MTB-1, prior to initiation of the fields, no difference between sham and real fields was found; after 6 hr of exposure, N200-P300 amplitude was less under real than under sham field conditions. There was also a significant interaction between field condition, day and stimulus type for N200-P300 amplitude (F = 10.17, MSe 0.3, df 1,9, P = 0.011). On Day 1, differentiation between fields was greater for target stimuli ("hits") while on Day 2, differentiation was greater for nontargets (correct rejection).

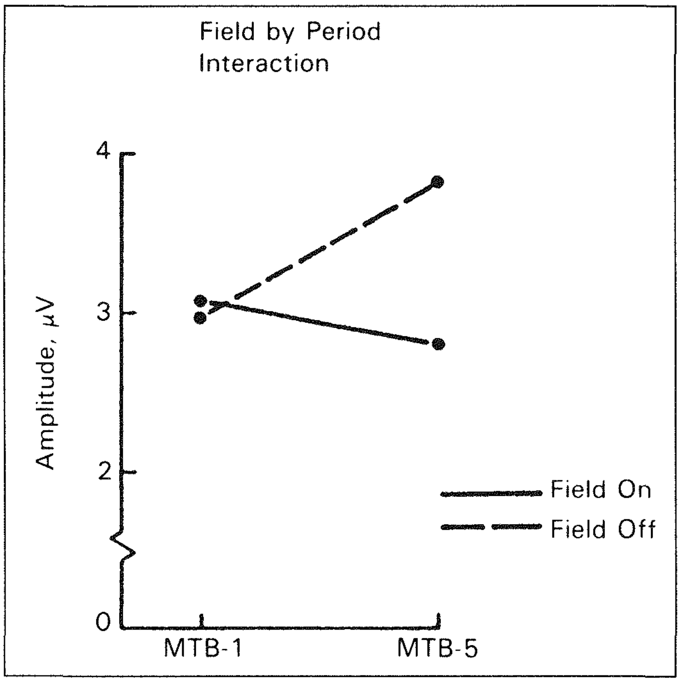

Figure 3. N200-P300 Amplitude During the Signal Detection Task: Interactions with Field Condition (P = 0.0005).

A number of other complicated interactions involving the field were found. They were quite similar to the interactions reported for the other tasks in which evoked-response measures were obtained. All indicated that effects were reversed, either over exposure days or over measurement periods. However, for this task there appeared to be two distinct categories of interaction effects: those involving field, day and period had an impact only on component latencies; those involving stimulus-type affected only component amplitudes.

DISCUSSION

Much of the research in this area has been concerned with the effects of field exposure on animals or biological preparations; few controlled human studies have been conducted. Of these few, this is the first to evaluate field effects on humans under double-blind control conditions. Given this context, we view the present study as an initial screening experiment to evaluate the impact of specific field-exposure conditions on multiple areas of human function.

The first conclusion that can be drawn from the findings presented is that exposure to the real field versus the sham field had no significant effect on the overwhelming majority of measures obtained. To make this point even more clearly, Table 3 presents all the measures for which no differences were found as a function of exposure to the real versus the sham field.

TABLE 3. Summary of Human Functions Not Affected by Exposure to 60-Hz Electric and Magnetic Fields

No Effects (Real versus sham field exposure under double-blind control conditions)

Vital Signs

Pulse rate
Oral temperature
Blood pressure

Physiology

Respiration rate
Skin conductance level
Skin conductance response

Field-Related Symptoms and Daily Life Activities

Sleep
Appetite
Sexual activity
Cognitive function
Physical function

Mood

Tension/anxiety
Depression/dejection
Anger/hostility
Vigor/activity
Fatigue/inertia
Confusion/bewilderment

Performance

Simple reaction time
Memory span
Focused attention
Time estimation
Internal timing sense
Signal detection
Information processing
Simple decision-making
Complex decision-making

Our second conclusion is that field-related effects were observed in IBI and in a number of components of the evoked response. Caution should be exercised, however, in interpreting these statistically significant effects as biologically significant. For example, the slowing of heart rate observed after exposure to the real field occurred consistently over both exposure days for 8 of the 12 subjects in this study. However, the magnitude of the field-related difference observed was only 3 beats/min, or the equivalent of a deep breath. Second, the change in IBI was observed only during the resting base line of the battery administered after field exposure, primarily during the first minute of the base-line measurement. As soon as subjects began to perform the battery tasks, IBI was not different as a function of exposure to the real or the sham field, and no differences in task performance were observed.

The pattern of change observed in IBI may imply that field effects are most clearly seen during the resting physiological state and are obscured by motivational influences and task demands during performance. Alternatively, the differences observed between the resting state and during task performance might imply that the observed cardiac changes were merely transitory, since they were overcome during task performance. Nevertheless, it is obvious that more detailed measures of cardiac function should be included in future research to further clarify this small but highly significant effect.

Similar problems arise in relation to field effects on components of the evoked response. First, this study evaluated the effects of short-term exposure; the long-term consequences of the findings reported here are unknown. Second, although field effects on evoked-response components were found for the selective attention task and the signal detection task, no differences in performance were found as a result of exposure conditions. Third, the changes observed in the evoked response were all well within the normal ranges typically obtained using these measures. These considerations may imply that, as in the IBI, field effects on EEG activity may be masked by task performance demands or may be merely transitory. Alternatively, although EEG changes occurred, the effects on the physiological system may not have been great enough to be exhibited on the behavioral level. In addition, changes in the same component were not always consistent across tasks. For example, N200 amplitude under real-field exposure increased during the signal detection task and decreased during the visual oddball task. Such differences, however, may well be a reflection of differences in the performance demands of the two tasks.

Finally, many significant interactions suggested reversal of field-by-period effects between Day 1 and Day 2, or reversal of field by stimulus type. These data are particularly puzzling. It is difficult to postulate a mechanism by which the fields could affect the evoked response differently on Day 1 and Day 2, particularly since the day of exposure was counter-balanced. Thus, exposure Day 1 could have been separated from exposure Day 2 by a minimum of one or a maximum of 3 weeks. Our initial hypothesis was that some error in computer processing or sample labeling had occurred. Eight weeks of effort were devoted to trying to find such an error, without success. In addition, other data collected in this study were entered in a different data analysis process, and these data also show differences between Day 1 and Day 2 of exposure.

The evoked response findings reported here were not the result of data generated by only a few individuals; they occurred for the majority of the subjects tested. Although it is possible that the results were random and cannot be replicated, the consistency of the effects observed across subjects makes this unlikely. No simple explanation, such as an increase in neural transit time as a function of field exposure, is adequate to explain the results obtained.

Three alternative hypotheses have been considered. First, habituation to task demands may interact with field effects to produce the results obtained. This is also somewhat unlikely, since habituation generally acts to decrease effects and, in our experiments, both increases and decreases were observed over exposure periods. Second, sensitization to the field may occur over time, so that physiological responses and, perhaps, some perceptual mechanisms, are more profoundly influenced on the second day of exposure, regardless of whether the second day is 1, 2 or 3 weeks after initial exposure. Third, the double-blind control system was such that subjects who made many body movements were exposed to a greater number of changes in electric field strength than subjects who had fewer body movements. Such differences tended to cluster in particular orders of field presentation. If this is the reason for our findings, the implication is that the changes in field strength within an exposure period, rather than the strength of the field, affect human physiology.

The "Cheshire Cat" phenomenon (Graves, Long, and Poznaniak, 1979), which has plagued research on the effects of powerline fields, makes it clear that significant findings such as these must be replicated before they are interpreted as being relevant to health effects and health risks in the general population. However, this study has demonstrated the feasibility of conducting controlled, double-blind investigations of 60-Hz field effects on humans and has screened a large number of human performance and physiological variables to provide specific avenues of exploration for future research.

We recommend that future research should focus more directly on specific human functions which have been shown here to be of interest. These studies should include the monitoring of CFF, cardiovascular and EEG variables before, during and after exposure to real and sham fields. We have now developed the capability to obtain physiological measures during field exposure and are preparing to carry out such studies.

ACKNOWLEDGMENTS

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GENETIC AND REPRODUCTIVE HAZARDS IN HIGH-VOLTAGE SUBSTATIONS

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ABSTRACT

A total of 542 male employees at Swedish power stations were included in a retrospective study of pregnancy outcome in their wives. Data from questionnaires (answered by 89%) and hospital records were analyzed. Chromosomal aberrations were studied in lymphocytes from 20 of the employees after work at energized 400-kV substations and 17 controls. Chromosomes were also examined in lymphocytes exposed in vitro to 50 Hz, at 1 mA/cm^2 current density, and to transient current pulses with internal peak electric-field strengths of 2.5, 3.0, and 3.5 kV/cm, respectively. A follow-up in vivo study of chromosomal breaks was performed in 19 workers at energized high-voltage substations and 19 controls. An increased frequency of congenital malformations was found ($P < 0.001$), and the frequency of couples with difficulties in having children was higher ($P < 0.025$) when the male had been working at high-voltage substations. The differences could not be explained by any of the confounding factors analyzed. The rate of chromatid and chromosome breaks was increased in the 20 exposed workers ($P < 0.0005$), with a fivefold increase of chromosome breaks compared to controls. The follow-up study confirmed a significant increase of chromosomal breaks in exposed workers. There was no significant increase in aberrations in cells *exposed to 50-Hz current. In cells exposed to pulses, however, the rate of chromosome aberrations* was higher, especially after exposure to pulses of 3.5 kV/cm ($P < 0.001$). The results suggest that chromosomal aberrations may be caused by spark discharges. Although effects in substation workers may be restricted to peripheral blood cells, possible connections between chromosomal damage and reproductive hazards cannot be excluded. However, no direct connection has been made between chromosomal breakage and the congenital malformations found in this study.

Possible medical and biological effects from exposure to electric and/or magnetic fields have been widely discussed during recent years. The question has been raised as to whether such exposure causes genetic or reproductive hazards. Several investigations concerning biological effects on different species have been performed, but the results presented are often somewhat contradictory. The question as to whether power-frequency electric and magnetic fields exert harmful genetic effects in man is of extraordinary interest since gene mutations and chromosomal aberrations may have consequences not only for the exposed adults but also for the unborn children. Fertility problems and reproductive hazards may also be connected with nonegenetic biochemical disturbances in germ cells or early embryonic cell lines.

For these reasons, we decided to perform a study of pregnancy outcome among wives of workers at high-voltage substations as well as a study of chromosomal aberrations in cultured lymphocytes from some of these workers. The investigation included: 1) a retrospective study of reproductive hazards among 542 male employees at the Swedish State Power Board (SSPB) and the South Swedish Power Company (SSPC) (Nordström, Birke, and Gustavsson, 1983), and 2) a study of chromosomal aberrations in cultured lymphocytes from 20 of those employees shortly after work at high-voltage (400-kV) substations, (Nordenson et al., 1984). The investigation was completed with 3) an experimental in vitro study of chromosomal aberrations in exposed human lymphocytes (Nordenson et al., 1984) and 4) a follow-up in vivo study of chromosomal aberrations in cultured lymphocytes from 19 exposed and 19 controls among workers at Swedish power stations (to be published).

MATERIALS AND METHODS

Retrospective Study

The 542 employees were classified according to risk for exposure at energized high-voltage substations (switchyards) or lines. The entire cohort included all known living employees presently or formerly working in 400-kV establishments (331 individuals), a random sample of workers working primarily with 380- or 220-V transmission lines, who only very occasionally worked with high voltages up to a maximum of 40 kV (145 individuals), and a random sample of employees in occupations where they were exposed to a maximum of 130 kV (66 individuals).

Questionnaires concerning their wives' pregnancies, their working conditions and confounding factors (smoking, drugs, chemical exposure at or outside work, medical treatments, etc.), were mailed to the 542 employees and answered by 483 of them (89%). Data on pregnancies were checked by studying hospital records.

All induced abortions were excluded, and the remaining 880 pregnancies were classified as: spontaneous abortion, perinatal deaths (stillbirths and deaths before 7 days of age), children with a congenital malformation that survived the perinatal period, and children with no known congenital malformation that survived the perinatal period (normal outcome).

Male exposure before pregnancy was classified according to type of occupation: working around energized equipments at high-voltage switchyards; construction or repair of de-energized switchyards and transmission lines; other tasks, such as working in offices and stores; and according to electric-field exposure at the working place: less than 70 kV, 130-220 kV, 400 kV.

Pregnancies that occurred when the father was not employed at SSPB/SSPC or when he was working exclusively with 380/220 V, served as a reference group (control).

In Vivo Study of Chromosomal Aberrations

Heparinized venous blood from 20 of the 582 employees was cultured and analyzed for chromosomal aberrations at the Department of Medical Genetics, University of Umeå. All except one of the donors had been working at 400-kV switchyards for a period of 1-8 wk immediately before sampling blood. Controls were 17 men (salesmen and clerks) with no known exposure to electric fields.

In Vitro Study of Chromosomal Aberrations

Part of the heparinized venous blood from two healthy volunteers was exposed in special exposure chambers constructed for this purpose at the research department of the National Board of Occupational Safety and Health (See Nordenson et al., 1984). Another portion of the blood sample was put in a control chamber. Except for exposure, both chambers were always handled in exactly the same way.

The cells were exposed to a simulated 50-Hz field (current density, 1 mA/cm^2) at a temperature of 37° C, for 3 hr, or electrical discharges by 10 pulses (intensity, 2.5, 3.0 or 3.5 kV/cm) of 3 μsec, separated by intervals of about 5 sec. Loading of the chambers and exposure took place at room temperature. The experimental set-up for spark discharge exposure has been described by Hansson-Mild et al. (1982).

Immediately after exposure, cell cultures were established from exposed as well as control cells, and the frequency of chromosomal aberrations was analyzed. For more details on the experimental set-up see Nordenson et al. (1984).

Follow-Up in Vivo Study of Chromosomal Aberrations

Heparinized venous blood was collected from 19 employees at Swedish power plants, who were exposed immediately before blood sampling to energized 400-kV equipment, and from 19 unexposed workers from the same geographical location that were matched for age. Blood samples were coded and sent to the Department of Medical Genetics in Umeå, where they were cultured and submitted to cytogenetic examination. Analyses of chromosomal preparations were carried out as described earlier (Nordenson et al., 1984).

RESULTS

Retrospective Study of Pregnancy Outcome

There was a significantly ($P < 0.05$) lower frequency of normal pregnancy outcome (81%) when the father had been working in energized high-voltage substations than for the other occupational subgroups (89 and 92%, respectively) or the reference group (87%). There were no differences among the three subgroups that related to their voltage exposure. In the lower field-exposure groups, the frequency of pregnancies with a normal outcome varied between 87 and 90%; it was 88% in the entire group. The lower frequency of normal outcome observed in high-voltage workers seemed to be due to an increased frequency of congenital malformations (12 out of 119 children, compared to 5 out of 294 children in the other occupational subgroups, and 9 out of 225 children in the reference group). The increase of malformations in the exposed group was statistically significant ($P \cong 0.025$) as compared to the reference group.

Pregnancy outcome varied with the mothers' smoking habits ($P < 0.001$ for comparison of congenital malformations) but was not related to the fathers'. The mothers' use of medicines (or diseases accompanied by use of medicine) and alcohol also seemed to affect pregnancy outcome. In both cases, the increase of congenital malformations was statistically significant. The groups established by the fathers' occupations were, however, very similar with regard to the distribution of these confounding factors. Thus, the differences in pregnancy outcome could not be explained by those factors.

No interactions between father's occupation, smoking habits, and use of medicines or alcohol by the mother were observed.

Questions about exposure to ionizing radiations in connection with radiological examinations and/or treatments and environmental and occupational exposure to chemicals were also answered, but analysis of those answers indicated no correlation of pregnancy outcome with such exposure. Nor did we find any correlation with the duration of father's employment at SSPB/SSPC.

Pregnancy outcome was also analyzed regarding differences between subgroups comprising age of the mother, distribution of pregnancies in time and by pregnancy order. None of those confounding factors correlated with differences in pregnancy outcome for the wives of the exposed high-voltage workers and other groups. Answers on the questionnaires concerning fertility problems were analyzed among males born between 1925 and 1951 who were employed before the age of 31. The risk for exposure from energized 400-kV equipment during reproductive ages was estimated to be greatest in this group. Out of the 331 males who worked in 400-kV substations, a total of 164 individuals were in this group. The frequency of infertile couples was higher in this group when the father was still working at energized high-voltage switchyards (Table 1).

TABLE 1. Frequency of Males with Fertility Problems According to Occupation and Voltage at the Work Place at the Time of Fertility Problems[a]

Voltage Maximum	Working in High Voltage Switchyards at Time of Fertility Problems		
(kV)	Yes %	No %	Total %
200	7 out of 28 (25)	2 out of 41 (5)	9 out of 69 (13)
400	17 out of 62 (27)	6 out of 33 (18)	23 out of 95 (24)
TOTAL	24 out of 90 (27)	8 out of 74 (11)	32 out of 164 (20)

[a] Heterogeneity: working in high-voltage switchyards (Yes/No), $X^2 = 6.5$, 1 df, $P < 0.025$; voltage maximum (200/400 kV), $X^2 = 3.2$, 1 df, $P > 0.05$

Studies of Chromosomal Aberrations

In the in vivo study, no differences in the frequency of gaps in chromosomes were found between the 20 exposed workers and the 17 controls. There were, however, significant increases of chromatid and chromosome breaks ($P < 0.0005$), with a five-fold increase of chromosome breaks in the exposed group (Table 2). The frequency of aberrant cells was also significantly increased ($P < 0.0005$) in exposed workers as compared to controls. No difference between exposed and non-exposed cells was observed when they were exposed in vitro to 50 Hz at 1 mA/cm^2 current density. When exposed to pulses, however, there was a significant increase of chromosomal breaks and other aberrant cells, especially after exposure at the highest internal field strength (Table 3).

TABLE 2. Rate of Chromosomal Aberrations (per 100 Cells) in Switchyard Workers (400 kV) and Controls

	Exposed			Nonexposed		
	Smokers	Non-Smokers	All	Smokers	Non-Smokers	All
N	9	11	20	7	10	17
Numbers of cells	1,800	2,200	4,000	1,400	2,000	3,400
Gaps	2.8	2.4	2.6	3.0	2.0	2.5
Chromatid breaks	1.9	1.3	1.6	0.5	0.5	0.5
Chromosome breaks	1.3	0.9	1.1	0.3	0.1	0.2
Total rate of chromosomal aberrations	6.0	4.1	5.0	3.8	2.6	3.1
Aberrant cells (%)	5.8	5.1	5.4	3.8	2.6	3.1

TABLE 3. Chromosomal Aberrations (per 100 Cells) in Lymphocytes Exposed in Vitro to Spark Discharges (2.3-3.5 kV/cm, 10 pulses) and Controls (600 Cells per Exposure Dose)

		Aberrations				
	Exposure (kV/cm)	Gaps	Chromatid breaks	Chromosome breaks	Total Rate of chromosome aberrations	Other aberrant cells[a] (%)
Donor 1	0	0.3	0.7	0.2	1.2	0.3
	2.5	1.5	0.8	0.8[c]	3.2[b]	0.8[c]
	3.0	1.7	0.5	0.5[c]	2.7[b]	2.3[d]
	3.5	0.3	0.3	2.7[e]	3.3[d]	0.8[c]
Donor 2	0	1.2	1.5	0.3	3.0	0.0
	2.5	0.7	0.5	1.5[c]	2.8[c]	0.3[c]
	3.0	1.5	1.3	1.3[c]	4.2[c]	1.0[b]
	3.5	1.7	1.0	3.0[e]	5.7[b]	1.2[d]

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[a] Cells with polyploidy, premature chromosome condensation or unidentified marker chromosomes

[b] $P < 0.05$ compared to unexposed cells

[c] Not significant

[d] $P < 0.01$ compared to unexposed cells

[e] $P < 0.001$ compared to unexposed cells

The follow-up study of chromosomal aberrations in 19 exposed and 19 unexposed workers at Swedish power plants also showed a significant increase of chromosomal breakage but no increase in gaps after exposure (Table 4).

