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PHYSICAL PROPERTIES OF HIGH-VOLTAGE ELF ELECTROMAGNETIC FIELDS AND THEIR INTERACTION WITH LIVING SYSTEMS

T.S. Tenforde

April 1985

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T.S. Tenforde

Biology and Medicine Division

Lawrence Berkeley Laboratory

University of California

Berkeley, California 94720

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T.S. Tenforde
Biology and Medicine Division
Lawrence Berkeley Laboratory
University of California

1. INTRODUCTION

During the last two decades an increasing level of concern has been voiced in regard to the environmental impact and health effects of high voltage electrical systems. The interest of both the general public and the scientific community in these issues was greatly increased during the 1970's as a result of the environmental assessments resulting from the Navy's proposal to develop a submarine communication system transmitting extremely-low-frequency (ELF) electromagnetic fields (Hastings et al., 1977), and the hearings conducted by the New York Public Service Commission on the environmental compatibility and public need for a 60-Hz, 765-kV transmission line in upstate New York (Scott-Walton et al., 1979). As demonstrated by these environmental assessments, the range of potential biological effects from ELF fields is broad, and varies from direct physical phenomena such as contact currents to reports of subtle behavioral and physiological changes in animals and plants exposed to external fields. The study of these factors under controlled laboratory conditions has received increased financial support during the last decade from the Department of Energy, the U.S. Navy, the Electric Power Research Institute, and several public utilities. As a result, there has been a substantial increase in the extent to which the effects of ELF fields on living systems is understood (Graves et al., 1985 a,b).

The principal objective of this report is to describe the physical interaction of high-voltage ELF fields with living organisms, and especially human subjects. The emphasis will be placed on fields from 60-Hz transmission lines operating at high voltage, although many of the physical principles underlying the interaction of these fields with living systems pertain as well to other sources of high-intensity electric fields. The discussion of electromagnetic fields will also be limited to ELF fields and will not specifically consider static fields from high-voltage DC transmission lines or other sources.

2. HIGH-VOLTAGE TRANSMISSION LINE FIELDS

The transmission of 60-Hz electric power over long distances is generally accomplished through overhead transmission lines operating at high voltages on polyphase conductors. The associated 60-Hz electric and magnetic fields in the environment of these lines depend upon several parameters, including the line voltage, load current, phase spacing and line height (Zaborsky and Rittenhouse, 1954; Farr, 1980; Pansini, 1983). The maximum fields at one meter above ground level for line voltages of 345, 500 and 765 kV are shown in Table 1 (adapted from IEEE, 1984):

TABLE 1 60-Hz Electric and Magnetic Fields from High-Voltage Transmission Lines

Operating Characteristics and Fields	Line Voltage		
	345 kV	500 kV	765 kV
Load current (kA)	1.0	1.5	2.0
Conductor spacing (m)	7.3	10.4	13.7
Line height (m)	9.8	10.7	12.2
Maximum electric field (kV/m) at one meter above ground	5.3	8.8	12.9
Maximum magnetic field (G) at one meter above ground	0.194	0.279	0.330

Within a few meters of the centerline, the fields in air at ground level are reasonably uniform. Beyond the outer conductors, both the electric and magnetic fields decrease rapidly as a function of lateral distance and reach levels at the edge of the right-of-way that are typically less than 20% of the maximum values. Using the fundamental equations of electromagnetism, the spatial variation of fields associated with high voltage transmission lines can be predicted with

reasonable accuracy (Deno, 1976; Tell et al., 1977; Graves et al., 1985b). However, a fundamental limitation on the ability to calculate the ambient electric field is imposed by shielding from vegetation, large buildings, vehicles and other objects within the vicinity of a transmission line.

The 60-Hz electric fields that exist within the right-of-way under a high-voltage transmission line (typically 45 to 75 meters in width for line voltages of 345 to 765 kV) are one to three orders of magnitude greater than the fields usually encountered in the household environment. Although fields up to 0.25 kV/m may exist in the vicinity of small motors or electric blankets, the electric field levels from household appliances at a distance of 30 cm are typically 30 to 60 V/m (Sheppard and Eisenbud, 1977). The average electric fields within dwellings and away from appliances are generally in the range of 3 to 6 V/m (IIT, 1984; Deno, 1984; Graves et al., 1985b).

In contrast to power-frequency electric fields, the commonly encountered 60-Hz magnetic fields in the household and work environment can significantly exceed the field levels under transmission lines. Numerous rotatory devices such as hair dryers, electric shavers, mixers, circular saws, etc., produce local 60-Hz fields (within a few cm) that exceed 1 Gauss (Gauger, 1984). These fields, however, decrease rapidly as a function of distance and the average magnetic flux density at locations away from appliances within representative homes has been reported to fall in the range of 0.05 to 8 milligauss (Deno, 1984; Graves et al., 1985b).

3. INTERACTION OF POWER-FREQUENCY ELECTRIC FIELDS WITH MAN AND OTHER LIVING ORGANISMS

There are several important aspects of the interaction of ELF electric fields with living objects, including the perturbation of the field in the vicinity of an object (field enhancement effects), the induced surface charge, the induced internal electric field, contact currents and spark discharges. Each of these topics will be considered here, with emphasis being placed on describing the general physical features of the electric field interaction using simple concepts derived from electromagnetic field equations.

