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Cell Membrane Potentials Induced During Exposure to EMP Fields

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Abstract

Internal current densities and electric fields induced in the human body during exposure to EMP fields are reviewed and used to predict resulting cell membrane potentials. Using several different approaches, membrane potentials of about 100 mV are predicted. These values are comparable to the static membrane potentials maintained by cells as a part of normal physiological function, but the EMP-induced potentials persist for only about 10 ns. Possible biological implications of EMP-induced membrane potentials including conformational changes and electroporation are discussed.

Introduction

The question of biological effects related to EMP exposure is perplexing because the physical effects are both unimaginably intense and infinitesimally brief. A numerical study conducted by A.W. Guy (1990) offers some data concerning EMP-induced fields and currents that allow at least a rough examination of these effects. From Guy's data, a total of about 0.24 Joules is deposited in the body during a 10 nanosecond (ns) interval. This value indicates an average power dissipation of over 20 million watts for 10 ns. In other words, exposure to a 100 kV/m EMP is comparable to shorting the output power of a 24 megawatt electric power plant through one's body to ground for 10 billionths of a second. Such a short time interval is difficult to visualize, but some perspective can be gained by noting that even at this enormous power level, the total energy deposited in the body by the pulse would be only enough to raise a gram of water about one-tenth of a degree Fahrenheit. If this energy is spread evenly over the entire body, the temperature increase is obviously far too small to be detected.

Biological effects of EMP can not be thermal in the macroscopic sense, and any further consideration of this question must resort to a different approach. A better understanding can be obtained by reformulating the question: Is the internal energy absorbed from the

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EMP concentrated or localized in any areas of the body? If so, are the changes in some biological structure comparable to or in excess of ordinary thermal fluctuations? These questions address the crux of the matter. Biological effects of EMP appear to be impossible unless some kind of energy concentration takes place.

Adair (1990) described a quantitative approach for evaluating the possibility of EMP-related biological effects. His method is based largely on calculations of impulse or total momentum delivered to various biological components such as ions, macromolecules, and cells during EMP exposure. While that paper is an important attempt to evaluate the possibility of microscopic effects, it overlooks certain aspects of the energy concentration issue. We have shown in an earlier report (Aldrich et. al., 1988), that substantial concentration of the EMP energy occurs in the cell membrane. Further analysis of this process is presented here along with a discussion of some possible biological implications.

Review of A.W. Guy's Model and Results

Guy (1990) predicted the currents and fields induced in a model of man using a method-of-moments computer code called NEC2D. Guy's model approximated the body as a series of cylindrical sections with varying electrical properties. Further studies using an anatomically-based model are likely to produce more detailed results, but Guy's findings are useful for the level of analysis presented in this paper. Using an EMP with a peak electric field strength of 100 kV/m, he found that significant fields and currents were induced in the body for approximately 20 ns. Generally speaking, the body appears to act as a resonant antenna which agrees with the frequency response data found in continuous wave studies (Gandhi, 1982). Even though the EMP exposure fields persist for two hundred nanoseconds, the current pulse induced in the body has largely decayed in about 18 nanoseconds.

As the induced current passes through the legs and into the ankles, it is confined to a decreasing cross-sectional area. This "focusing" of the current results in higher current density and internal electric fields. The effect is further enhanced by the low conductivity of bone resulting in confinement of most of the current in the higher conductivity regions of muscle and blood. Consequently, the highest exposures occur in the ankles where the peak current is predicted to reach 552 amperes and resulting current density is $1.75 \times 10^5 \text{ A/m}^2$. The peak electric field associated with this current density is about 210 kV/m which is about twice the value of the external electric field strength.

Cell Membrane Potentials Induced During EMP

The internal structure of the body is highly complex from an electrical viewpoint. Electrical properties (conductivity and permittivity) can vary dramatically from one tissue type to the next and within individual tissue types as a function of frequency. As a result, the

distribution of current density will also be complex and difficult to predict. Biological systems have increasingly complex structures and properties at the microscopic level. Even when numerical techniques are used that subdivide the body into blocks with appropriate electrical properties, the values used for each block must represent some type of average over a relatively large area. Thus, effects occurring on the microscopic scale are often overlooked. It is important to recognize that attempts to model microscopic effects, such as the approach described here, typically resort to simplistic representations of biological structure at the cell level. These models are intended as preliminary explorations of the possibility of biological effects, and any number of unaccounted-for microscopic factors may significantly alter the results. More detailed models can be developed if sufficient concern is raised by these preliminary evaluations.

Much attention has been given to the cell membrane as a possible site for interaction of electric fields with biological systems. The membrane defines the cell boundary, protects it, and serves as the communication organ between the cell and its environment. In simplistic models, the cell membrane is thought of as a lipid bilayer essentially two lipid molecules thick (about 50 to 100 Angstroms). It is important to recognize that actual cell membranes are composed of a variety of different lipids, contain cholesterol within the molecular matrix, and are literally teeming with various macromolecules that serve as receptors, ion pumps, and other (mostly unknown) functions. Lipid bilayers exhibit very low conductivities and can be considered nonconducting to a first approximation. A value of $1 \mu\text{F}/\text{cm}^2$ is often used for the capacitance per unit area.