TABLE 4. Chromosomal Aberrations (per 100 Cells) in Nonsmoking Switchyard Workers (400 kV) and Controls in the Original Study and in a Follow-Up Study.

		Aberrations/100 cells			
	Number of Cells	Gaps	Chromatid breaks	Chromosome breaks	All
Exposed					
original study	2200	2.4	1.3[c]	0.9[c]	4.1[b]
follow-up study	3400	2.3	0.2	0.7[c]	3.2[a]
TOTAL	5600	2.3	0.6[c]	0.8[c]	3.7[c]
Controls					
original study	2000	2.0	0.5	0.1	2.6
follow-up study	3600	2.2	0.1	0.1	2.4
TOTAL	5600	2.1	0.3	0.1	2.5

[a] $P < 0.05$
[b] $P < 0.01$
[c] $P < 0.001$

DISCUSSION

The total number of children with congenital malformations was very small, and the frequency also varied strongly over time. Therefore, this result, although statistically significant, must be interpreted with caution. However, the rate of infertility in males that worked in high-voltage switchyards was higher than that of employees in other occupations. Fertility problems may be connected with the type of disturbances found by Andrienko et al. (1977). They showed that a continuous, 24 h/day exposure for 3.5 mo to electrical fields (50 Hz, 5 kV/m) caused a significant reduction of viable spermatozoa in adult male rats. The frequency of dead spermatozoa was 46.4%, versus 23.0% in nonexposed rats. Exposure for 1.5 mo caused an increase of atypical spermatozoa from 15.9% in the control to 30.7% in exposed rats.

Of course, there are great differences in exposure between rats in an experimental situation and males working around energized equipment. In some working situations, the men may have been exposed to spark discharges through the testes as well as in other parts of the body. Cell disturbances, including chromosomal aberrations, might have been caused by such discharges.

Our study on chromosomal aberrations in cultured lymphocytes clearly suggests that working in energized high-voltage substations increases the risk of having chromosomal breaks. The in vitro study suggests that exposure to electric fields (50 Hz, 1 mA/cm^2 current density) does not induce chromosomal breaks in lymphocytes. However, exposure to repeated pulses (ten 3-μsec-long pulses at 2.5-3.5 kV/cm peak field strength), caused a significantly increased frequency of chromosome breaks. Our findings are contrary to those published by Bauchinger et al. (1981). The difference in working conditions for the employees in the latter study (32 workers at 380-kV switchyards) compared with those in our study may account for some of this discrepancy.

Results from the follow-up study of chromosomal aberrations in 19 exposed and 19 nonexposed workers at Swedish high-voltage power plants strongly suggest a connection between working conditions in Swedish high-voltage substations and an increased risk of chromosomal breakage.

Besides an increased frequency of chromosome breakage, other cell aberrations (polyploidy, endoploidy and premature chromosome condensations) were more frequent in exposed cells. Although such anomalies may arise in the cell cultures due to faulty cell divisions, another possible mechanism is cell fusion. Zimmermann and Vienken (1982) found that exposure of mammalian cells in vitro to pulsed electric fields, i.e., transient currents, caused such cell fusions.

It is quite possible that chromosomal aberrations in substation workers exposed to electrical discharges may be restricted to peripheral blood cells. Depending on work situation, however, other parts of the body, including the testes, may also be exposed to the spark discharges. In such cases, genetic damage in germ cells may cause malformations or a reduced reproductive capacity. Among the malformations found in children of exposed fathers in this study there was one case with Turner's syndrome and one with unspecified multiple malformations. None of the other malformations could be connected with possible chromosome damage; however, a tie between genetic damage in germ cells and an increased incidence of fertility problems cannot be fully excluded.

ACKNOWLEDGMENTS

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60-Hz ELECTROMAGNETIC-FIELD EXPOSURE RELATED TO FETAL DEVELOPMENT

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ABSTRACT

Several independent sets of data suggest that 60-Hz electromagnetic fields may affect fetal development adversely: 1) Two sets of data, designed to study childhood cancer in relation to power lines near the home, each showed a pattern suggesting that prenatal exposure to high-current power lines near the home might have resulted in a higher than usual number of abortions; hypothetically, these were abortions of those infants most susceptible to harmful effects from the 60-Hz magnetic fields produced by high-current wires. 2) A case-control study also indicated that high-current wires near the home were associated with perinatal death or congenital defects. 3) The hypothesis that use of electric blankets (E) or heated waterbeds (W) might increase abortion rates was supported by a seasonal change in sex-ratio (fewer surviving males among winter conceptions) seen in United States births between the 1940s and the 1970s. 4) A direct survey of E and W use by families of newborns provided further evidence that such use might have detrimental effects on fetal development.

PILOT STUDIES

Three pilot studies are presented which examine evidence pertinent to the hypothesis that increased abortion and other problems of fetal development may be associated with prenatal exposure to 60-Hz magnetic fields. Although all of the pilot studies yielded findings consistent with the hypothesis, they do not rule out the possibility that other explanations might account for the findings.

Indirect Evidence from Studies of Cancer and Power Lines

In childhood disorder studies, high-risk infants are sometimes eliminated from a study population by spontaneous abortion, thus reducing the expected rate of disease among the remaining liveborn infants. If a toxic agent is capable of inducing abortion of the exposed fetus, then any population subjected to that agent before birth could have its most susceptible members removed by abortion. Consequently, the residual, liveborn population may be especially resistant to the responsible agent because the individuals most susceptible to it were aborted. Since the majority of abortions may well occur in very early pregnancy, even before the mother knows she is pregnant (Edmonds et al., 1982), accurate direct evidence of abortion is difficult to obtain. The occurrence of early, "silent" abortions can, however, sometimes be deduced by noting unusual gaps in the numbers of live births that occur 8 or 9 mo after a period of suspected high abortion.

In two studies, one in Colorado (Wertheimer and Leeper, 1979), and one in Rhode Island (Fulton et al., 1980), data originally gathered to explore the association between high-current configuration (HCC) and childhood cancer show a pattern suggesting that the cancer rates observed may have been affected by the abortion of susceptible infants. This was especially true where gestation took place in homes where wiring configurations were indicative of unusually high magnetic-field exposure (discussed below).

On the average, the greatest magnetic-field exposure from power lines would be expected from wiring consisting of large-gauge, three-phase primaries or high-voltage lines very near the home. Configurations where such wires are closer than 50 ft to the home we have called Extremely High Current Configurations (EHCC); they showed an interesting pattern. In both Colorado and Rhode Island they were, as might be expected from the hypothesis that magnetic fields promote cancer, more strongly associated with childhood cancer than were other configurations. However, this was true only for addresses first occupied *after* the child was born. For fetuses exposed to such EHCC before birth, no positive association with cancer was seen (Figure 1). It is possible that fetuses exposed to EHCC fail to show the expected cancer excess because, as a group, they are especially resistant to any damaging effects of magnetic fields. Such a resistant population might be generated if the fetuses most susceptible to magnetic-field damage were aborted when exposed to high magnetic fields from EHCC during gestation.

Direct Evidence of Fetal Damage Associated with Power Lines

The indirect evidence discussed above is, by itself, only suggestive. In an attempt to get more direct evidence, we compiled a sample of 285 infants in Colorado who were aborted or died shortly after birth, or who had congenital defects. Each case was matched to a normal birth that reflected the same birth order and approximately the same birth year, age of mother, and education level of father. Also matched were parents' residence type (single- or multiple-unit dwellings), length of residence and, to a large extent, the father's age and the mother's education level.

Wiring configurations were coded at all the case and control gestation addresses according to criteria developed elsewhere (Wertheimer and Leeper, 1982). Overall, 59% of the 285 infants who died or were malformed had been exposed to HCC at their gestation address, compared to only 46% of the corresponding controls ($X^2 = 7.2$, $P < 0.01$). This result is consistent with the hypothesis of increased fetal damage from exposure to HCC, but it is not definitive because the information needed for matching cases and controls was not extensive and was sometimes incomplete. For these reasons we could not entirely rule out the possibility that the higher incidence of fetal damage was the result of a difference between the cases and controls in some factor such as socioeconomic status.

The unfavorable outcomes were not, on the whole, associated with EHCC to a greater extent than with HCC (Table 1). However, this does not necessarily invalidate the hypothesis that unfavorable outcomes are most common at EHCC. The most common unfavorable outcome (and the one that might be expected under the most severe conditions) may well be very early, "silent" abortion, which would leave no medical record. Consequently, the indirect evidence for abortion presented in Figure 1 may give a truer idea of the locus of fetal damage than the more direct assessment.

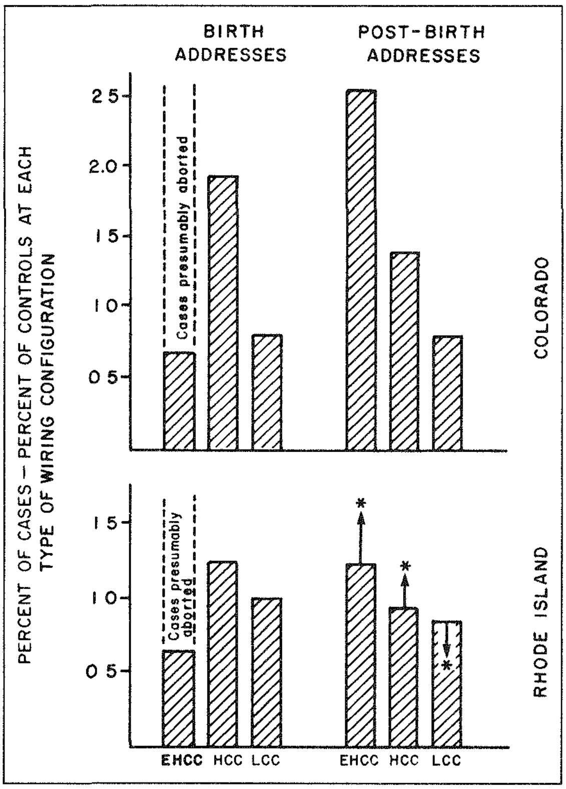

Figure 1. Ratio of Cases/Controls Residing, Before or After Birth, at Homes with Various Wiring Configurations; EHCC = Extremely High-Current Configurations, HCC = High-Current Configurations; LCC = Low-Current Configurations. Since postnatal control addresses were not collected in Rhode Island, the postnatal ratios presented here are calculated using birth-address values in the denominator. An appropriate postnatal control group would very likely have been more suburban, and so would have included more LCC at the expense of EHCC and HCC. The asterisk indicates what the ratios would have been, given a denominator with a 10% increase in LCC, at the expense, proportionately, of EHCC and HCC.

TABLE 1 Unfavorable Outcomes of Pregnancy Related to Wiring Configurations Near the Home[a]

	Congenital Malformations			Fetal Deaths			Early Postnatal Deaths			Total		
	EHCC	HCC	LCC	EHCC	HCC	LCC	EHCC	HCC	LCC	EHCC	HCC	LCC
Number of Cases	3	23	38	7	33	104	7	22	48	17	78	190
Number of Controls	0	21	43	5	23	116	7	9	61	12	53	220
Percent Cases	100	52	47	58	59	47	50	71	44	59	60	46

[a]EHCC = Extremely High Current Configurations
HCC = Other High-Current Configurations
LCC = Low-Current Configurations

Indirect Evidence Suggesting That Abortion Is Associated with Using Electrically Heated Beds

In both the Colorado and the Rhode Island studies, discussed above, evidence that susceptible fetuses exposed to HCC were sometimes aborted was stronger for males than for females. (Male cancer cases more often showed the pattern of prenatal exposure to a relatively low-current configuration, followed by a higher-current configuration at homes occupied after birth.) This suggests that susceptibility to damage from 60-Hz magnetic fields may be more common in male than in female fetuses. If males are more frequently aborted than females, a shift in the sex-ratio of the surviving liveborn population might be expected among those exposed to such fields.

Between the 1940s and the 1970s,[1] a seasonal shift in sex-ratio has occurred among United States births: Proportionately *fewer* males were recorded in the 1970s than in the 1940s for August through January births (births corresponding roughly to conceptions occurring in the six coldest months of the year, November through April). Proportionately *more* males were recorded in the 1970s than in the 1940s for births corresponding to conceptions in the six warmest months of the year, May through October (Figure 2). These differences, though slight, are extremely significant statistically ($P < 0.000001$) because of the large number of births involved.

A number of different hypotheses might explain the seasonal sex-ratio shift.[2] However, we looked for such a shift specifically because it was predicted by the hypothesis that use of electric blankets (E) and heated waterbeds (W), both of which expose their users to relatively high 60-Hz electromagnetic fields,[3] might contribute to early abortion, especially of males. The use of E and W almost certainly increased between the 1940s and the 1970s, and such usage is maximal in the cold months.

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[1] The United States Vital Statistics (U.S. Department of Health, Education, and Welfare, 1945-78) that provided our data covered only the years 1945-1949 in the 1940s, and 1970-1978 in the 1970s.

[2] The proportion of *total* births conceived in the warm months was also increased in the 1970s, compared to those in the 1940s. Although this finding supports the abortion hypothesis presented here, we have not focused on it because it might as easily be due, at least in part, to increasing use of air-conditioning over the years. Although heat can, under some conditions, have an effect on sperm that decreases male fertility (VanDemark and Free, 1970), we know of no evidence that the effect of heat on sperm affects the sex-ratio. In the data from 1945 through 1978, the highest male/female birth ratios generally correspond to late summer and fall conceptions, while low male/female ratios most commonly correspond to May conceptions. This pattern does not suggest that the M to F sex-ratio is lowered by summer heat. Furthermore, a comparison of southern and northern states in the years from 1945-1950 (when air-conditioning was less of a factor) indicated that the South showed a proportionate decrease in *total births* corresponding to summer conceptions, but did not show a decreased M to F *sex-ratio* for summer conceptions, either in comparison with those in the North or in comparison with other seasons of conception in the South.

[3] Users of E are exposed to 60-Hz fields at approximately 250 V/m (Miller, 1974) and 15 mG (Wertheimer and Leeper, 1982); heated waterbeds provide exposure at lower intensities (by our measurements, on the order of 100 V/m and 3 or 4 mG). These exposures are somewhat stronger (but more intermittent) than the exposure to be expected from power lines (Wertheimer and Leeper, 1982).

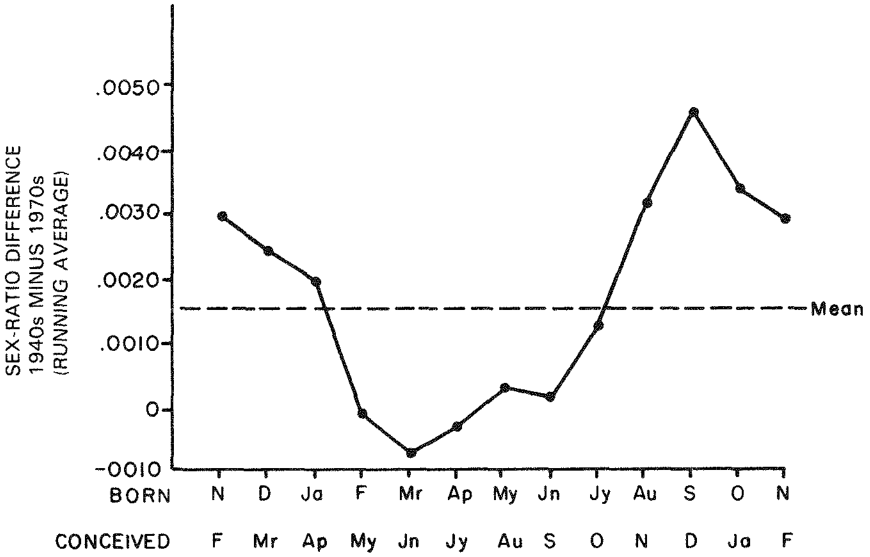

Figure 2. Seasonal Pattern of the Sex-Ratio Difference Observed Between Births in the 1940s and Births in the 1970s.

FETAL DEVELOPMENT AMONG USERS OF ELECTRICALLY HEATED BEDS

A full-scale investigation of fetal development in users and nonusers of E and W is presented here. Because patterns which could reasonably be attributed to the seasonal use of E and W were seen, but *only* among E and W users, the study strongly suggests a direct effect of E or W use on fetal development.

Procedures and Samples

Using all announcements published on births in two Denver-area hospitals over the course of one full year, we contacted each family that could be reached by telephone (approximately 70% of our sample). We asked them if (and when) they had used either E or W. After the survey was completed, data from Colorado birth records were analyzed for the 1256 announced births (index births) and also for the 528 earlier births (sibling births) that occurred for these same parents from 1976 onward, that could be located among the Colorado birth records.

Fifty-four percent (673) of these families had used E or W during the index pregnancy; 46% (583) had used neither (N); 37% (193) had used E or W during the earlier pregnancies (sibling births); 63% (335) had used neither. The population of E + W users did not differ significantly from the N group in sibling order or parental age and education, except that the N group had a modest excess of third-or-later births (17% versus 12%). Adjustments for this difference did not change the results in any important way.

Results

Gestation Time. Gestation time was calculated as extending from 2 wk after the last normal menstrual period until the date of birth. Infants of E + W users had more gestation times above the median for their sex and sibling order distribution than did those in the N group ($P < 0.05$, by X^2). This longer gestation time was seen *only* for E + W infants who were conceived in the months September through May ($P < 0.005$), when E are commonly used in our climate, and when W are generally energized for longer periods (Figure 3). The long gestations seen may reflect slow fetal growth, since infants of E + W users conceived from September through May tended to have an excess of birth weights that were low in spite of a long gestation period, and a lack of high birth weights achieved after relatively short gestations (Table 2).

