EFFECT OF EMP FIELDS ON CELL MEMBRANE POTENTIALS

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A simple model is presented for cell membrane potentials induced during exposure to electromagnetic pulse (EMP). Using calculated values of internal electric field strength induced during EMP exposure, the model predicts that cell membrane potentials of about 100 mV may be induced for time frames on the order of 10 ns. Possible biological effects of these potentials including electroporation are discussed.

INTRODUCTION

Electric field strengths occurring inside the body during EMP exposure are substantially higher than those produced during other types of field exposure. This concept is most easily understood by considering the body as a thick, lossy antenna with a broad resonance in the tens of megahertz range depending on height and grounding conditions. Near whole-body resonance, internal and external electric field strengths are comparable, and substantial energy may be absorbed by the body. This efficient energy absorption limits the field strengths to which an individual can be safely exposed near resonance for continuous wave or high-duty-cycle signals. Voluntary exposure guidelines in the United States recommend limiting power density to 1 mW/cm^2 near whole-body-resonance frequencies. For a free-space plane wave, this power density implies an electric field strength of about 60 V/m. Consequently, internal electric field strengths are seldom in excess of this value under ordinary conditions.

Electromagnetic pulse (EMP) exposures differ from typical environmental field exposures in that the body experiences very intense electromagnetic fields for a short time interval. A substantial fraction of the energy in the pulse may occur in the whole-body-resonance frequency range. During a 100 kV/m EMP, electric field strengths inside the body can reach values as high as 200 kV/m for approximately 10 ns (Guy, 1990). These high field strengths produce no measurable heating of the body because very little energy is deposited during the short time interval. However, EMP-induced internal electric field strengths can be three or more orders of magnitude greater than those induced by the more common cw exposures, and questions about possible nonthermal biological effects cell are raised. In this paper, we discuss cell membrane potentials induced during EMP exposure.

INTERNAL FIELD CHARACTERISTICS

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. Using an EMP with a peak electric field strength of 100 kV/m and about 200 ns duration, he found that significant fields and currents were induced in the body for approximately 20 ns. 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 internal electric field associated with this current density is about 210 kV/m which is more than twice the value of the external electric field strength.

SIMPLE MODEL FOR MEMBRANE POTENTIALS

For the simplified model used here, the cell membrane is thought of as a lipid bilayer essentially two lipid molecules thick (5 -10 nm). 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 interspersed with various macromolecules that serve as receptors, ion pumps, and other functions. Lipid bilayers exhibit very low conductivities and can be considered nonconducting to a first approximation. A value of $1 \mu\text{F/cm}^2$ is often used for the capacitance per unit area.

Several approaches can be used to find the membrane potential induced during an EMP, but the simplest is to use the current density and membrane capacitance. If the current density is assumed constant over some time interval, then the membrane potential at the end of that time interval is simply

$$V_m = \frac{J \cdot \Delta t}{C_m}$$

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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. 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 1.5×10^5 A/m² lasting for 10 ns. Using these values, a maximum membrane potential of 150 mV is predicted during the EMP exposure.

Considering 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, but one must also consider the limiting potential to which the membrane will 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, 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 roughly 5% of 2000 mV or about 100 mV. 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

While it is impossible to reliably draw conclusions 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. 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.

A potential biological effect that should be considered carefully is electroporation. Pore formation results in rapid changes in membrane potential and exposes the cell cytoplasm

to the extracellular medium. 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 which assumes 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. Other potential effects include conformational changes and rotational forces on membrane macromolecules.

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