This capacitance value can be thought of as a series impedance to currents flowing through the biological tissue. The value of this impedance varies with frequency, and at high frequencies, the impedance is so low that the membrane is often deliberately ignored in simple models. Current density is essentially the same inside the cell as it is outside the cell in contrast to the low frequency case where the membrane effectively shields the interior of the cell from external currents (Foster et al, 1986). At this point, it is essential to review the meaning of the membrane impedance or capacitive reactance. Current flowing through a capacitor is displacement current rather than conduction current. Charge carriers do not readily pass through the dielectric material of the capacitor, and the accumulation of these charge carriers on both sides of the dielectric describes a displacement current. The important point is that (displacement) current can only flow through a capacitor by charging the surface, and although charging is smaller at high frequencies, it still occurs.

With the above concept in mind, several approaches can be used to find the membrane potential induced during exposure to EMP. The simplest approach is to use the current density and membrane capacitance per unit area. If the current density is assumed constant over some time interval, then the membrane potential at the end of that time interval is simply

$$V_m = \frac{J \cdot \Delta t}{C_m} \quad (1)$$

where J = current density,
 Δt = time interval,
and C_m = capacitance per unit area.

This simple model assumes that the current flows uniformly through the membrane and extracellular medium surrounding the cell. As indicated above, this assumption is reasonable to a first approximation because the membrane impedance is small compared to the conductivity of the extracellular medium. However, if significant charging of the membrane occurs, the current will follow the gradient of the potential and tend to flow around the cell. The initial positive-going current pulse predicted by Guy can be approximated as a constant current density of $1.5 \times 10^5 \text{ A/m}^2$ lasting for 10 ns. Using these values, a maximum membrane potential of 150 mV is predicted during the EMP exposure.

Alternatively, a continuous wave formulation (Foster et al, 1986) can be used to approximate the induced membrane potential.

$$V_m = \frac{J}{\omega C_m} \quad (2)$$

where ω = the angular frequency of the continuous wave exposure.

According to Guy's results, the EMP-induced current pulse rises to a peak value and then falls to zero after about 18 ns. This current pulse can be roughly approximated as the positive half cycle of a 27.8 MHz sinusoidal excitation. Using this value in the above expression yields an induced membrane potential of about 100 mV which is in reasonable agreement with the constant current result found earlier.

A slight refinement of the model can be obtained by considering the cell to be a dielectric spherical shell with conductivities roughly equal on the inside (cytoplasm) and outside (extracellular medium). Adair (1991) uses this approach for a cell of 10 micron radius and a resulting total capacitance of about 6 pf. If the total current passing through the cross section of the cell during the pulse is considered, a maximum membrane potential can be calculated and again results in a value of about 100 mV. Adair (1991) erroneously states that such potentials will not be induced because the membrane impedance is small at high frequencies. However, as described above, the membrane passes current only by charging its surface--there is no other mechanism for current to pass through the membrane.

An example given by Foster et al (1986) illustrates this point. The example considers a current density of 10 A/m^2 at a frequency of 1 GHz, and shows that the induced membrane potential will be about 0.16 microvolts using equation (2). On this basis, the observation is

made that membrane charging is unimportant at these frequencies. This is a valid observation, because a continuous wave field strong enough to induce significant membrane potentials would also be strong enough to vaporize the biological tissues. EMP exposure differs in that it is so brief that extremely intense fields can occur inside the body without significant heating. Noting that Guy's calculation for EMP-induced current density is 1.75×10^4 times greater than the (10 A/m^2) value used in the example, and that the apparent frequency of the EMP current pulse (27.8 MHz) is about 36 times lower than the 1 GHz value used in the example, the EMP-induced membrane potential should be about 6×10^5 times larger. A careful examination of the numbers reveals that the Foster et. al. example is entirely consistent with the computations performed here for EMP-induced membrane potentials.

It is easy to be misled when considering the charging time constant of the cell membrane. This value is obtained by considering the series resistance through which current must pass to charge the cell membrane capacitance. Taking a value of 0.2 microseconds for the charging time constant of the cell (Foster et. al., 1986), the effective duration of the EMP-induced current pulse is only about 5% or 10% of the charging time. It would appear on this basis that significant charging of the membrane will not take place. These numbers are misleading, however, unless one also considers the limiting potential to which the membrane would charge in the infinite time limit. This limiting value is about 1.5 times the radius of the cell times the electric field strength in the surrounding medium. Using Guy's prediction of maximum field strength in the ankles (210 kV/m) and a cell radius of 10 microns, it is easy to see that the membrane potential will reach about 3000 mV in the infinite time limit or about 2000 mV after one charging time constant. Considering that the EMP-induced charging lasts for about 5% of a time constant, the membrane potential will be (very) roughly 5% of 2000 mV or about 100 mV. This line of reasoning arrives at the same result found earlier, and verifies that significant charging of the membrane occurs. Even though the maximum EMP-induced value is a small fraction of the fully-charged value, it still may represent a significant potential.