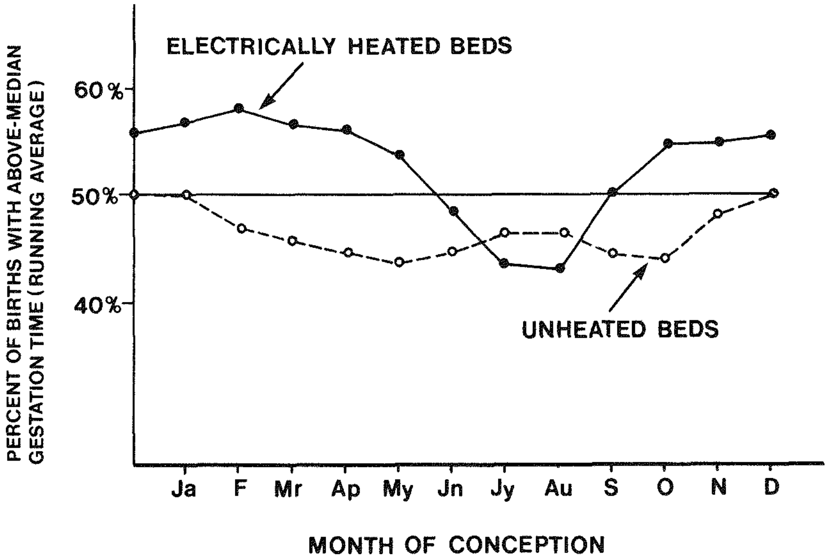

Figure 3. Seasonal Variations in Length of Gestation Time for Users and Nonusers of Electrically Heated Beds.

Favorable and Unfavorable Outcomes of Pregnancy. Because the use of official birth records to generate a sample for a telephone survey is not permitted in Colorado, our sample of index births was derived from published birth announcements. Such birth announcements are, unfortunately, ill-suited for studying most unfavorable outcomes of pregnancy, since parents of defective infants seem less likely to publish announcements than parents of healthy infants. Only three (0.2%) of the 1256 announced index births had a congenital defect reported on their birth record; six (1.1%) of the 528 infants in the sibling group, which was not limited to announced births, had such defects.

TABLE 2. Season of Conception Related to Birth Weight and Gestation Time[a]

Birth Weight: Gestation Time:	< median > median	> median > median	< median < median	> median < median
	Number of Fetuses Conceived[b]			
E + W Users[c]				
June - August	23 (17.7%)	47 (22.6%)	49 (27.2%)	36 (35%)
September - May	107 (82.3%)	161 (77.4%)	131 (72.8%)	67 (65.0%)
Nonusers				
June - August	27 (26.5%)	42 (28.6%)	43 (26.5%)	26 (23.2%)
September - May	75 (73.5%)	105 (71.4%)	119 (73.5%)	86 (76.8%)

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[a] Since birth weight and gestation time data were not independent for siblings, only index births are entered in this table. However, sibling births showed the same trends.

[b] Totals are reduced by the number of cases for which pertinent information (gestation time, birth weight) was unavailable.

[c] E = electric blanket, W = waterbeds

In the sibling sample, where defects were not selected out, a significantly higher number of congenital defects was seen in the E + W group (5 of 193 births, or 2.6%) compared with those of the N group (1 of 335 births, or 0.3%; $P < 0.05$ Fisher's Exact Test). All but one of the total of six congenitally defective fetuses in the entire E + W group was conceived in the six coldest months, November through April. In a complementary pattern, none of the 10 sets of twins born to E + W users was conceived in the six coldest months. (Viable twin births might be seen as an outcome of pregnancy that requires relatively optimal conditions to proceed normally.)

Fetal Loss. The most recent fetal loss occurring prior to a registered birth is routinely reported on the birth registration in Colorado. Such previous fetal loss appeared in the records of the index births as often as in the sibling sample. Currently, no differentiation is made between induced and spontaneous abortions. However, for a brief time in 1978, spontaneous and induced abortions were differentiated. For that period, 16% of all reported abortions that occurred in women over age 16 were induced, but only 8% of those abortions reported as occurring within the year prior to conception of a live birth were induced. Therefore, in order to maximize the probability that a reported abortion was spontaneous, we calculated fetal loss rates only for the year which immediately preceded conception of each live birth. This limitation also allows comparison of years with a reasonably similar probability of pregnancy (and a similar risk of abortion) for all families.

To maximize the number of years at risk that could be considered, we counted each year before conception of an index case or of a sibling as "at risk" of abortion. We included not only the 528 siblings born from 1976 onward which we had found among the Colorado birth records, but also the 164 siblings who were listed on index or sibling birth records as having been born since 1976 whose birth records could not be found in Colorado. (Abortions were reported as having occurred in the year preceding conception of these siblings at the same rate as for the siblings whose records were found.)

Altogether, we examined 1948 years at risk. Abortions were reported in 24 (7.5%) of the 319 years at risk when E were in use, in 28 (6.3%) of the 448 years at risk when W were in use, and in 50 (4.2%) of the 1181 years at risk when N were in use. The difference between the rates for E and N is significant by *t*-test ($P < 0.02$); the difference between the rates for W and N shows the same trend but is not statistically significant ($P = 0.10$).

It is quite possible that the differences seen here in abortion rates are the result of some artifact of our sampling procedures or some unassessed difference between the E, W, and N groups. Harder to dismiss, however, is the marked seasonal skewing of fetal loss, especially in the E users: All but one of the 24 abortions in the E group occurred between the months of September and May. This concentration of abortions differs significantly from an even seasonal distribution ($P < 0.05$, by X^2). A similar concentration in the W group was not significant. A still more significant concentration was seen for E users in the months September through January ($P < 0.005$).

When we considered all reported abortions rather than only those within 1 yr of a live-birth conception, we found the concentration of abortions in September through January to be significant for W users (59% of 54 abortions, $P < 0.02$) as well as for E users (73% of 37 abortions, $P < 0.001$). Users of unheated beds never showed a significant concentration of fetal loss in any month or series of months (Figure 4). (In this analysis we excluded only abortions that occurred before 1976, when our information on E and W use was often inadequate, and abortions that occurred to mothers aged 16 and under, which were probably largely induced.)

The importance of the period from September through January is, perhaps, that cold nights are *increasing* then (Figure 4), so at any time in this period the fetus is especially likely to be exposed to more intensive use of E or W than in the previous weeks of gestation. Such an increased exposure may be important in producing a *recognized* abortion. Strong exposure in the first weeks of pregnancy might produce only a "silent" (unrecognized) abortion. But when the exposure is increasing, week by week, a susceptible fetus may sometimes survive the earliest weeks of exposure, only to be aborted later, as the exposure increases. By then the mother will have had time to realize that she is pregnant, so the abortion will be a recognized rather than a "silent" one.

Electric Blanket Settings. The seasonal patterns seen suggest that slowed growth or, more rarely, fetal damage, may result from the use of electrically heated beds. High bed temperatures may be responsible, perhaps through the known effect of heat on sperm (VanDemark and Free, 1970). Our limited data do not, however, support the idea that the effect is due to overheated sperm: For users of electric blankets, which often have dual controls, both prolonged gestation and fetal loss appeared to be associated with the high blanket settings used by the mother, but not with those used by the father (Table 3).

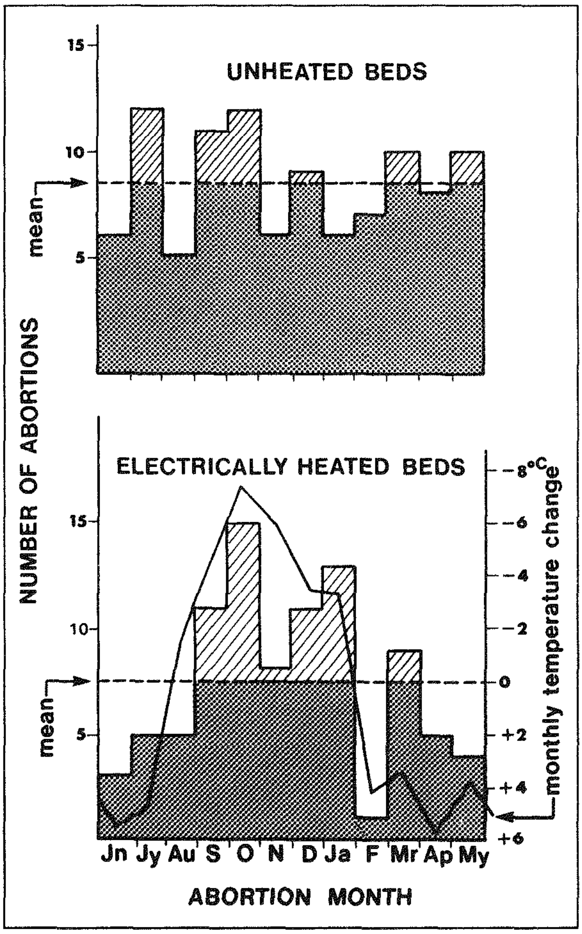

Figure 4. Monthly Incidence of Abortion Related to Monthly Change in Mean Minimum Ambient Temperature.

TABLE 3 Relationship of Individual Electric Blanket Settings Preferred by Parents to Length of Gestation and Fetal Loss

Blanket setting used		Low (0 to 2)		Medium (2 to 5)		High (5+)	
		Number Births	Percent Long Gestation	Number Births	Percent Long Gestation	Number Births	Percent Long Gestation
Percent exceeding median gestation by 1 week or more[a] (index cases)[b]	Mother's setting	87	21 8	104	28 8	48	41 7[c]
	Father's setting	115	26 1	92	33 7	32	25 0
		Years at Risk	Percent Loss	Years at Risk	Percent Loss	Years at Risk	Percent Loss
Fetal loss per year at risk[a] (total years)[b]	Mother's setting	107	5 6	126	7 9	68	10 3
	Father's setting	142	6 3	114	9 6	45	6 7

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[a] Totals are reduced by the number of cases or years at risk for which pertinent information (blanket setting, gestation time, etc) was missing

[b] The years at risk of abortion include all years preceding conception of an index case, or of a sibling, during which an electric blanket was used Since each abortion came from a different family, the risk involved in each such year can be considered independently Long gestations, on the other hand, are sometimes characteristic of a family, so only one child per family (the index child) was included in the gestation data to assure that independent data are presented

[c] The difference between the high settings and the low settings used by the mother is significant (t = 2 43, P $<$ 0 02)

Discussion

Two factors, heat and electromagnetic-field exposure, are possible causes of the patterns of fetal development seen among E and W users. Our limited data suggest that, if heat is the important factor, it operates through some effect on the mother rather than on the father. It is possible, but somewhat unlikely, that such heating would be intense enough to by-pass the body's internal regulating mechanisms and overheat the fetus directly.

The other factor, electromagnetic-field exposure, could affect the fetus directly. There is evidence that embryos normally develop electric currents that may play a role in their further development (Marx 1981). One could hypothesize that this process would work less smoothly if "foreign" eddy currents produced by external sources of an electromagnetic field were present in the fetus and surrounding tissue and fluid.

Whatever the mechanism, several recent studies suggest that exposure to electromagnetic fields at extremely low frequencies (ELF) may disturb fetal development. Exposure of miniature swine to 60-Hz electric fields during pregnancy produced equivocal results which may indicate fetal damage (Sikov et al., 1983). Similar exposure of rats, however, produced no obvious problems (Sikov et al., 1984). Chick embryos exposed to ELF pulsed magnetic fields were reported to suffer developmental damage (Delgado et al., 1982), a finding as yet unconfirmed. Nervous-system effects were seen in animals prenatally exposed to strong electric fields (Hansson, 1981; Albert et al., 1984). And the offspring of men who worked in high-voltage substations have been reported to show a higher than normal incidence of congenital disorders (Nordstrom, Birke, and Gustavsson, 1983).

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SOME FIRST STEPS TOWARD ASSESSING POSSIBLE HEALTH RISKS FROM EXPOSURE TO 50- AND 60-Hz ELECTROMAGNETIC FIELDS

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ABSTRACT

While scientific uncertainties preclude a full risk assessment of 60-Hz electromagnetic fields, it is possible to structure much of the problem and perform a set of bounding and other order-of-magnitude calculations. Approximate estimates of average per-capita exposures to 60-Hz fields from transmission lines, distribution lines and typical household sources are reported for the case of a linear "exposure metric." As a specific illustration, a framework for evaluating the experimental literature on prenatal developmental abnormalities is presented and, in this context, a preliminary assessment of much of the direct experimental literature is presented. For the special case of a linear effects function, an approach to estimating the magnitude of possible impact is illustrated. Finally, attempts to set a quantitative upper limit on the magnitude of possible impact are discussed.

The assessment of the health risk of an agent such as power line frequency electromagnetic fields involves:

- Modeling the processes by which people are exposed and estimating the exposures they receive;
- Modeling the biological effects or changes, if any, which result from those exposures and estimating their magnitude.
- Describing the processes by which people perceive and value any changes which may occur and applying those valuations to decide whether a risk exists and, if so, of what magnitude (Morgan et al., 1983).

A variety of different kinds of uncertainty can arise at each stage (Morgan, 1981). Ideally, one would like to work the problem through sequentially from exposure modeling, to effects modeling, to modeling human perception and valuation processes, at each step using the output of the previous stage as the input to the next. However, in the case of power-line-frequency electromagnetic fields, the scientific and technical uncertainties involved are still so large that, while the problem can be set up in such a sequential step-by-step way, it can not yet be worked all the way through.

In another paper we have reported our initial efforts to deal with the risk perception aspects of this problem (Morgan et al., 1984). In this paper, we use the end-point of "prenatal developmental abnormalities," just one of several possibly significant health end-points that have been suggested in the literature (Phillips, 1983), as a specific context within which to begin addressing the problems of modeling exposure and effects processes. Our focus is on setting up the problem and on identifying uncertainties. Because of these uncertainties, a complete sequential step-by-step risk assessment is not yet feasible; however, it is feasible to perform a number of parametric calculations in order to try to put some bounds on the range and types of possible risks.

We hope to complete such an analysis over the course of the coming year. In this paper, we offer some initial calculations and arguments for the purpose of illustration.

While it is not usual to present results that are as preliminary as ours at a symposium such as this, we have chosen to do so for a very specific reason. We are still feeling our way, and we need all the help we can get. We hope that the discussions that follow will stimulate both critical reactions and advice. If they do, please communicate them to us.

DEFINITIONS AND USES OF EXPOSURE METRICS

In order to estimate the exposure that people receive to some known or suspected risk-inducing agent, one must first define an "exposure metric." To be useful, this metric should be related to the resulting level of effect in some monotonic and reasonably straightforward way. For the physical agent of ionizing radiation the metric of person-Sieverts, or the more traditional metric of person-rem, meets this criterion. For many environmental chemicals the metric of milligrams of chemical ingested per kilogram of body weight meets the criterion. Not only is the effect of these agents in laboratory experiments usually found to be a monotonically increasing function of exposure, but when measured in rem or mg/kg in laboratory experiments, these exposure metrics also have intuitive appeal from a mechanistic viewpoint.

The scientific literature on 50 or 60-Hz biological effects is ambiguous both with respect to the question of whether effects of public-health significance can result from exposure and with respect to the question of how, if effects exist, their levels depend upon exposure conditions. There is, however, evidence that suggests this dependency may be rather complex (Blackman et al., 1983; Adey 1981; Byus et al., 1983; Bawin and Adey, 1976).

Figure 1 displays our current version of a taxonomy of the factors that are important in defining an exposure metric. This diagram poses three questions. First, if developmental abnormalities can be produced by field exposure, what range of field strengths are effective? Second, are all power-line-frequency fields within that range effective, or only those of specific amplitudes; that is, are there amplitude windows? Finally, is the magnitude of the effect proportional in some continuous way to the magnitude and/or duration of the exposure, or is the effect more discrete or binary in nature, switching on only after certain exposure conditions have been met? Of course, the first two questions could logically be combined into a single question, but we have kept them separate because of the public policy importance of sorting out the relative significance, if any, of exposure from power lines and exposure from other sources.

The various direct and indirect studies of possible 50 to 60-Hz induced developmental abnormalities, discussed at greater length in later portions of this paper, cast little or no light on the choices available in this diagram. Laboratory studies such as the pig (Phillips, 1983; Sikov et al., 1983) and rodent studies done at Battelle (Sikov et al., 1982; Sikov et al., 1984) studies which were conducted at single field strengths, allow no choice among alternative possible exposure metrics except to exclude or include the particular exposure conditions studied.

The demonstration or rejection of an exposure metric that involves narrow amplitude windows presents a serious challenge. Indeed, even a study like that of Graves (1983), which considered a wide range of electric field strengths between 0.1 and 100 kV/m, cannot strictly preclude narrow amplitude windows. On the other hand, the narrower such a window is assumed to be, the less likely appears the possibility that it could lead to significant problems.

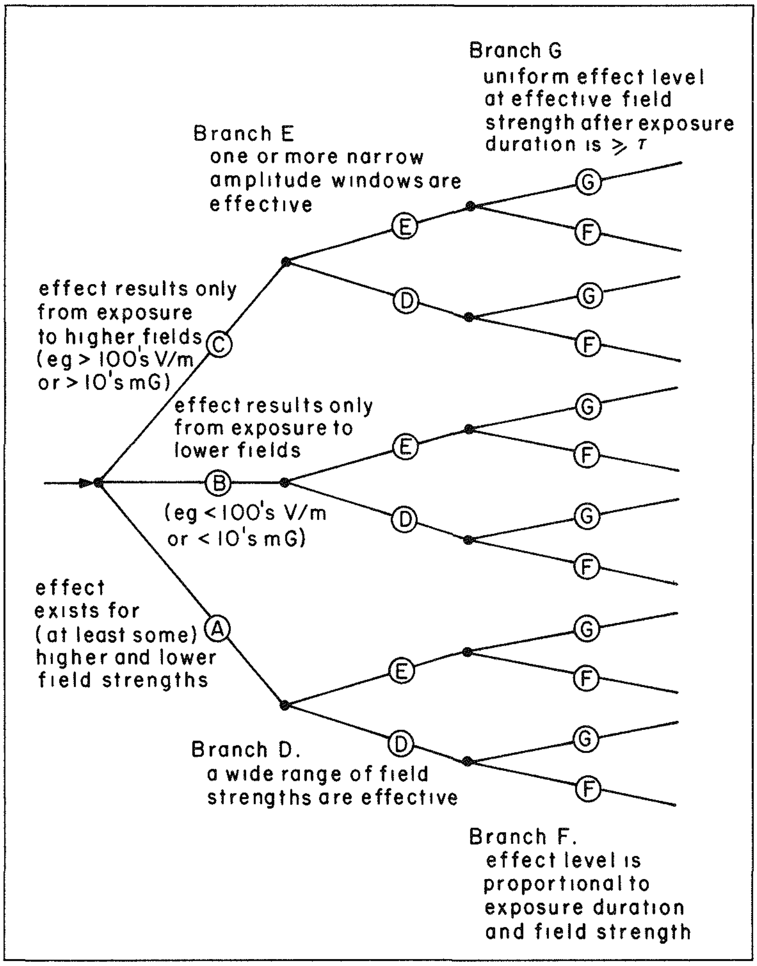

Figure 1. Taxonomy of Factors that are Important in Selecting an Appropriate Exposure Metric or Determining the Form of the Effects Function.

Despite these qualifiers, exposure estimates made with a number of possible alternative metrics can be used to explore the relative contribution to total exposure made by various sources such as transmission lines, distribution lines, and appliances. As we have previously demonstrated (Morgan et al., 1983) and illustrate below, most conclusions *one draws about exposure are very sensitive to the choice of exposure metric.* This finding emphasizes the urgency of obtaining improved scientific understanding and the danger of prematurely adopting an arbitrary exposure metric for regulatory or risk-assessment expediency.

In addition to ranking sources of exposure, one can rank the input variables of an exposure model in terms of the contribution they make to the uncertainty in the exposure estimate. Such rankings may be used to prioritize future research and data-gathering activities. One can expect these rankings of relative contribution to uncertainty to be much less sensitive to the choice of exposure metric than the exposure estimate itself.

In the paragraphs that follow we develop order-of-magnitude estimates of the distributions of the average annual, per capita, electric-field exposure produced by transmission lines, distribution lines, and sources in the home, using two linear exposure metrics, one with no threshold, and one with a 500-V/m threshold (i.e., routes A→D→F and C→D→F in Figure 1).

A QUANTITATIVE EXPOSURE ESTIMATE BASED ON A LINEAR EXPOSURE METRIC

In this example (Florig, 1984), we define electric field exposure, X_i for person i as:

$$X_i = \int u_\tau \left[E_i(t)\right] \left[E_i(t) - \tau\right] dt,$$

where $E_i(t)$ is the unperturbed or "equivalent" field strength, in V/m, to which person i is exposed, τ is the threshold value of 0 or 500 V/m, and u_τ is the unit step function that toggles at $E_i = \tau$. Per capita exposure is found by summing individual exposure and dividing by population size.

For exposure situations in which the unperturbed field is fairly uniform over the distance of a body dimension and the capacitive coupling between the body and the source is small, the unperturbed field strength is taken as the instantaneous measure of exposure. Under these circumstances, the variation of body-averaged internal currents and charge densities across most exposure situations having the same unperturbed field is a factor of only two or three. As we shall see below, this variability is small compared to the uncertainties in the exposure estimates that are contributed by other factors. The above criteria for using the unperturbed field are assumed to be satisfied for all exposures to fields from overhead lines and for exposures to sources in the home when the body-to-source distance is at least 0.5 m. For exposure situations, such as the use of electrically heated bedding, in which these criteria are not satisfied, an "equivalent" unperturbed field strength is used as the measure of instantaneous exposure. First defined by Deno (1977), the equivalent field for a particular exposure situation (such as lying under an electric blanket) is defined in terms of a standard exposure situation, which is taken to be a grounded person standing in a vertical field. The equivalent field is the field intensity in the standard exposure situation that would induce the same level of surface charge or internal current density as is induced by the exposure situation of interest.

ESTIMATING EXPOSURES FROM OVERHEAD LINES

Data are available on the lengths of transmission and distribution lines of various voltage classes operated by many utilities (Energy Information Administration, 1983; Smock, 1983), as well as on the size and population of utility service areas (Moody's Investors Service, Inc., 1983). To estimate annual per capita exposures, we assume that the exposure from the length, L_{jk}, of lines of voltage class j operated by utility k within its service area, A_k, is equivalent to the exposure that would be produced by a single line of length L_{jk} that bisects a swath of width A_k/L_{jk}. Figure 2 illustrates this geometry. To account for the fact that people do not usually live directly beneath lines, we place an exclusion zone of $\pm \varepsilon_j$ about lines of voltage class j and, in this order-of-magnitude estimate, assume for simplicity that population density is uniform outside this zone and zero within it. Annual per capita exposure (V-hr/m) produced by all J voltage classes of line operated by K utilities may then be written as:

$$X \text{ (V-hr/m)} = (8760 \text{ person-hr/yr}) \left[R_S \sum_{k=1}^{K} \rho_k \sum_{j=1}^{J} L_{jk} I_j \right] / \sum_{k=1}^{K} P_k ,$$

where R_S is the average shielding factor (ratio of shielded field strength to unshielded),

K is the number of utilities

ρ_k is the population density in utility k's service area in persons/m^2 (assumed to be uniform),

J is the number of voltage classes of line,

L_{jk} is the length of line (in structure-meters) of voltage class j operated by utility k,

I_j is the integral of the unperturbed electric-field profile (corrected for threshold) for lines of voltage class j in V-m/m, defined as

$$I_j = 2 \int_{\varepsilon_j}^{\infty} u_\tau \left[E_j(x) \right] \left[E_j(x) - \tau \right] dx,$$

where $u_\tau(E_j)$ is the unit step function that toggles at $E_j = \tau$.

P_k is the population of utility k's service area,

ε_j is the exclusion distance for lines of voltage class j,

$E_j(x)$ is the electric field profile for lines of voltage class j in V/m, and

τ is the threshold (0 or 500 V/m).

The swath width, A_k/L_{jk}, is so large, in all cases, that the contribution to the integral of the field profile from areas that lie outside the swath is less than 1%. This implies that using $+\infty$ for the upper limit of the field profile integral will not overestimate exposure within the swath.

Since there is considerable uncertainty about the values that should be attached to the shielding factor, population density, and field profile integral, these factors were described by subjective probability distributions across the range of plausible values (see the Appendix for details). These distributions were then used to stochastically estimate the average annual per capita exposure produced by the transmission and distribution lines operated by 25 utilities for which complete data were available.

Figure 3 presents a ranking of 14 voltage classes of transmission and distribution line by the upper and lower limits of estimated exposure produced by each. Also shown for comparison is a ranking of the 14 classes by the number of structures or pole miles currently in place. As one might expect, higher-voltage lines are ranked higher by exposure than by length of line. The voltage classes that produce the highest exposures are 230-, 345-, and 525-kV transmission lines, and 5 to 15-kV distribution lines. Currently, 765-kV transmission lines contribute little to average per capita exposure because the length of line in service is very short.

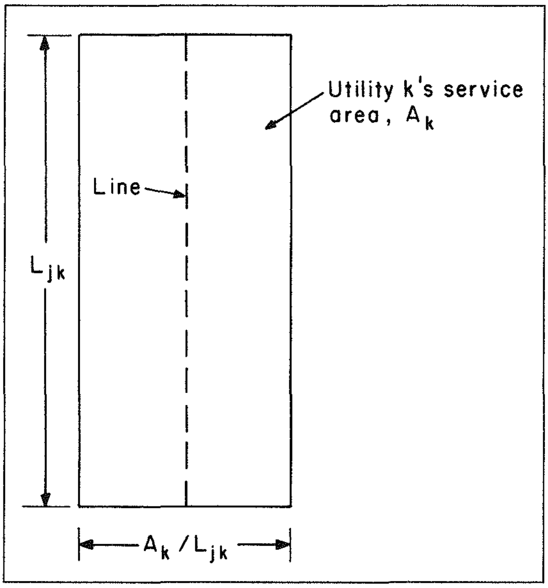

Figure 2. Geometry Used in the Order-Of-Magnitude Exposure Estimate. L_{jk} is the length of line operated by utility k at voltage j. A_k is the service area of utility k.

As mentioned above, one important reason for making exposure estimates is to rank the inputs to the exposure model by the uncertainty that they contribute to the overall result, thus providing a way to prioritize data gathering. In Table 1, we show approximately how the variance in the log of estimates of exposure from overhead lines may be apportioned among the uncertain input parameters of the exposure model. The procedure by which these numbers are derived is described elsewhere (Florig, 1984). The results show that uncertainty in the shielding factor, R_S, contributes the most to the overall uncertainty in exposure. Population distribution (ρ and ε) is the next largest contributor to exposure uncertainties. Compared to shielding factor and population distribution, the line design parameters that affect per capita exposure are fairly well known.

The line length data used for our estimates of overhead line exposure are based on structure-miles rather than on right-of-way-miles of line. Uncertainties due to shared rights-of-way are, therefore, not accounted for. Sharing probably does not amount to more than two structures per right-of-way, on average. Ignoring this factor, then, can make transmission line exposure estimates too high by a factor of two, at most. While significant, this uncertainty is smaller than those contributed by the factors listed in Table 2.

T/D	Voltage class (kV)	Ranking Decreasing effect or line length →													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
T	15													M	UL
T	25												LM	U	
T	35							M			L	U			
T	45								M	L			U		
T	69			M	L		U								
T	115				M			UL							
T	138					ULM									
T	161									U	M	L			
T	230	L			U		M								
T	345	U		L						M					
T	525		L	U								M			
T	765										U			L	M
D	5-15	M	U				L								
D	25-35		M						UL						

Figure 3. Rankings of 14 Voltage Classes of Transmission and Distribution Line by the Upper Limit (U) and Lower Limit (L) Exposure Estimate for Each, and by Miles of Line (M).

TABLE 1. *Ranking of Inputs to the Exposure Model for Overhead Lines Determined by* the Contribution made by Each Parameter to the Overall Exposure Estimate Uncertainty

Model Parameter	Variance in the log of the model parameter
Shielding factor, R_S	0.40
Population density, ρ	0.17
Population exclusion distance, ε	0.08
Line design factors that determine field profiles	0.08
Variance in log of exposure estimate	0.73

TABLE 2. Subjective Evaluation of Direct Studies of a Possible Association Between 60-Hz Electric- and Magnetic-Field Exposures and Prenatal Developmental Abnormalities. The kinds of evidence are classified into the following categories: N = no information relevant to the branch in question; C = evidence is consistent with the existence of the branch, I = evidence is not inconsistent with the branch, + = evidence argues for the existence of the branch — = evidence argues argues against the existence of the branch. We use a very bold **+** or **—** to indicate definitive evidence (in our view at the moment there is none), a bold **+** or **—** for evidence which argues for or against the existence of a branch, and a weak + or — for evidence which argues for or against the existence of a branch but which in our view is at best marginally persuasive because of problems in experimental power, design, and/or execution.

Study	Path												
	1	2	4	7	8	2	3	6	9	10	2	3	5
Direct Animal Studies with Electric Fields													
Chickens													
Graves et al. (1983)	I	I	N	N	N	I	I	N	N	N	I	I	—
Rodents													
Sikov et al. (1979, 1984)	**+**	—	—	—	—	—	—	—	—	—	—	—	—
Smith et al. (1981)	**+**	—	—	—	—	—	—	—	—	—	—	—	—
Fam (1980)	+	—	—	—	—	—	—	—	—	—	—	—	—
Cerretelli (1979)	I	I	I	—	N	I	N	N	N	N	+	N	N
Marino (1976, 1980)	—	+	C	C	C	+	+	+	+	+	+	+	+
Pigs													
Battelle Pig Studies	**—**	**+**	C	C	N	**+**	**+**	C	C	C	**+**	**+**	C
Mahmoud & Zimmerman (1984)	+	—	—	—	N	—	—	—	—	—	—	—	—
Cows													
Hennichs (1982)	I	I	—	N	—	I	—	—	—	—	I	—	—
Direct Animal Studies with Magnetic Fields													
Drosophila													
Ramirez et al. (1983)	—	+	C	C	C	+	C	N	N	N	+	C	C
Chickens													
Delgado et al. (1982)													
Ubeda (1983)[a]	**—**	**+**	N	N	N	**+**	**+**	N	N	N	**+**	**+**	**+**
Maffeo et al. (1984)[a]	I	I	N	N	N	I	I	N	N	N	I	I	—
Tell et al. (1984)[a]	I	I	N	N	N	I	I	N	N	N	I	I	—
Mild et al. (1984)[a]	—	+	N	N	N	+	+	N	N	N	+	+	+
Direct Animal Studies with Electric & Magnetic Fields													
Durfee et al. (1976)	I	I	N	N	N	I	N	N	N	N	I	—	—
Krueger et al. (1975)	I	I	—	—	—	I	N	N	N	N	I	—	—
Direct Human Studies with Electric & Magnetic Fields													
Kouwenhoven et al. (1973)	I	I	I	N	I	I	N	N	N	N	I	N	N
Knave et al. (1979)	C	I	I	N	—	I	N	N	N	N	I	N	N
Nordstrom et al. (1983)	—	+	+	N	+	+	N	N	N	N	+	N	N
Wertheimer et al. (1984)	—	+	C	C	C	+	C	C	C	C	+	C	C

[a] NOTE: These studies involved magnetic fields ($\sim$ 30 μsec rise time) and did not show an effect 60-Hz sinusoidal fields. They are thus not relevant to exposure from transmission and distribution line fields but may be relevant to occupational and residential exposures.

In the absence of many published measurements of electric-field shielding factors (Florig, 1984), we are attempting to improve our knowledge of this parameter for various exposure situations by eliciting subjective probability distributions (Wenkler, 1972; Morgan et al., 1981; Carl-Axel et al., 1979; Boyd and Gegulinski, 1979) from experts who have made such measurements. To improve our knowledge of populations in the vicinity of lines, we have made arrangements with several utilities to examine their aerial photographs and detailed maps of their transmission and distribution facilities. In this way we hope to develop better estimates of the distribution of homes around lines of various voltage classes in several different regions of the country.

ESTIMATING EXPOSURES FROM SOURCES IN THE HOME

To our knowledge, there are only two published estimates of annual electric-field exposures from household sources, both of which cite electric blankets as the greatest single contributor to household exposures. Using an effective field strength of 250 V/m for electric blanket use, Stopps and Janischewskj (1979), estimated the annual per capita exposure of Canadian high-voltage workers to electric blanket fields as 500 kV-hr/m. A worker's exposure from other household sources was estimated to be 80 kV-hr/m per year. A more recent investigation reported in the EPRI Journal (Douglas, 1984) estimates the average annual exposure of U.S. farmers to electric fields from household sources to be about 70 kV/m, over half of which is attributed to electric blankets. Neither study discusses the uncertainties associated with their exposure estimates. In this section, we estimate some upper and lower bounds on the average per capita exposures from electric bedding and other household sources.

Using a Model 111 field meter from Electric Fields Measurement Co., we measured the vertical electric-field strength at 148 uniformly spaced grid points throughout a typical residence. Each measurement point was at least 0.5 m from any object. The measurements were approximately log-normally distributed, with an average value of 4.1 to 5.5 V/m, depending on whether appliances and lights were off or on. Since much of the exposure from household sources is received when people are less than 0.5 m from the source, these measurements represent a lower bound on the fields to which people who do not use electric bedding are normally exposed. Since people spend, on average, about 15 hr per day at home (Szalai, 1972), a reasonable lower limit on annual per capita exposures from sources other than electric bedding is (4.1 V/m) (15 hr/day) (365 days/yr) = 22.4 kV-hr/m.

We place an upper limit on household exposures from sources other than electric bedding by assuming that people spend all their time at a distance of 0.5 m from a source during their time at home. Figure 4 presents electric-field profiles of several household sources that we obtained by measuring the gradient of space potential using a Model 111 field meter. These measurements indicate that 20 V/m represents a typical value for the unperturbed field at 0.5 m from a power cord, lamp, or appliance. An upper-limit estimate of annual per capita exposure from nonbedding household sources is, then, (20 V/m) (15 hr/day) (365 days/yr) = 110 kV-hr/m.

The recent epidemiological study by Wertheimer (1984) has suggested that besides electric blankets, heated water beds may represent a significant source of electric-field exposure. The Denver-area survey of electric bedding use performed by Wertheimer revealed that 65% of the study population used electrically heated bedding (27% blankets, 38% water beds). Since Denver has a relatively cool climate, and its population is fairly "modern" in its tastes, these usage fractions probably represent a reasonable upper limit on the average U.S. usage fraction.

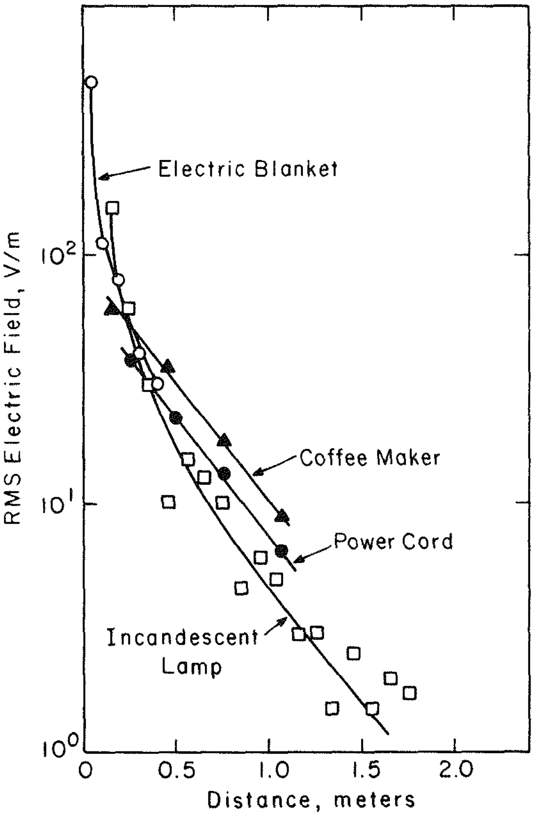

Figure 4. Electric Field Profiles of Various Household Sources Obtained by Differentiating Measurements of Space Potential Made with a Model 111 Field Meter from Electric Fields Measurement Co.

Due to large differences in source-to-body capacitive coupling, the unperturbed field should not be used as a basis to compare the magnitudes of instantaneous electric-field exposures from electric bedding with those from power lines or household sources that are electrically far from the body. Rather, various body electrical quantities should be compared directly, using the concept of "equivalent" field described earlier. Using an electrostatic image technique, in which the body is modeled as a long, ungrounded and uncharged cylinder, we estimated maximum and surface-averaged charge densities and cross-section-averaged current densities associated with the use of electric blankets and heated water beds. Results for electric blankets indicate that, depending on blanket design and the distance of blanket conductors from the body, maximum fields on the body surface range from 500 V/m to 3000 V/m, surface-averaged fields lie in the range 250-450 V/m, and perpendicular current densities averaged across the sagittal and frontal midplanes are, respectively, tens and hundreds of pA/cm^2. Calculations for an ungrounded person lying on an electrically heated water bed produced ranges of field intensities and current densities that are generally smaller than those estimated for electric blankets. Depending on the electrical quantity used for comparison, the ranges of surface fields and current densities calculated for electric-blanket exposure are comparable to those induced in a person who is standing grounded in an unperturbed vertical field of between 1 and 1000 V/m.

Silva (1984, personal communication) has measured the surface fields on the thorax and the total current crossing the neck and waist in the axial direction of a conducting manikin under an electric blanket. They found equivalent fields, based on maximum thorax surface charge averaged over a probe of 10 to 20 cm, to be about 320 V/m. Equivalent fields based on *axial* current density in the neck and waist were found to be 50 V/m and 40 V/m, respectively.

To bound the per capita annual exposure from electric bedding, we assumed that the appropriate value of equivalent field exposure lies in the range 50 to 500 V/m. We further assume that 10 to 65% of the population uses electric bedding for 8 hr per night for 30 to 150 nights per year. With these assumptions, one obtains a 95% confidence interval for per capita annual exposure from electric bedding of 8.1 to 230 kV-hr/m.

Figure 5 summarizes the results of the order-of-magnitude estimates of average per capita electric field exposures from all overhead lines and from domestic sources, using a linear exposure metric. The following qualifying statements should be noted.