Biological Implications of Induced Membrane Potentials

The important question is whether or not these brief membrane potentials have any biological significance. While it is impossible to unequivocally draw implications from simple modeling results, it is reasonable to consider a range of possible effects. The cell membrane maintains a natural potential of about 70 mV that is necessary for a variety of cell functions. This potential is maintained by pumping specific ions through specialized channels in the membrane. Considering the thickness of the membrane, the natural potential results in an incredibly intense static electric field of about 10^7 V/m . Addition of the EMP-induced membrane potentials predicted here will result in the membrane potential being raised to about 170 mV on one side of the cell, and depolarized to -30 mV on the other side of the cell. Depolarization of the membrane potential is generally unhealthy for a cell, but it is difficult to predict what effects, if any, will occur during 10 ns. Macromolecules embedded in the cell membrane are affected by the transmembrane field. Many of these molecules

contain charged groups that are sensitive to electric fields, and conformational changes in these molecules by fields can alter their function.

It is interesting to note that the cell membrane acts as a concentrator of the electric field. Guy's data illustrates that EMP-induced (gross) internal electric field strengths can exceed the external field by a factor of about two. On the microscopic scale, an EMP-induced membrane potential of 100 mV produces an electric field inside the membrane of about 10^7 V/m which represents a field concentration factor of two orders of magnitude. Macromolecules in the cell membrane experience this enhanced field, which implies a substantial increase in signal-to-noise ratio. If these induced fields are capable of producing non-reversible conformation changes in membrane macromolecules, the short duration of the pulses may not imply insignificance as suggested by Adair (1991).

A potential biological effect that should be considered carefully is electroporation. Several investigators have studied the formation of pores in lipid membranes (live cells and artificial membranes) exposed to electric field pulses (Weaver et al, 1988). Pore formation results in rapid changes in membrane potential and exposes the cell cytoplasm to the extracellular medium. At lower field levels, the pores are formed reversibly and tend to self heal, but at higher levels, the damage is long-lived or irreversible. Most studies of electroporation have used microsecond length pulses producing initial membrane potentials of over 1000 mV, but at least one study has examined the effects of 10 ns pulses (Benz et. al., 1980). This study revealed that 10 ns pulses producing initial membrane potentials near 1200 mV caused reversible breakdowns of the membranes resulting in a sudden switch to a high conductance state. These results may be applicable to EMP exposures. Weaver et. al. (1992) have developed a numerical model of electroporation based on energy considerations. An assumption of the model is that the resting conductance of lipid bilayers is due to very small pores which are spontaneously formed and destroyed. Application of pulsed fields below the values needed to produce electroporation provides energy for enlarging these natural pores, and may result in some biologically significant changes.

Because the EMP-induced membrane potentials are about one order of magnitude below the values needed for full electroporation, an obvious question is whether or not a more detailed model would lead to higher membrane potentials. At lower frequencies, the dimensions of the cell or biological structure under consideration determines the maximum membrane potential as described earlier. The model of a spherical cell used in this and other analyses is obviously far from accurate. Muscle cells, for example, are elongated and the expression for the limiting membrane potential must be modified by an enhancement factor. In general, the maximum possible membrane potential will be proportional to the electrical length of the structure. One interesting area of consideration is cell junctions. Gap junctions, for example, electrically connect groups of cells so that a calculation of induced membrane potentials at low frequencies must consider the dimensions of a group of cells along with the junctional conductivity. In the case of the EMP model described here, the electrical length is not very important because the membrane potential is limited by the amount of the charge (current times time) available rather than the infinite time value of membrane potential.

The value for capacitance of the cell membrane used in most models is so high that inadequate charge is available during the EMP-induced current pulse to approach the limiting value. If the membrane capacitance were lower, induced membrane potentials would increase because less charge would be needed per millivolt of induced membrane potential. Membrane capacitance could be decreased either by a smaller value of membrane dielectric constant or by a thicker membrane. The first case might occur for unusual membrane constituents (some membranes are composed of 50% proteins), and would result in higher electric fields inside the membrane than calculated above. Thicker membranes would also have a lower capacitance, but the electric field in the membrane would be the same as calculated above because field strength and capacitance are both directly related to thickness. Effectively thicker membranes may occur in areas where tight junctions bind groups of cells together. In certain tissue types, tight junctions bind cells closely so that fluids cannot pass between the cells. These adjacent membranes may act electrically as a single unit. A double thick membrane will have one-half the capacitance (per unit area) of a single membrane, and will charge to twice the potential for a given current density and charging time. The nonconductive properties of various biological components such as lipids may lead to other unusual capacitive effects or field enhancements depending on geometry. Perhaps the most important observation from this analysis is that microscopic effects are strongly affected by microscopic structure, and simplistic models are only the starting point for a meaningful evaluation of possible biological effects.

Conclusions

The results presented in this paper are not meant to imply any biological or health effects related to EMP, but they do raise a number of issues that should be addressed. It is important to recognize that this and other similar investigations employ simplistic, first-approximation models to obtain preliminary results. The complexity of real biological systems must be considered if realistic results are desired. More detailed models combined with complementary laboratory studies are the most reliable way to address these issues.

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