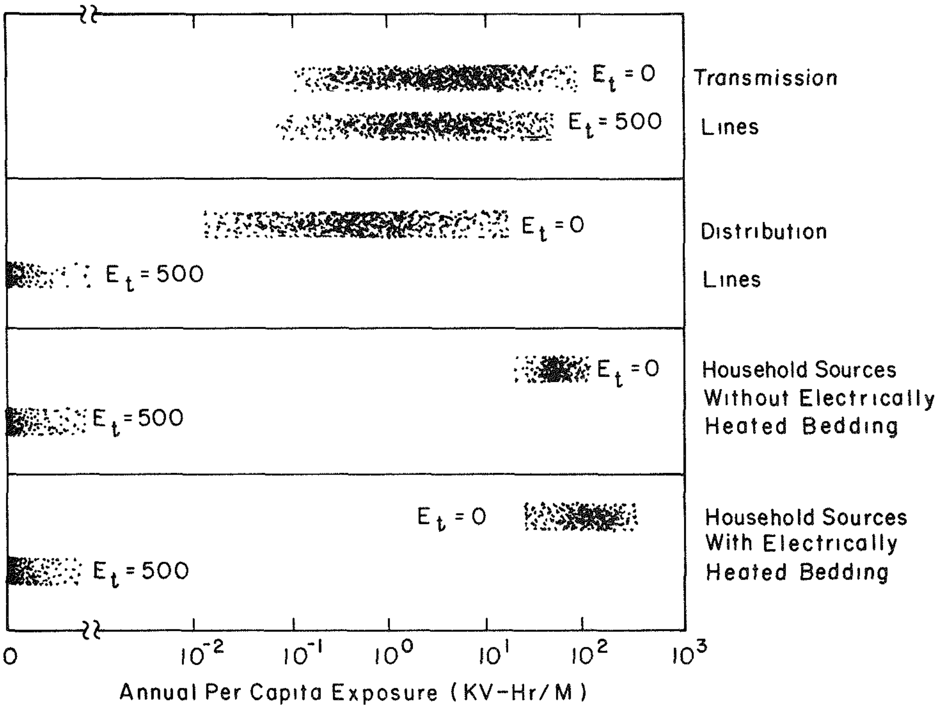

Figure 5. Estimates of Per Capita Annual Exposures to 60-Hz Electric Fields for Linear Exposure Measures with Thresholds of 0 and 500 V/m.

1. Under a linear, no-threshold exposure metric, average annual per capita electric-field exposures from household sources seem to exceed those from overhead lines, particularly if a reasonable level of electric bedding use is assumed. Note that this may not be the case for some persons working or living along high-voltage transmission line rights-of-way.

2. Under a linear, no-threshold exposure metric, per capita electric-field exposures from transmission and distribution lines are roughly equal.

3. As one would expect, exposures from distribution lines and household sources drop to near-zero with the introduction of a 500-V/m threshold. Transmission-line per capita exposures decrease very little by comparison.

4. The uncertainties in the exposure estimates for overhead lines (i.e., 95% confidence intervals that span three to four orders of magnitude) are much greater than the uncertainties in the exposure estimates for household sources.

A FRAMEWORK FOR CONSIDERING EFFECTS PROCESSES

We now leave exposure processes to move on to a consideration of effects processes. Before examining specific experimental results that either directly or indirectly provide evidence related to the possible public-health end-point of developmental abnormalities, we must first construct a framework that will allow us to sort and evaluate the evidence in terms of the various alternative causal routes through which this end-point might be reached.

We began by enumerating the known routes by which developmental abnormalities can arise. These include effects that are:

1. **Inherited.** The problem may already be present as an abnormal gene that either parent inherited (this is the case, for example, in phenylketonuria [PKU], hemophilia, or sickle-cell anemia), or it may be inherited extrachromosomally via the cytoplasm (for example, one of the many factors involved in spina bifida and anencephaly (Elwood and Elwood, 1980).

2. **Germinal.** The problem may arise from an insult that damages the chromosomes of the germ cell of either parent prior to or during fertilization. The aging of spermatozoa or ova, for example, is considered to be one cause of aneuploidy, or irregular number of chromosomes in the fertilized egg, leading to such syndromes as Down's (Trisomy 21). As another example, mutations caused by ingestion of LSD in the male parent can be reflected in the genes of the offspring (Bora et al., 1982), although it is not known whether such mutations lead to any specific developmental defect. It is conceivable that cytoplasmic factors might also be affected in this way.

3. **Transplacental.** An agent may reach the fetus by crossing the placenta in its original form (e.g., tetracycline; analogs of amino acids) or as a more reactive intermediate, causing injury to the fetus (Juchau, 1981). Alternatively, its presence might change placental properties such as reaction or diffusion rates and injure the fetus by affecting critical nutrient or metabolite levels. An example is the blockage of vitamin B_{12} by cadmium or mercury that accumulates in the placenta (Snell, 1982).

Another cause of transplacental injury to the fetus is a change in maternal metabolism. For example, teratogenesis in rats, caused by administration of salicylates and trypan blue, was shown to arise through the agents' effect on the maternal system rather than by direct embyronic cytotoxicity (Goldman and Yakovac, 1963). Some autosomal recessive disorders are known to be correlated with maternal blood levels of specific chemicals (e.g., PKU incidence is correlated with phenylalanine blood levels), and electric-field exposure might modify the maternal metabolism.

4. **Direct.** An agent (e.g., radiation) may cause a somatic injury or a genetic chromosomal injury to the fetus or may affect its metabolism or development directly. Physical agents, such as radiation, fields, and thermal shocks, in particular, are candidates for such direct action.

Of these four routes, the last three are probably more relevant to power-line-frequency electromagnetic fields, but the first cannot be completely excluded. Consideration of these routes, together with other factors, leads rather naturally to Figure 6, which displays the current version of our taxonomy of the pathways by which exposure to 50- or 60-Hz electric and magnetic fields might lead to developmental abnormalities. The tree structure in this figure and in Figure 1 should not be confused with decision trees. In a conventional decision tree, the branches at each node display mutually exclusive outcomes or possibilities; most of the nodes in these trees are not mutually exclusive.

In considering a piece of experimental evidence with the taxonomy of Figure 6 we first ask if the evidence casts light on the question of whether field exposure can give rise to developmental abnormalities: that is, whether it provides evidence on branches 1 or 2 in Figure 6. The fact that an experiment is negative is not sufficient to lend positive evidence for branch 1. While a negative finding is consistent with branch 1, it must exclude branches 3 and 4 (and, strictly speaking, also the less likely branch 4a), before it argues positively for branch one. If the evidence is at least consistent with branch 2, we then move on to ask what, if anything, it suggests about branches 3 through 10. For convenience, we classify the kinds of evidence into several simple categories: N = no information relevant to the branch in question; C = evidence is consistent with the existence of the branch; $\overline{I}$ = evidence is not inconsistent with the branch; + = evidence argues for the existence of branch; and - = evidence argues against the existence of the branch. In our view, at the moment, there is no definitive evidence; therefore, a bold + or - indicates evidence which (despite questions of experimental power and/or design) we believe seriously argues for or against the existence of a branch; and a weak + or - represents evidence which argues for or against a branch but which, in our view, is (at best) marginally persuasive because of problems in experimental power, design, and/or execution.

Note that branches 3 and 4 define the critical exposure time period, and branches 5, 6, 7 and 8 define the critical individual or exposure location. At the end of each chain of branches the question is also implicit whether the field is itself sufficient to produce the effect, or whether it potentiates or acts synergistically with some other factor(s). Since, at the moment, there is almost no evidence available on this issue, we have left it out of the framework to keep the diagrams and tables a little simpler.

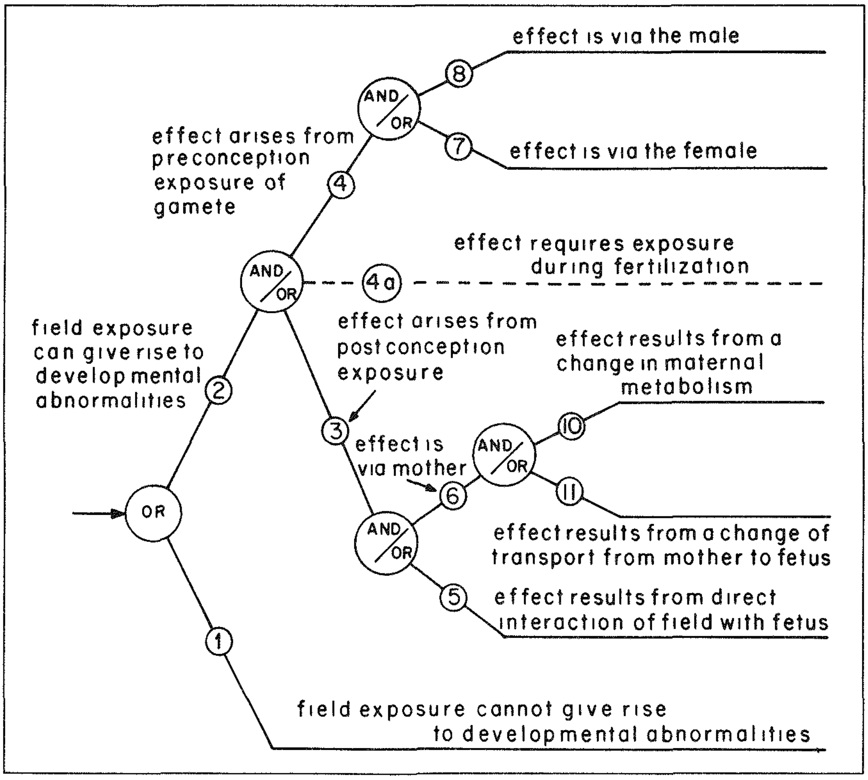

Figure 6. Taxonomy of Pathways by Which Exposure to 50/60-Hz Electric and Magnetic Fields Might Lead to Developmental Abnormalities.

Table 2 provides our preset subjective evaluation of a number of the direct studies of a possible association between 50- or 60-Hz electric and magnetic fields and developmental abnormalities. We welcome readers' critical comments on the basic structure of the taxonomy, changes they believe should be made in our evaluations, and additional studies that should be included.

We are trying to evaluate the indirect evidence for teratogenic potential in a parallel fashion. Ideally, *in vitro* screening tests would look for effects of extremely low-frequency (ELF) fields on processes important in differentiation and morphogenesis. Moscone (Wilson, 1978) has suggested that in evaluating an agent that may potentially produce developmental abnormalities, one should look at evidence on cleavage of the egg, muscle differentiation, innervation, morphologic cell aggregation, tissue interactions and hormonal interactions. We are re-examining the available cellular- and tissue-level ELF experimental evidence, asking what, if anything, this literature suggests with respect to each of these categories. We have only recently begun this effort and are not yet persuaded that we are on the right track. No matter how we ultimately deal with the indirect evidence, we hope to enlist the assistance of a number of active biological investigators in guiding and reviewing our work. In particular, alteration of nucleic acid synthesis rates, of differentiation schedules, or of protein synthesis and other biochemical rates caused by electric and magnetic fields must be examined for their potential to affect prenatal development. Any advice or suggestions that readers may have on how we should proceed would be greatly appreciated.

If, at some stage, we are able to persuasively argue that routes other than branch 1 (in Figure 6) exist, this will not necessarily imply a significant public health problem. If fields produce development-related effects, these effects may be so far "down in the noise" of other environmental influences on development that, in terms of public health, they are inconsequential. If effects exist and are significant, identifying the operating route(s) by means of Figure 6 would not, in itself, provide us with sufficient knowledge to develop an appropriate strategy for risk management. For that, we must attach the framework of Figure 1 to the tip of each of the final branches of Figure 6, then deal with the question of how the magnitude of the final effect is related to the magnitude of the exposure or dose. Clearly, we are far from being able to perform such a general calculation for all the possible routes through these frameworks. In the section that follows we illustrate how some first steps can be taken in this direction for the single, simple case of a linear exposure metric and a linear-effects function.

QUANTITATIVE ASSESSMENT OF POSSIBLE PUBLIC HEALTH IMPACT

Suppose one has a particular set of experimental evidence, such as the swine study done at Battelle (Phillips, 1983), the Nordström et al. substation workers study done in Sweden (Nordström, 1983), or the electric blanket and waterbed study done by Wertheimer (1984). If, for a moment, we set aside all the serious questions about the meaning of these studies and, for the sake of argument, accept them as indicating the existence of field-related developmental abnormalities, how far could we get in an attempt to extrapolate from these results to an assessment of public-health impact?

Despite the various problems in exposure assessment that we discussed above, it is clear that the biggest stumbling block arises in making our way through the taxonomy of Figure 1. None of the direct studies of possible developmental abnormalities allows one to exercise much discrimination in trimming possible routes out of this tree. In principle, this should not be a problem. One can merely perform a separate assessment for each route through tree. Of course, one doesn't know any of the necessary coefficients but, in principle, that, too, should not be a problem. One can simply perform the assessment parametrically over a wide range of parameter values. For the routes A→D→F and C→D→F in Figure 1 that correspond to a linear-effects function, with or without threshold, this strategy is feasible. However, for routes in Figure 1 that correspond to effects functions that are windowed or "switched," we have so far been unable to figure out how to perform a reasonable parametric assessment. In these cases, the number of undetermined parameters is so high that one or two experimental values are of little or no help in reducing the complexity. For example, in the case of a windowed effects function we need to know the center of location, the amplitude, and the shape and width of each window. A single data point provides virtually no leverage on the problem since one doesn't known where in the window it falls (e.g., near the minimum or maximum), whether there are other windows and, if there are, how the amplitude, width and other parameters of these windows relate to the one measured valued in the observed window. If such complicated effects functions are indeed serious contenders, and our reading of the literature to date has not provided us with an adequate argument to discount them, then risk assessments of the 50- or 60-Hz field problem face a set of very difficult methodological issues that have not been seriously addressed in the literature.

However, in the case of a linear-effects function (routes A→D→F and C→D→F), even a single experimental value reduces parameter uncertainty enough to allow some simple impact assessments to be performed. Our work is not yet at the stage where we can produce results that we consider adequate. However, to illustrate what we have in mind, we have performed a rough calculation. Since our exposure modeling work has not yet provided the kinds of exposure estimates that such a calculation will require, we have used our judgment and our familiarity with the experimental literature to construct some hypothetical exposure estimates (Table 3) for use in this illustration. For this simple illustration, no description of the uncertainty in exposure has been included.

TABLE 3. Histograms of Average Per Capita 60-Hz Electric-field Exposure Used in the Rough Calculation Described in the Text, the Results of Which are Shown in Figure 8. These numbers are estimates constructed for illustrative purposes.

	Fraction of Time at Each Field Strength			
Field Strength, V/m	At Home	From Distribution Lines	From All Transmission Lines	Person Living Near 345-kV Line
10	0.845	0.993	0.991	0.92
10 - 50	0.130	6×10^{-3}	5.6×10^{-3}	0.07
50 - 100	0.010	1×10^{-3}	2×10^{-3}	4×10^{-3}
100 - 500	0.015	4×10^{-4}	9×10^{-4}	8×10^{-4}
$2.5 - 2 \times 10^{3}$			4×10^{-5}	4×10^{-4}
$2 - 5 \times 10^{3}$			1.8×10^{-5}	2×10^{-4}
$5 - 10 \times 10^{3}$			3.6×10^{-6}	10^{-4}
10^{3}			1.7×10^{-7}	0

If we have a single experimental observation of effect level, obtained under conditions of continuous exposure at a given field strength, we can postulate a range of alternative linear effects functions, as illustrated in Figure 7. Since we are considering the routes A→D→F and C→D→F through the taxonomy of Figure 1, an estimate of dose under circumstances of exposure to various field strengths is given by:

$$\sum_{n} \alpha_n F_n$$

where α_n is the fraction of time spent in field strength F_n and n is the number of different field strengths encountered.

Of course, the circumstances of the experimental exposure may differ from the exposure of interest in a variety of other important ways. For this reason we define a scaling factor:

$$S = \frac{H \cdot R_a \cdot O}{F \cdot R_f}, \quad \text{in which}$$

H = the background human incidence rate in developmental abnormalities per live birth,

R_a = the relative sensitivity of man with respect to the animal test species,

O = $(I_o - I_b)/I_b$ (where I_o is the observed incidence rate and I_b is the background incidence rate in the study population),

F = the experimental field strength in V/m corrected by the experimental shielding factor, and

R_f = the man/animal equivalent field ratio

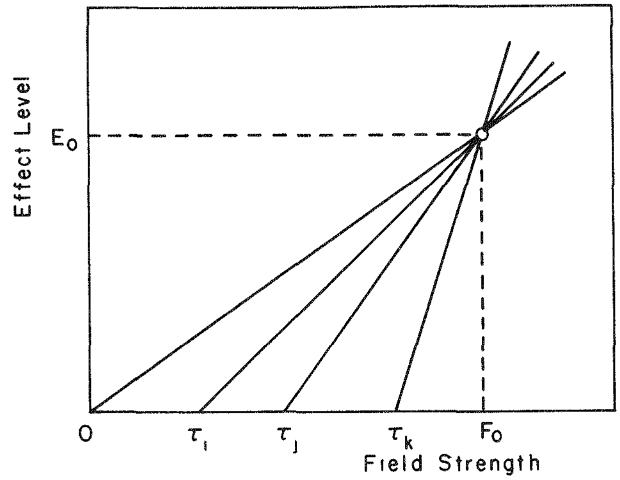

Figure 7 Illustration of a Range of Linear-Effects Functions with Varying Threshold, Given a Single Experimental Observation of an Effect Level E_0 at Exposure Level F_0

Using the hypothetical dose estimates of Table 1 and this definition of scaling factor, the resulting assessment of the incremental incidence rate of developmental abnormalities was calculated and is shown in Figure 8

Before we illustrate how to use this result by inserting some specific numbers we must stress that it is valid

1. only to the extent that there is evidence for a route other than route 1 through the taxonomy of Figure 6 (at the moment this remains arguable) and
2. only if route A→D→F or C→D→F through the taxonomy of Figure 1 is shown to be the sole operating route (at the moment there is no persuasive evidence for this limitation)

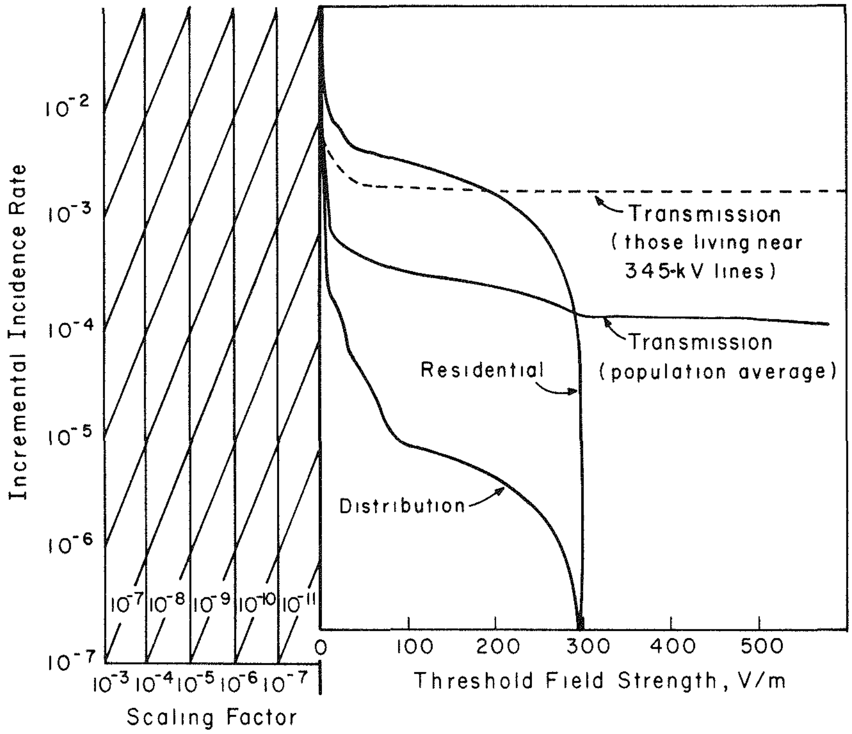

Figure 8. Illustrative Results of an Estimate of the Incremental Contribution to the Incidence of Developmental Abnormalities as a Function of Threshold Field Strength that Would Result if One Believed the Results of an Experimental Finding with Scale Factor S (See Text) and Used a Linear-Effects Function. Values should be taken as approximate.

To set the vertical scale on Figure 8, compute the value of S, then construct a vertical line up from that value. The vertical scale is set by the values of the intersecting diagonal lines. For example, if $S = 10^{-6}$ we see that the residential and total population transmission curves intersect at an incremental incidence rate of 1.4×10^{-7}, whereas if $S = 1.5 \times 10^{-5}$, they intersect at 10^{-5}.

Since this paper is being presented at Hanford, it seems appropriate to illustrate the use of Figure 8 with data from the Battelle pig study (Phillips, 1983). Given the considerable uncertainties that are involved, we are reluctant, even for the purposes of illustration, to plug single "best-estimate" values into the relation for the scaling factor. Instead, we have constructed what we believe are some plausible, subjective, probability density functions to describe each of the necessary coefficients. These, along with the resulting distribution in scaling factor, are displayed in Figure 9. In this illustration, the mean value of S is about 1.4×10^{-6}; with 90% probability, 1.5×10^{-8} $S = 4.5 \times 10^{-5}$. In an actual application of this technique, one would want to properly account for uncertainty in exposure, and in estimating S one would probably want to use distribution carefully elicited from appropriate experts (Winkler, 1972; Morgan et al., 1981; Carl-Axel et al., 1979; Boyd and Gegulinski, 1979).

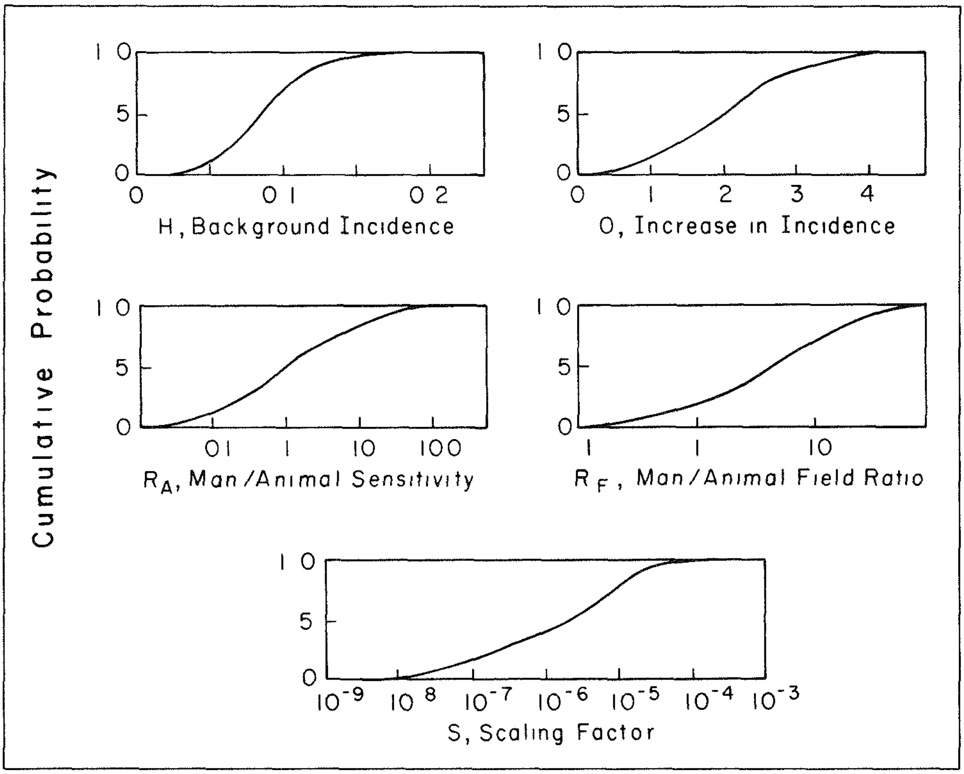

Figure 9 Distributions of H, R_a, O, and R_f Used to Evaluate S (Lowest Graph) to Illustrate the Use of Figure 9 for the Data of the Battelle Pig Study Values are approximate and are provided only for illustration

INDIRECT BOUNDING ARGUMENTS

In addition to bounding the possible effects of power-line-frequency field exposures by working directly through an estimate of exposure and effects processes, it may also be possible to set some limits on the range of such effects (if, indeed, any exist) by considering various lines of indirect evidence For this reason we have undertaken a review of the statistical literature on human developmental abnormalities, including a rather detailed look at the available large data bases

The basic question is simple. If there were public-health impacts on the rate of developmental abnormalities arising from public exposure to power-line-frequency electric and magnetic fields, how big might they be? We'd like to be able to construct as tight an argument as we can for an upper bound.

We know the answer could not be as high as 65 to 70%. Wilson (1973), and others, have estimated that 30 to 55% of developmental abnormalities observed can be attributed in the following ways·

Known genetic transmission and chromosomal aberrations	23 to 25%
Radiations	1%
Infections	2 to 3%
Maternal metabolic imbalance	1 to 2%
Drugs and chemicals	2 to 3%
Potentiative interactions	?
Unknown	65 to 70%

Since many agents are suspected teratogens, and there are likely to be many more not yet suspected, it seems most improbable that all the unexplained events can be attributed to a single source, such as electric-field exposure. On the other hand, it is not implausible that a single source might explain 20 to 30% of the unexplained incidence, especially if the source is ubiquitous and does not lead to a single syndrome but rather increases the incidence rates of several classes of defects.

There is some ambiguity in assessing the background rate of occurrence of human developmental abnormalities in live births. Retrospective studies, usually based on birth certificates, produce estimates of 1 to 3% (Stewart et al., 1969; Shapiro et al., 1958; Woolf et al., 1968). Prospective studies have yielded estimates of major defects on the order of 7 to 9% (Bergsma, 1975; Mild et al., 1984, personal communication; Stewart et al., 1969). Studies that include follow-up exams for 1 yr after birth have shown that only approximately 40% of abnormalities are detected at birth (Bergsma, 1975; Mild et al., 1984, personal communication). Variations of these estimates depend on the classes of abnormalities included; the rates quoted above are for significant abnormalities. Studies that include minor abnormalities (e.g., unusual skin folds) report incidence rates on the order of 15 to 18% (Bergsma, 1975; Harris and Steinberg, 1954).

Unlike birth and death rates, developmental abnormalities are not demographically reported (e.g., by county). Good time-series data on incidence rates are also not available.

One might try to set a bound by comparing populations that have different levels of electric-field exposure (e.g., compare the Amish with other residents of central Pennsylvania). We are looking for data sets that might provide such evidence, but because of the limitations in the data outlined above, we think it is unlikely we will succeed.

We have made order-of-magnitude evaluations about how much higher incidence rates would have to be in small populations living along transmission lines in order to be detected by those populations. These assessments suggest that increases in total incidence rates of as much as a factor of three might go undetected by the general population. The only general health study of the populations living around transmission facilities is the work reported by Strumza (1970). It is not clear whether he would have seen an increased incidence of developmental abnormalities if it had existed; his paper makes no mention of this issue.

To put it bluntly, we are stuck. We can construct a persuasive, though still probabilistic, argument that if electric-field exposures give rise to developmental abnormalities in people they cannot be contributing more than several tens of percent of the presently observed incidence. We hope that we will be able to figure out how to set a tighter upper bound.

CONCLUSIONS AND A WORD OF CAUTION

While it is not yet possible to perform a complete risk assessment of 50- or 60-Hz electromagnetic fields that works sequentially through the problem from exposure to effects process, it is now possible to structure much of the risk assessment problem and to perform bounding and other order-of-magnitude calculations on various parts of the problem. In this paper, using the specific possible health end-point of prenatal developmental abnormalities, we have provided some initial illustrations of the kinds of things that can now be done.

While analysis of the type illustrated in this paper cannot resolve fundamental scientific uncertainties, we believe that once it has been refined it can help concerned parties to understand the implications of currently available science. They can then make full and effective use of this science, both in considering possible alternative risk-management strategies and in setting future research priorities.

Our purpose in preparing this paper has been to illustrate, as concretely as possible, the various analytical approaches on which we are now working. We hope that this will stimulate readers to provide us with advice and suggestions on how we should, and should not, proceed.

Readers are warned that the quantitative results presented in this paper are primarily for illustration. While we believe the numbers used are plausible, many will be substantially refined as our work progresses and should not, at this stage, be used in any major way as an input to regulatory or other policy-making decisions.

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APPENDIX: SETTING BOUNDS ON UNCERTAINTY IN THE VALUE OF THE SHIELDING FACTOR, POPULATION DENSITY AND FIELD PROFILE FOR USE IN EXPOSURE ESTIMATES

In order to perform the order-of-magnitude exposure estimates reported in this paper, subjective probability distributions were constructed to describe our uncertainty about the values of the shielding factor, population density, and field profile integral The form of these distributions is described in this appendix

Upper and lower bounds on average shielding factor were chosen as 1 0 (completely unshielded) and 0 003, the lowest value reported in the literature for a house (Jacobs and Dietrich, 1984) A log-uniform distribution was assigned for the purpose of this illustrative calculation

Upper and lower bounds were placed on the population density within each utility's service area, using the values for the two counties within the service area that had the highest and lowest population densities These were identified by comparing maps of utility service areas (Moody, 1983) with maps of county-by-county population density, as computed by the 1980 census (Infomap, 1980) For most of the 25 utilities used in our calculations, upper- and lower-bound population densities identified in this way differed by at least one order of magnitude A log-uniform distribution was assigned to each of the 25 ρ_k

Upper and lower bounds were placed on the integral of electric-field profile, I_j, for the jth voltage class by assigning the same line design to all lines of that voltage class where the design was chosen to either maximize or minimize the profile integral within the constraints of existing line design parameters Tables A1 and A2 list the range of line heights, conductor spacings, and conductor diameters used on existing transmission and distribution lines (Project UHV and Transmission Engineering, General Electric Company, 1982; American National Standards Institute, 1977; Electrical Transmission and Distribution Reference Book, 1964). The design parameters that extremize the profile integral were chosen from these ranges. The integral of field profile depends on the exclusion distance, ε, as well as on the line design. For the upper-bound profile integral, the exclusion distance was set to zero (i.e., uniform population everywhere, even under the line). For the lower-bound profile integral for high-voltage transmission lines, the exclusion distance, ε, was taken to be the half-width of the right-of-way since, for these lines, construction is prohibited in this region. Lower-voltage transmission and distribution lines, however, do not require cleared corridors. For the lowest-voltage distribution lines, setting $\varepsilon = 10$ m is certainly conservative with respect to a lower-limit estimate of exposure. That is, one can be fairly sure that many homes lie within 10 m of these lines. A least-squares fit to $\varepsilon = 10$ m for 5-kV lines, and to data on typical right-of-way half-widths for a number of higher-voltage lines (Commonwealth Associates, Inc., 1979; Chas. T. Main, Inc., 1982; Rusch, 1979) gives the following expression for the low-exposure limit width of the exclusion zone:

$$\varepsilon\,(\text{meters}) = 9.9 + (3.9 \times 10^{-5})\ (\text{line potential in volts})$$

Upper and lower bounds on the profile integral obtained as described above are shown in Table A3. We used a uniform distribution across this range.

Further details on this order-of-magnitude calculation of exposure are available elsewhere (Florig, 1984).

TABLE A1. Ranges of Transmission Line Design Parameters by Voltage Class

Voltage (kV)	Minimum Height (m)	Maximum Height (m)	Minimum Phase Space (m)	Maximum Phase Space (m)	Minimum Conductor Diameter (cm)	Maximum Conductor Diameter (cm)
15.0	4.572	18.5[a]	0.357	3.0[a]	0.0105[a]	0.0161[a]
25.0	5.182	18.5[a]	0.470	3.0[a]	0.0105[a]	0.0161[a]
35.0	5.182	18.5[a]	0.567	3.0[a]	0.0105[a]	0.0161[a]
45.0	5.182	18.5[a]	0.674	4.0[a]	0.0105	0.0185
69.0	5.375	18.5[a]	2.44	5.79	0.0105	0.0185
115.0	5.842	18.5	3.47	6.69	0.0135	0.0185
138.0	6.08	22.5	3.77	7.29	0.0147	0.0198
161.0	6.31	23.5[a]	4.53	7.60	0.0147	0.0198
230.0	7.30	25.8	5.23	9.42	0.0203	0.0318
345.0	7.62	26.7	6.10	10.67	0.0447	0.2057
525.0	9.08	31.4	8.53	12.80	0.1929	0.3240
765.0	12.2	39.3	11.99	15.24	0.4229	0.5681

[a] Subjective estimate; no data available.

TABLE A2. Ranges of Distribution Line Design Parameters by Voltage Class

	Voltage Class	
Design Parameter	5 - 15 kV	25 - 35 kV
Max primary height (m)	18.5[a]	18.5[a]
Min secondary height (m)	4.6	4.6
Min prim/second spacing (m)	2.0[a]	3.0[a]
Min phase/phase spacing (m)	0.41	0.61
Max phase/phase spacing (m)	3.0[a]	3.0[a]
Min conductor diameter (cm)	1.05[a]	1.05[a]
Max conductor diameter (cm)	1.61[a]	1.61[a]

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[a] Subjective estimate based on extrapolation from transmission line data and on observations of distribution lines in the Pittsburgh area.

TABLE A3. Upper and Lower Limits on the Integral of Electric-field Profile for 14 Voltage Classes of Transmission (T) and Distribution Line (D)

T/D	Voltage Class (kV)	Upper Limit of Electric-Field Profile (V-m/m)	Lower Limit of Electric-Field Profile (V-m/m)
T	15	6180.0	386.0
T	25	9090.0	634.0
T	35	12700.0	890.0
T	45	20300.0	1220.0
T	69	40000.0	2780.0
T	115	68500.0	5560.0
T	138	85000.0	6540.0
T	161	98600.0	8180.0
T	230	154000.0	12100.0
T	345	340000.0	20300.0
T	525	549000.0	40900.0
T	765	786000.0	69600.0
D	5-15	6010.0	102.0
D	25-35	14000.0	578.0

GUIDANCE ON ACCEPTABLE LIMITS OF EXPOSURE DURING NUCLEAR MAGNETIC RESONANCE CLINICAL IMAGING

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ABSTRACT

During nuclear Magnetic Resonance (NMR) clinical imaging, individuals being scanned and staff operating equipment are exposed simultaneously to three types of magnetic field: static magnetic fields, time-varying magnetic fields, and radiofrequency magnetic fields. Patient exposure may last for up to 45 min and may be repeated. Volunteers may be exposed more regularly. Staff operating the equipment are intermittently exposed to weaker fields in the vicinity of the imaging equipment. Several thousand patients and volunteers have now been exposed without incident, and there have been no reports of adverse effects attributable to NMR imaging. However, these observations were confined to clinically recognizable early effects. The National Radiological Protection Board (NRPB), with the help of an advisory group, has formulated recommendations on the conditions to be fulfilled during the operation of NMR clinical imaging equipment in the UK. The biological basis for these recommendations will be discussed.

During nuclear magnetic resonance (NMR) clinical imaging, individuals being scanned are exposed to three types of magnetic field simultaneously; static magnetic fields, time-varying magnetic fields, and radiofrequency magnetic fields. Patient exposures may last for up to 45 min and may be repeated. Volunteers may be exposed more regularly. In addition, staff operating the equipment are intermittently exposed to the weaker fields that are present in the vicinity of the imaging equipment. Guidelines (NRPB, 1981) for limiting exposure conditions in the UK were proposed by an NRPB advisory group in 1981, when the first machines were being developed or tested. In this early period, careful monitoring of volunteers revealed no adverse effects. Several thousand patients and volunteers have now been exposed without incident and there have been no reports of adverse effects attributable to NMR imaging. It is stressed, nevertheless, that observations are confined to clinically recognizable early effects. In view of this and later experience, and on further consideration of the biological basis of the limits on exposure to the magnetic fields (discussed below), the advisory group recommended a revision (NRPB, 1983) of the original guidelines. These guidelines are endorsed by NRPB and published in their Advice on Standards for Protection (ASP) series (NRPB, 1984).

STATIC MAGNETIC FIELD EFFECTS

The evidence of effects at the molecular, cellular, tissue and intact-animal level of organization is contradictory, due in part to results from poorly designed experiments.

In a well-designed experiment at the Pacific Northwest Laboratory (Kelman et al., 1983), it was concluded that spermatogenesis, fertilization and prenatal development in mice were not adversely affected in field strengths of 1 T (1 T = 10^4 gauss). Furthermore, continuous exposure for up to about 600 days did not adversely affect weight gain, hematological and biochemical profiles, mortality rate, or tumor incidence and type when compared with these measures in sham-exposed controls. More detailed investigations are planned in this continuing experiment.

In support of these findings, there was no evidence of unusual chromosome damage or gene mutation in cultured human or mammalian cells exposed to 1 T (Cooke and Morris, 1981; Schwartz and Crooks, 1982); or of abnormal hematology in male Swiss mice exposed to 1 T for up to 25 days (Eiselein, Boutell and Biggs, 1961) or in rhesus monkeys exposed to 1 T for a few days (Battocletti et al., 1981). However, the absence of gene mutation is not, in itself, an indication of noncarcinogenicity, and it is important that experiments to test for tumor induction in an appropriate species be undertaken.

Electrocardiographic changes and sinus arrhythmia have been reported in squirrel monkeys exposed to 7 T for 1 hr (Beischer and Knepton, 1964) but were not observed at 10 T for 15 min (Beischer, 1969). In this latter experiment, "flow" potentials induced by the flow of blood perpendicular to the magnetic field were superimposed on the T-wave of the electrocardiogram. However, the fraction of this potential which will be applied across individual cardiac fibers in a field of 2.5 T is considered well below their stimulation threshold (Saunders and Smith, 1984). Transient behavioral changes (a suppression of responses to visual vigilance tasks) have also been reported in squirrel monkeys exposed to fields in excess of about 5 T for tens of minutes (Thach, 1968; De Lorge, 1978). However, these findings and the transient changes in heart rhythm may have resulted from stress, since the animals were physically restrained during exposure.

Although it has been reported that men crawling through magnetic fields of up to 2 T while adjusting large cyclotrons experienced nausea, disorientation and confusion, these reports are isolated and anecdotal (Beischer, 1962). These effects have not been reported in patients undergoing NMR imaging, who were exposed to similar fields for short periods.

Exposure limits for workers in high-energy physics laboratories, such as the Stanford Linear Accelerator Center in California, were recommended in the USA in 1971 based on experience over many years (Beischer and Reno, 1971). The static magnetic field limits for exposures of less than 15 min are 0.2 T for the whole body and 2 T for the arms and hands. For prolonged exposures, the field limits are 0.02 T for the whole body and 0.2 T for the arms and hands. A recent American survey (Marsh et al., 1982) of workers exposed to up to 0.02 T fields for prolonged periods concluded that there were no unacceptable effects, in contrast to the findings of a Russian survey that reported nonspecific behavioral, cardiovascular, and skin changes (Vyalov, 1971). The magnetic fields in the Russian study were either static or modulated at 50 Hz. Average exposures were in the range 0.0005 to 0.005 T but reached a maximum of 0.1 T. General symptoms included headaches, chest pains, rapid development of fatigue, blurred vision, dizziness, loss of appetite, insomnia, itching and burning sensations in the wrists, and sweating. Systolic blood pressure was decreased by 10 to 15% of normal in more than a third of the workers. The hands were also affected; symptoms included subcutaneous edema and desquamation of the skin of the palms. Although the working conditions were not defined, the author indicated that the exposed groups were also subject to other, sometimes unpleasant, conditions, such as exposure to airborne metallic dust, various emulsions and degreasing agents, or to high working temperatures. It is suggested that the nonspecific symptoms described could have been as much a reflection of environmental working conditions as of exposure to magnetic fields. A more critical study is required before positive correlations with magnetic fields can be claimed.

TIME-VARYING MAGNETIC FIELD EFFECTS (Excluding Radiofrequency Fields)

Rapidly changing magnetic fields induce in tissues electric currents that could be sufficiently large to interfere with the normal function of nerve cells and muscle fibers. Nerve and muscle cells conduct electrical impulses in the form of a localized membrane depolarization produced by the flow of ions. Depolarization can also be caused by magnetically induced electrical currents flowing through tissue, and, once a threshold level is reached, impulses will be generated which may produce sensation or muscle contraction. There is also limited evidence to suggest that weak electric currents, including those induced by magnetic fields, can affect the organization of embryonic tissue. The abnormal development of chick embryos after exposure of fertilized chicken eggs for 48 hours to weak (0.12 to 12 μT), 10- to 1000-Hz magnetic fields has been reported by a group in Spain (Delgado et al., 1982). The effects were considered to depend strongly on the shape of the magnetic pulse (Ubeda et al., 1983). It is important that these studies be replicated.

A well-established, sensitive response of the body to rapidly changing magnetic fields is the sensation of flashes of light (magnetic phosphenes), caused by electrical stimulation of the retina. This was first reported in 1896 by D'Arsonval (1896) and is not considered hazardous. The threshold for this effect in man is at about 2 to 3 T/sec at 20 Hz (Budinger, 1979), but it will be much higher for individual pulses. Effects on nerves or muscles, particularly the heart, could be hazardous, but they would require exposure to much higher rates of change of flux density. Very short (180-μsec) pulses of about 10^4 T/sec have been used to stimulate peripheral nerves in man (Polson, Barker, and Freeston, 1982) and thoracic muscles in rats (Polson, Barker, and Gardiner, 1982). A strongly damped sinusoidal magnetic field (period = 0.33 msec) was perceived by people whose forearms were exposed, when the rate of change of field was in excess of 2400 T/sec (McRobbie and Foster, 1984). They calculated a threshold current density of 5 A m^{-2} for human perception of currents induced in the superficial tissues of the forearm by damped sinusoidal magnetic fields. However, the significance of these perception or modulation effects for the well-being of people undergoing NMR scans is not clear.

The threshold for excitation is dependent not only on pulse length and pulse repetition frequency but also on the duration of exposure and on the diameter of the exposed object. There is insufficient information in the experiments described above to define a safe upper limit for exposure of the human body. It was therefore necessary for the advisory group to derive limits from considering the effects of electric currents applied directly, via electrodes, to experimental preparations or to the human body.

It has been estimated that current density required to induced phosphenes in man is 0.01 A m^{-2} (at 20 Hz; Adrian, 1977). This value agrees well with a threshold of 0.02 A m^{-2} derived from the magnetic-field experiments described above (Budinger, 1979). The modulation of neural activity may also have a low threshold. In some elegant studies of the effect of applied currents on pacemaker neurons of the marine mollusc Aplysia, Wachtel (1979) reported that the modulation threshold was about 0.01 A m^{-2}.

Ventricular fibrillation is the most serious response to electric currents flowing through the body. It is known to result from stimulation by power-frequency electric currents applied directly to the heart in dogs and man (Roy, 1980; Watson, Wright, and Loughman, 1973). Fibrillation occurs when the current density in the heart tissue contacting the electrodes exceeds $\sim$3 A m^{-2} (rms) and is applied for 3 sec or longer. In order to achieve an adequate margin of safety, the advisory group considered that the operating conditions in NMR imaging should be limited so that the induced current density in the tissues of the exposed individual should not exceed 0.3 A m^{-2} (rms) for current pulse widths above 10 msec (i.e., a factor of 10 below the threshold value for fibrillation). For sinusoidally or other continuously varying periodic currents, this restriction applies when the half-period of the waveform exceeds 10 msec.

Where the duration of the current pulse or half-period (t) is less than about 10 msec, the biological evidence suggests that, as the duration decreases, the threshold rms current density for fibrillation (I_{th}) increases, so that the quantity $(I_{th})^2 \times t$ remains constant (International Electrotechnical Commission, 1983). Thus, in these conditions, the induced current density will be such that

$$(I_{th})^2 \times t < 9 \times 10^{-4}. \tag{1}$$

Limits applicable to NMR operating conditions can be derived from these limits on current density. Currents induced in the tissues of exposed individuals when the magnetic field changes with respect to tissue can be estimated using Faraday's law of induction. Assuming an average value for tissue conductivity of 0.2 S m^{-1}, a body radius of 0.15 m, and a limiting current density of 0.3 A m^{-2} (rms), the rms rate of change of the magnetic flux density (dB/dt) becomes 20 T/sec when the duration of magnetic field change exceeds 10 msec. In the case of sinusoidally or periodically varying gradient fields, this restriction applies where the half-period of the magnetic waveform exceeds 10 msec. For shorter durations (t) or half-periods of magnetic field changes, the rms rate of change of the magnetic flux density should be such that

$$(dB/dt)^2 \times t < 4. \tag{2}$$

These derived limits depend on a number of assumptions and do not allow for such factors as tissue inhomogeneity. However, because the largest current densities are induced in peripheral tissues, in the event that significant currents are induced, sensation or muscle contraction in these tissues will occur before the onset of fibrillation.

RADIOFREQUENCY MAGNETIC FIELD EFFECTS

Absorption of the radiofrequency magnetic fields used in NMR clinical imaging results in the increased oscillation of atoms and molecules and the generation of heat. If this occurs in human tissue, a compensatory dilation of blood vessels results in an increase in blood flow and the removal of the excess heat, which is dissipated mainly through the skin. The lens of the eye is a notable exception; being completely avascular, it cannot lose heat as quickly as other tissues.

A measurable rise in temperature will occur if the rate of heat production or absorption exceeds the rate of heat loss. Changes of up to 1°C can occur in the body core temperature as a result of changing environmental or physiological conditions. If, however, a temperature rise of several degrees is maintained in any tissue, adverse biological changes can occur.

The majority of the effects reported in animals exposed to radiofrequency and microwave radiation can be accounted for in terms of this heat gain.

The lens of the eye is particularly sensitive to radiofrequency and microwave radiation for the reasons stated above. Excessive localized energy absorption in the eye can lead to the formation of cataracts. Acute experiments with rabbits have shown that the threshold rate of energy absorption in the eye sufficient to cause a cataract is about 100 W kg^{-1} (Kramer et al., 1978), resulting in a temperature rise of several degrees in the lens tissue.

Teratogenic effects from exposure of pregnant animals have been reported (O'Connor, 1980). Acute experiments have shown that whole-body specific energy absorption rates in excess of 20 W kg^{-1} were required to cause anatomical deformities in the offspring of pregnant animals. These levels of absorbed power caused a rise of several degrees in the body temperature of the mothers and would have been fatal if prolonged.

A more sensitive and less hazardous biological response is the reduction in an animal's ability to perform tasks for which it has been trained. A disruption of operant behavior was observed in rats and monkeys during or shortly after exposure to microwave radiation for 1 hr. The exposure resulted in whole-body specific absorption rates of 4 to 5 W kg^{-1} and a corresponding rise in body temperature of about 1°C (De Lorge, 1979).

After reviewing these and other animal data on acute exposure, a subcommittee of the American National Standards Institute concluded (ANSI, 1982) that the most sensitive measures of biological effects that could be used to derive limits on exposure were based on behavior. They also decided that a threshold for reversible behavioral effects occurred between 4 and 8 W kg^{-1} (expressed as average, whole-body, specific absorption rate), despite considerable differences in radiofrequency, mode of irradiation and animal species.

Some reports quote effects below 4 W kg^{-1} but it is difficult to relate these to detrimental human effects. One example is the increased efflux of radiolabeled calcium ions from chick brain tissue exposed in vitro for 20 min to sinusoidally modulated, 147-MHz radiofrequency radiation (Blackman et al., 1979). The specific energy absorption rate was estimated to be 2.3×10^{-3} W kg^{-1}, too low to cause a measurable rise in temperature.

The possibility that radiofrequency or microwave radiation might have a mutagenic effect has also been studied experimentally in vitro and in vivo. An increase in the frequency of chromosomal lesions has been reported in cultured human lymphocytes and in Chinese hamster cells exposed to 5 to 40 MHz (Heller, 1970); and in cultured human amnion cells and Chinese hamster cells exposed to 2.45 GHz (Chen, Samuel, and Hoopingarner, 1974). However, there is evidence to suggest that the chromosomal aberrations observed resulted from a radiation-induced temperature rise in the culture medium (Alam et al., 1978). No increase in chromosomal aberrations was found in dividing bone-marrow cells or in stimulated lymphocytes from male Chinese hamsters exposed to 2.45 GHz at an estimated specific energy absorption rate of up to 16 W kg^{-1} (Huang et al., 1977). Nor was there an increase in sister chromatid exchange (SCE) in dividing bone marrow cells taken from mice exposed to 2.45 GHz at 21 W kg^{-1} (McRee and MacNichols, 1981). Lloyd et al. (1984) were unable to find any increase in chromosome aberration or SCE in human lymphocytes maintained at up to 36°C and exposed for 20 min in vitro to 2.45 GHz at 104 W kg^{-1} or 193 W kg^{-1}. The acute exposure of male mice to 2.45 GHz at 44 W kg^{-1} (Saunders, Darby, and Kowalczuk, 1983) and the chronic exposure of male rats to 2.45 GHz at up to 5.6 W kg^{-1} (Berman, Carter, and House, 1980) did not result in an increase in the rate of dominant lethal mutations, although there was evidence of a temporary, reversible decrease in fertility in the mice. However, other authors have observed microwave-induced increases in the incidence of chromosome translocations in mouse spermatogenic epithelia (Manikowska-Czerska, Czerski, and Leach, 1982) and in the rate of dominant lethal mutations (e.g., Varma, Dage, and Joshi, 1977; Goud et al., 1982).

While most of the experimental evidence supports the view that unacceptable morphological or mutagenic changes are unlikely at the threshold level of exposure for reversible behavioral changes, further experimental work is necessary to clarify the inconsistencies in some of the observed effects. A recent review (Silverman, 1980) of several epidemiological studies of workers and military and naval personnel in the USA concluded that no pathological changes have been observed that relate specifically to exposure to radiofrequency or microwave radiation. An association between microwave exposure and cancer has been examined in two "prospective" epidemiological studies, but neither has revealed any form of cancer that can be interpreted as microwave-related. In contrast, effects attributable to changes in the central nervous and cardiovascular systems have been reported by Russian and Eastern Bloc Countries (Sadchikova, 1974). The behavioral changes, which are subjective in nature, include headache, disturbance of sleep, fatigue, general weakness, lowering of sexual potency, depression and irritability. Associated with these symptoms are endocrine and metabolic changes. However, it is not possible to state categorically that these nonspecific effects are related solely to exposure to radiofrequency fields.

GUIDELINES FOR NMR CLINICAL IMAGING RECOMMENDED BY THE NRPB ADVISORY GROUP BASED ON THE EVIDENCE DESCRIBED

Supervision of Exposed Persons

Volunteers participating in experimental trials of NMR imaging techniques should be medically assessed and pronounced suitable candidates before exposure. There is no reason, on the biological evidence, to exclude volunteers with a history of epilepsy or cardiac disease, but this should be judged at the time of examination. Volunteers who are exposed frequently should be checked at regular intervals for evidence of abnormal changes in electrocardiogram recordings.

Patients should be exposed only with the approval of a registered medical practitioner, who should be satisfied that the exposure is likely to contribute to the treatment of the patient or is part of a research project approved by a local research ethics committee.

Although there is no firm biological evidence to suggest that the developing mammalian embryo is sensitive to magnetic fields encountered in NMR clinical imaging, unconfirmed studies have reported developmental abnormalities in the chick embryo. It was considered prudent, therefore, on the basis of this tentative evidence, to exclude from experimentation pregnant women in their first trimester, when major organ development is taking place in the embryo. There is no need to exclude women who will subsequently undergo a planned abortion.

As a precaution, persons fitted with cardiac pacemakers should not be exposed unless corrective procedures are available and they have been made aware of the potential hazard before being exposed. The time-varying gradient fields can induce electric currents in pacemaker leads which, in the case of demand pacemakers, may be "mistaken" for the natural electrical activity of the heart, thus inhibiting pacemaker output (Pavlicek et al., 1983).

The exposure of individuals with large metallic implants, such as hip prostheses, should be stopped immediately if discomfort, caused by heating of the implant (Davis et al., 1981), is experienced. Intracranial metallic clips, particularly those used to treat aneurysms, may also present a hazard if the clips are made of magnetic materials because of the magnetic torque and possible movement of the clips (New et al., 1983). Patients fitted with such clips should be excluded from examination.

As a precautionary measure, in view of the remote possibility of induced currents affecting myocardial muscle contractility, appropriate resuscitation equipment should be available during imaging, and a registered medical practitioner trained in the techniques of resuscitation should be available at short notice, although not necessarily during the exposure.

Exposure Limits

Static Magnetic Fields

For those exposed to the NMR imaging process, the static magnetic field should not exceed 2.5 T to the whole or a substantial portion of the body. Staff operating equipment should not be exposed for prolonged periods to more than 0.02 T to the whole body or 0.2 T to the arms or hands. A number of such short exposures in any day is permissible, provided reasonable intervals occur between examinations. These recommendations correspond to the guidelines used at the Stanford Linear Accelerator Center.

Time-Varying Magnetic Fields (Excluding Radiofrequency Fields)

For periods of magnetic flux density change exceeding 10 msec, exposures should be restricted to rms rates of change of less than 20 T/sec for all persons. For periods of change less than 10 msec, the relationship $(dB/dt)^2 \times t < 4$ should be observed, where dB/dt is the rms value of the rate of change of magnetic flux density in any part of the body in T/sec, and t is the duration of the change of the magnetic field in seconds. For sinusoidally varying magnetic fields or other continuously varying periodic fields, the duration of the change can be considered the half-period of the waveform. These limits apply to patients and volunteers being scanned (Limits on nonmedical exposure (i e , occupational and public) to radiofrequencies and electric and magnetic fields are currently under review by the U K National Radiological Protection Board)

Radiofrequency Fields

Exposure should be such as to avoid any significant rise in the temperature of the sensitive tissues of the body Acceptable exposures result in a rise in body temperature of no more than 1 °C, as shown by skin and rectal temperature, or no more than 1 °C in any mass of body tissue not exceeding 1 g This may be ensured by limiting the mean specific absorption rate in the whole body to 0 4 W kg^{-1} and the specific absorption rate in any mass of tissue not exceeding 1 g to 4 W kg^{-1} These limits apply to volunteers, patients and staff exposures

Other Precautions

Notices should be posted, where appropriate, to warn passers-by of the presence of magnetic and radiofrequency fields and of the possibility that these may affect the functioning of cardiac pacemakers and other electronic equipment Loose ferromagnetic objects should not be permitted in the vicinity of strong magnetic fields

These guidelines on exposure conditions and on the restriction of certain individuals should be considered as interim and cautionary They will be reviewed as experience is gained in the use of imaging procedures

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ELF BIOEFFECTS: USE OF NEGATIVE DATA IN A STRUCTURED ARGUMENT

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ABSTRACT

Data on effects of extremely low-frequency (ELF) fields reported in human studies are contrasted with those from laboratory animal studies. A growing body of evidence suggests a possible relationship between ELF field exposure and human cancer. However, no directly supportive or antagonistic laboratory data are available, and indirect evidence is relatively neutral. Only a few recent animal studies might support inferences based on human studies. In an attempt to reconcile human and animal data, careful reanalysis, especially of reported negative laboratory data, may be useful. In the six years since the last Hanford Symposium which focused on ELF bioeffects, a substantial quantity of laboratory animal data has been accumulated. A modest quantity of human data has also been published. Taken as a whole, the accumulated human data appear to be in sharp contrast with the animal data. Generally, data from ELF experiments report many perturbations in biological systems. However, negative (no-effect) data are also reported for a wide range of biological endpoints. Such conflicting data provide little basis for direct human health-risk assessments. Recent human data, on the other hand, report specific health endpoints which provide a relatively consistent direction for observed effects, as well as a perspective for assessing risk. Most laboratory experiments have been designed to study effects of exposure only to electric fields of high-voltage transmission lines. Human studies generally include a more diverse set of electromagnetic exposure conditions, including confounding factors resulting from exposures to multiple household, environmental, and industrial influences.

HUMAN STUDIES

The human studies which will serve as a basis for discussion are of several different designs and are presented in Table 1. Estimates of effect are presented as risk ratios, with an assignment of 95% confidence limits around the risk ratio estimates, which vary between 1 and 3; most are between 1.5 and 2. Some of these data were reported as negative and some as positive, which did not always coincide with the lower 95% confidence limit being below or above a relative risk estimate of 1.0.

Causality, in a physical sense, relates a very specific condition or event with a very specific effect. For some diseases, e.g., malaria, this deterministic relationship is clear: The disease is transmitted only by the bite from an infected female mosquito. For other diseases, the cause-effect relationship may not be so clear, as is the case for endpoints such as heart disease, cancer, and reproductive anomalies. For this latter class of biological endpoints, which are of interest in risk assessment, a particular biological response may result from a host of different insults. Conversely, a single type of insult can contribute to several distinct biological endpoints. These factors suggest that a purely deterministic line of reasoning may be misleading when attempting to relate ELF bioeffects data to possible human health events.

TABLE 1. Results of Epidemiologic Studies of Extremely Low-Frequency Electric Fields

Author	Endpoint	Risk Estimate	Confidence Interval[a]	Power[b] (R = 2)
Milham (1982)	Leukemia	PMR = 1.37[c]	(1.12-1.67)	0.99
	Acute Leukemia	PMR = 1.63	(1.14-2.25)	0.99
Wright (1982)	Leukemia	PRR = 1.29[d]	(0.85-1.88)	0.99
	Acute Leukemia	PRR = 1.73	(0.93-2.93)	0.91
	All Myeloid Leukemia	PRR = 2.07	(1.02-3.75)	0.85
McDowell (1983)	Leukemia	PMR = 1.25	(0.65-2.19)	0.88
	All Myeloid	PMR = 1.79	(0.66-3.88)	0.65
	All Myeloid Leukemia	PMR = 2.31	(0.61-6.00)	0.49
McDowell (1983)	All Myeloid Leukemia	OR = 2.10[e]	(1.24-3.59)	0.97
Coleman (1983)	Leukemia	PRR = 1.17	(0.95-1.44)	0.99
	All Myeloid Leukemia	PRR = 1.23	(0.81-1.80)	0.99
Wertheimer (1979)	Leukemia	OR = 2.98	(1.77-5.01)	0.99
Fulton (1980)	Leukemia	OR = 1.08	(0.67-1.74)	0.99
(Wertheimer Reanalysis)		OR = 1.65	(0.99- 2.77)	0.99

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[a] Using a single, chi-square technique for uniformity or a Poisson Estimator (Beaumont, J. J., 1981, "Power Considerations in Epidemiologic Studies of Vinyl Chloride Workers," *Am. J. Epidemiol.* 114: 438.)

[b] Assumes 1-tail test with Alpha = 0.05; Power = 1-Beta.

[c] PMR = Proportional Mortality Ratio

[d] PRR = Proportional Risk Ratio

[e] OR = Odds Ratio

In spite of the inference difficulties, a sequence of arguments encompassing a modified deterministic concept is used in epidemiology to perform a defensible evaluation of "risk factors." This sequence of arguments, as employed in public health studies, uses tenets based on contiguity of findings in a variety of settings and the succession of results in repeated observations with different study designs. Evidence for these characteristics is reviewed below for human studies.

Strength of the Association

The studies listed in Table 1, taken together, place the strength of association for ELF fields with leukemia at about 2.0. When compared with that for some known hazardous agents, a relative risk of 2.0 is not large, especially when the confidence limits reach 1.0 (or less) on the lower side. In contrast with many laboratory studies discussed later, the population sizes of the human studies were adequate to detect a twofold increase in risk, with high degrees of reliability, often greater than 99%. However, when viewed deterministically, the strength of association is not large, and, taken alone, would not be a strong argument for causality with this association.

Temporality

Many of the epidemiologic studies (Milham, 1982; Wright, Peters, and Mack, 1982; McDowall, 1983; Coleman, 1983) in Table 1 are cross-sectional. They have looked at the prevalence of disease states across the population at a point in time and can provide no temporal distinction between presumed exposure and response. Wertheimer and Leeper (1979), however, supported the concept of temporality by using residential data at birth and death. In their adult cancer study (Wertheimer and Leeper, 1982), data were provided on the duration of residence. From this they postulated a 7- to 10-year induction period--not an unreasonable time. The subtle nature of ELF fields, inferred from laboratory data, suggest the absence of acute effects and that bioeffects, if seen, might have some characteristic latent period. This concept is supported in part by several of the human studies. McDowall (1983) also gives some temporal perspective with his decedent case-comparison study.

Consistency

The consistency in the level of risk for the seven studies presented in Table 1 is noteworthy. Nearly all studies report a risk between 1.5 and 2, and six of them reported a positive association with leukemia. The similar levels of risk found despite the diversity of geographic locations, time periods, and study methods provide a reasonable basis for consistency arguments.

The single study reporting negative treatment effects in Table 1 is by Fulton et al. (1980). One possible explanation for the single negative report is that there may be a bias for literature selection of only positive studies.

Each study, whether positive or negative, contains methodological frailties, principally in 1) the exposure measurement (either a surrogate or marginal in completeness) and 2) the reliability of the comparison group (for representativeness and absence of confounding factors).

Coherence

A coherent picture is provided by epidemiology reports, animal studies, and human experience: with a few exceptions (e.g., shock, startle, etc.), large effects resulting from exposure to ELF fields are not immediately present. Moreover, the risk ratio of about 2, as suggested by the human data, is relatively small. Animal data, which measure different endpoints, do not suggest higher levels of risk.

If serious effects are related to ELF exposures, they could be stimulated by biological perturbations of relatively small size, extended over a long period of time. Similar conditions have been observed for chronic exposures to chemical agents (Arcos et al., 1982; Moolgavkar, 1983; Nettesheim et al., 1978). Inference that a physical agent could function as a promoter is coherent with carcinogenesis theories which include the long suspected role of multiple promotional factors.

Biological Plausibility

In any type of deterministic reasoning, biological plausibility is of crucial importance. For the carcinogenesis endpoint presented in Table 1, little if any laboratory evidence would indicate a primary role for ELF fields. Complete carcinogens participate in both the initiation or transformation of cells, and the promotion or growth of these cells. Some agents contribute only to a potentiation of growth; examples of the latter are wounding by surgery, burns, etc. Mathematical analogues have shown the utility of cellular population growth kinetics, in terms of carcinogeneic risk modeling, for a number of toxic agents (Jones, Griffin, and Walsh, 1983). To date, no evidence suggests an initiation capability or mutagenic capacity for ELF fields. However, a growing number of reports suggest that some types of ELF exposures may result in a growth stimulus (e.g., Winters and Phillips, 1984; Barbiroli et al., 1984; Liboff et al., 1984).

Additionally, other work indicates some possibility for ELF modification of homeostatic conditions (e.g., Goodman et al., 1984; Ragan et al., 1983). (A discussion of this issue will appear in the section on animal data.) Thus, both cellular and animal systems appear to be perturbed by ELF fields in a manner consistent with a change in cellular dynamics. Finally, the long history of ELF fields being used therapeutically to stimulate bone growth is in complete agreement with the concept that ELF exposure acts as a growth stimulus.

LABORATORY STUDIES

Results of laboratory animal studies have led to a contrasting perspective on ELF-induced bioeffects when compared with human studies. Recent human studies, involving primarily domestic and industrial exposures, have focused on carcinogenesis and reproductive effects. These two endpoints generally represent the issues which dominate human health-risk assessment for suspected toxic agents. In contrast, laboratory studies have focused on exposures from high-voltage transmission lines and have been designed to investigate a wide spectrum of possible biological effects in order to elucidate mechanisms. Biological studies have included work in hematology and serum chemistry, immunology, bone growth and repair, endocrinology, neurochemistry, neurophysiology, behavior, genetics, and growth and development. With few exceptions, measurements in exposed animals have been essentially indistinguishable from results in controls. Experience has demonstrated that, under most laboratory exposure conditions, biological effects, if present, are at a low level.

The use of data for multiple inferences and the rigid application of arbitrary decision rules (i.e., the use of the $P < 0.05$ criterion for assigning statistical significance) may also contribute to confusion in data interpretation. The following examples illustrate these points by examining a small subset of available laboratory data in order to support or negate any biological plausibility for the human studies.

Sample Size: Limitations and Implications

Laboratory studies of ELF effects require elaborate exposure facilities and planning to avoid bias from other, related effects. Coupled with animal care requirements, this has usually led to the use of fairly small sample sizes. Many experiments have been limited to 10 to 20 rats per group. Such small sample sizes do not result in an adequate level of statistical sensitivity (power) to detect low-level effects.

For example, Jaffe et al., 1980, examined the effect of chronic ELF field exposure on synaptic transmission in rats. Table 2 in Jaffe et al. (1980) summarized data from a postsynaptic compound-action-potential test. For a test interval of 25 msec in experimental series I, mean responses of 1.18 and 1.16, respectively, are reported for the exposed- and sham-exposed groups. Each group is made up of 13 test animals, and each sample mean has a standard error of 0.05; hence the within-group standard deviation is approximately 0.18.

By using standard sample size and power calculations for *t*-tests, properties of these experiments may be examined. It is assumed that two-sided tests were performed, and that P-values of 0.05 or less are considered significant. If the true difference between treatment and control levels is as large as 0.2 (i.e., 1.2 versus 1.0), the test would detect this difference with a probability of approximately 80%. However, if the true difference were 0.1 (i.e., nearly 10% of the mean values given), the corresponding probability would be only about 30%. A sample size of 45 rats per group (90 total) would be required to increase the probability of rejection to 75% in this latter case (0.1 difference).

We are not suggesting that the experimental plan of Jaffe et al. (1980), or of any other investigators, was "flawed" in any sense. Indeed, as suggested above, these experiments are difficult enough to carry out at the sample sizes mentioned. The point is that a necessary consequence of small samples is relative insensitivity for a study's ability to detect true effects. Moderate power characteristics can also lead to inconsistent conclusions, even from repeated experiments. This inconsistency represents the "Cheshire cat" phenomenon often observed in ELF laboratory studies, and contributes to the great difficulty in attempting to determine the true level of human health risk that may be associated with exposure to ELF fields.

Negative Results Versus Inconclusive Findings

Many laboratory studies have a problem with multiple statistical inferences. This difficulty occurs when several test statistics, calculated from the same or different data, are examined or interpreted together. For example, it is well known that if a large number of independent experiments are performed to test the same hypothesis, approximately 5% of the correctly performed analyses will result (randomly) in a P-value of less than 0.05 when no true treatment effect exists. The problem is more difficult when many test statistics are calculated from the same or related data. In this case, the P-values are correlated, and considerably more than 5% of significant (<0.05) P-values may occur. Investigators are, therefore, inclined to replicate experimental work, where possible, so as to avoid this "false positive" phenomenon.

The mathematical fact that leads to the situation described above can be explained as follows. In a properly designed experiment, where no true difference exists between the study groups, the correctly performed analysis will lead to a P-value which is randomly and uniformly distributed between 0 and 1 (Dixon and Massey, 1969). That is, when several tests are performed, and these tests are statistically independent, these P-values are also independent random variables. From a mathematical basis, statistical distribution theory can be used to show that in many, many replications of such experiments, X% of the P-values will be less than X/100 (i.e., $P < 0.05$) when, in fact, no difference exists.

The concept of a uniform distribution for P-values may be used to shed some light on this related problem. Often, experimental results are termed "suggestive" of an effect without detecting what is usually thought of as a statistically significant effect. A group of identical or similar experiments may yield individual P-values of from 0.10 to 0.30 and thus may be classified as "interesting" but "negative." An example of this may be found in Table 2 (from Ragan et al., 1983). This data set is of particular interest due to a possible biological connection to the human leukemia studies. Here, two sets of P-values are displayed for multivariate tests of the effects of ELF fields on the hematology and serum chemistry of rats.

TABLE 2. Data from Table 2, Ragan et al. (1983)

Tests	Replicate	Exposure Days	P-value
Hematology	1	15	0.52
	2	15	0.53
	1	30	0.29
	2	30	0.14
	1	60	0.64
	2	60	0.21
	1	120	0.46
	2	120	0.04
Serum Chemistry	1	15	0.49
	2	15	0.04
	1	30	0.26
	2	30	0.68
	1	60	0.25
	2	60	0.45
	1	120	0.11
	2	120	0.33

In the first set of P-values, only one is less than 0.05 (the 120-day exposure group from replicate number 2), and in view of the "false positive" phenomenon associated with multiple P-values, an investigator would be well advised to avoid pointing out this treatment group as being different.

However, the overall pattern of P-values does not indicate a uniform distribution, that is, what would be expected if no real difference exists between the groups. In fact, seven of the eight P-values in the hematology group are less than 0.55.

An overall test of the departure of independent P-values from the expected uniform distribution may be accomplished using the Kolmogorov-Smirnov (K-S) test for goodness of fit. Here, one is testing whether the P-values are actually drawn from a uniform distribution, i.e., that there is really no treatment effect in any group. With this application, a useful alternative hypothesis is that the P-values tend to be smaller than expected under the hypothesis of no effect, i.e., that small P-values are overrepresented in the sample. The theory and application of one- and two-sided K-S tests is well known. (See, for example, Gibbons, 1971.)

If one-sided K-S tests are applied to the two groups of independent P-values from Table 2, the overall significant levels are 0.09791 for hematology and 0.07072 for serum chemistry. While these numbers do not meet the usual arbitrary 0.05 level of significance, they offer a suggestion that is not seen in the P-values associated with the individual tests. The indication here is that the P-values are "clustered" at lower values than would be expected under no experimental effect (i.e., a uniform distribution). Thus, this data set should not be used to demonstrate proof of the null hypothesis for ELF-induced hematological effects.

This technique of assessing the aggregated significance of P-values must be used with some care, but it may shed additional light on other ELF bioeffects data. The test *requires* that all P-values be generated independently. This appears to be a reasonable assumption in the data of Ragan et al. (1983) since each test is performed on data from a separate group of animals. Additionally, it is assumed that the P-values have not been screened ahead of time. For example, with a set of P-values collected from the scientific literature, a bias against large values has already been effected by selection of publications, and one could not expect a uniform distribution of values even if there is no true experimental effect.

Do Laboratory Data Support or Reject Human Studies?

It is unfortunate that more similar types of data have not been collected in the human and nonhuman data bases. However, laboratory researchers often ask quite different experimental questions from those of epidemiologists. As a consequence of the divergent data sets, it is necessary to rely on indirect information to judge the biological plausibility of human data in light of animal data.

Relevant data may be found in animal hematology studies, cell culture studies, immunological studies, mutagenesis assays, and in molecular mechanism studies. It may be argued that studies involving molecular mechanisms, especially those factors related to growth stimuli, are directly related to the question of carcinogenic potential. Such studies are undoubtedly important to the understanding of the action of ELF fields; however, until the molecular descriptions of the genesis of cancer are made, direct application of this level of detail to human inferences is very tenuous.

Animal carcinogenesis data are the classical source of information for evaluating human cancer risk, but such data are not yet available for ELF fields. *In vitro* mutagenesis tests have shown promise as preliminary screens for carcinogenicity (Ames, 1979). Since different *in vitro* assays yield various results, a battery of short-term tests is a useful strategy for 60-Hz risk assessment. Several such tests have been performed, and none have indicated evidence that ELF fields have mutagenic potential (Frazier, 1982; Williams, 1982; Ley, Tobey, and Price, 1982). Various additional assays would be useful, but the currently available data show little evidence that ELF fields are a complete carcinogen.

Most theories of carcinogenesis require some type of growth stimulus, so it is important to examine evidence for, or against, growth stimuli. One interesting investigation was made on the effect of high-strength, constant, 60-Hz electric fields on virus-induced leukemia in chickens (Schneider and Kaune, 1981). This study was designed to study ELF effects on the immune system. Implicit in this experiment was an investigation of cell division regulation. The study found no consistent ELF treatment effect on the incidence or development rate of leukemia after injection with avian myeloblastosis virus. The quantity of virus was adequate to result in a 50% disease incidence in 1 month, thus the virus treatment could easily overshadow any small promotional ELF effects, especially with small treatment groups. Thus, since the experiment was designed to look at a very different biological response, little information for risk assessment needs is obtainable from this "negative" experiment. Other similar experiments have been performed with transplanted tumors (e.g., Chandra and Stefani, 1979), using high-strength, constant magnetic fields. Small sample sizes and large variability have inevitably resulted in inconsistent results.

Recently, cell culture studies have been performed using relatively low-level electric and magnetic fields at or near power frequencies (Liboff et al., 1984; Winters and Phillips, 1984). An important feature of this research is that the cell lines used represent both normal human and transformed human tissue. Using normal human fibroblasts, Liboff et al. (1984) observed enhanced DNA synthesis with ELF exposures. Transformed (solid tumor) human cells were observed by Winters and Phillips (1984) to grow at accelerated rates when compared to nonexposed cells. Different rates were observed for different combinations of electric and magnetic fields. Thus, there is some evidence that cells in culture may be stimulated by ELF fields to grow at accelerated rates. Of further interest is the recent work of Barbiroli et al. (1984). They exposed rats to 50-Hz, 6-mT electromagnetic fields after partial hepatectomy. Several measures of growth indicated ELF-stimulated increases over untreated controls. Thus, accelerated growth rates have been seen in several experimental systems.

In considering the human leukemia data, it is appropriate to examine laboratory data dealing with effects on the hematopoietic system. A very detailed study, performed by Ragan et al. (1983), on hematologic and serum chemistry effects was cited in the previous section. Rats were exposed to continuous, high-strength, 60-Hz electric fields. The Ragan analysis concluded that no consistent ELF treatment effect was present. Such an observation seems to provide evidence against the stimulated lymphyocyte growth expected in a leukemia condition. However, results of the above analysis of P-values suggest that a closer scrutiny of this study and others is warranted in order to obtain a consistent picture for human and laboratory results.

CONCLUSIONS

When human and laboratory data are compared, two separate pictures of potential health effects emerge. Except for some of the more recent cell culture and liver regeneration work (which have yet to be duplicated) and a few trends in blood chemistry seen previously, laboratory data provide no positive support of inferences stemming from the human studies. There may be a number of reasons for the apparent inconsistency affecting either or both of the data sets, some of which have already been suggested. From a comparison of experimental conditions, presented in Table 3, it is evident that major differences are present in the endpoints chosen for examination, the exposure scenarios, and the power of resolution.

From both human and laboratory data, it is clear that most ELF effects occur at a very low level, which in itself implies neither a hazardous nor a nonhazardous condition. Of the large number of negative animal studies now on record, some had the potential to detect only relatively large effects such as could be found with many known toxic agents.

TABLE 3. Major Differences Between Human and Animal Data on Effects of ELF Electric Fields

Issue	Human	Laboratory	
		Animal	Cell Culture
End Point	Carcinogenesis	Reproductive Assays	Mutation
		Organ Weights	Growth Rate
	Reproduction	Bone Healing	Cell Killing
		Nerve Transmission	(Other End Points)
		Behavioral Assays	(Other End Points)
		Hematologic Chemistry	
		Muscle Recovery	
		(Other End Points)	
		(Other End Points)	
Exposure Scenario	Time and Frequency Varying E + B	Fixed E	Fixed E^a Fixed B^b Fixed E + B
Power of Resolution	High	Low	High

[a] Pure electric field
[b] Pure magnetic field

Examples in the previous section illustrate some of the implications. Many similar examples are probably present within the current large body of ELF laboratory data, and a careful review may bring to light a more consistent perspective of ELF-induced bioeffects. Using animal data, a quantitative exposition of the strengths and weaknesses of the results is possible, since many potentially confounding factors have been controlled. Such is not the case for the human studies, in which only a few of the major confounding factors are controlled. The strength of the latter studies comes from replication and arguments of consistency, temporality, and biological plausibility. In light of the emerging strength of the human studies, it seems appropriate to reexamine both the human and animal information.

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