3.1 Quasi-Static Approximation

The radiating properties of power-frequency electromagnetic fields can be neglected. In analyzing their interaction with humans or other living objects, the fields can therefore be treated as resulting from static sources. This simplification, which is known as the "quasi-static approximation," results from two factors (Kaune and Gillis, 1981): (1) the wavelength of a 60-Hz field in a medium with the electrical properties of tissue is approximately 5000 m, which is much greater than the largest dimension of the body; (2) the skin depth, which is the distance from the body surface where the induced current

density is reduced to 37% of its value at the surface, is greater than 50 m in living tissues. This distance is also much greater than the largest dimension of the body.

As a consequence of the quasi-static approximation, the electric and magnetic field components of a 60-Hz electromagnetic field behave as though they were uncoupled in their interaction with body tissues. The electric and magnetic fields can therefore be treated separately in a theoretical analysis of the interaction of power-frequency electromagnetic fields with living objects.

3.2 The External Electric Field in the Proximity of a Living Object

The electrical conductivity of air is extremely small, $\sim 10^{-14}$ S/m, and air can therefore be treated as an insulator. In contrast, the conductivity of living tissues is in the range 0.02 to 1.5 S/m (Schwan, 1957, 1963; Schwan and Kay, 1956, 1957). A human within the electric field of a high-voltage transmission line thus behaves as a conducting object within an insulating medium. The presence of a man or other conducting objects significantly perturbs the local electric field, and this effect is most pronounced on portions of the body with small radii of curvature, such as the head or a raised hand. By treating the head as a sphere of radius R with a uniform capacitance and surface charge (Deno, 1977), it can be shown from electrostatic equations that the local electric field at the top of the head, E_o, is greater than the unperturbed field, E_∞, at a distance from the head. For a man of height, h, the approximate relation between E_o and E_∞ is given by the equation

$$E_o \simeq E_\infty (h/R) \tag{1}$$

Using the representative values h = 1.7 m and R = 0.08 m for an adult man, it is predicted from equation (1) that $E_o \simeq 21\ E_\infty$. Significant field enhancement thus occurs near the human head.

3.3 Induced Surface Charge Density on Living Objects

The induced surface charge density, σ, at the body/air boundary is given by the equation:

$$\sigma = \varepsilon_o \hat{n} \cdot \vec{E}_o - \varepsilon_i \hat{n} \cdot \vec{E}_i \tag{2}$$

where $\vec{E}_o$ and $\vec{E}_i$ are, respectively, the electric field intensities immediately outside and inside the body surface, $\hat{n}$ is a unit vector normal to the surface, and ε_o and ε_i are, respectively, the electric permittivities of air (8.85×10^{-12} F/m) and the body tissue. This expression for the surface charge can be simplified based on a consideration of the equation for charge conservation at the body/air boundary (Kaune and Gillis, 1981):

$$(\Lambda_o + j\omega\varepsilon_o)\hat{n}\cdot\vec{E}_o = (\Lambda_i + j\omega\varepsilon_i)\hat{n}\cdot\vec{E}_i \qquad (3)$$

where Λ_o and Λ_i are, respectively, the electrical conductivity of air and body tissue, ω is the angular field frequency (= $2\pi f$), and $j = \sqrt{-1}$. The first and second terms on each side of the equation represent, respectively, the conduction and displacement (capacitative) currents. In air $\Lambda_o \approx (3 \times 10^{-6})\omega\varepsilon_o$ and the conduction current can be neglected. For body tissues and fluids, Λ_i ranges from 0.02 to 1.5 S/m and the electrical permittivity is extremely large, $\gtrsim 10^5\ \varepsilon_o$ (Schwan, 1957, 1963) at ELF frequencies. For a 60-Hz field, $\Lambda_i \gtrsim 60\ \omega\varepsilon_i$ and the conduction current greatly exceeds the displacement current. Equation (3) can then be approximated as

$$j\omega\varepsilon_o\hat{n}\cdot\vec{E}_o \approx \Lambda_i\hat{n}\cdot\vec{E}_i \qquad (4)$$

Combining equations (2) and (4) gives the final simple expression for the induced surface charge density:

$$\sigma = \varepsilon_o(1 - j\omega\varepsilon_i/\Lambda_i)\hat{n}\cdot\vec{E}_o \approx \varepsilon_o\hat{n}\cdot\vec{E}_o \qquad (5)$$

The induced surface charge density is therefore dependent only on the normal component of the external electric field at the body surface, and is independent of the conductivity of the body tissues.

The surface charge acquired on the skin and body hair can lead to the perception of strong electric fields by humans and other forms of animal life. The surface charges induced by the field exert oscillatory forces which lead to hair vibration and a tingling sensation. Several laboratory and field tests have been carried out to determine the threshold electric field intensity perceived by humans (Kouwenhoven, 1966; Deno and Zaffanella, 1975; IEEE, 1978; Graham et al., 1984). These studies indicate that there is considerable variability in the threshold for perception of high-voltage electric fields, with some indication that women may be less sensitive than men, possibly because of hair length. A small fraction of individuals (< 5%) can perceive fields as low as 2 to 4 kV/m. The field levels at which 50% of the tested subjects reported a sensation on the skin or hair were generally in the range 10 to 20 kV/m. In one study, the 50% perception level was lowered to about 7 kV/m when the subjects raised their hands (IEEE, 1978). This reduced threshold is a result of the field enhancement effect described above.

3.4 Short-Circuit Current to Ground in Living Objects Exposed to High-Voltage Electric Fields

The current passing from a grounded animal to earth is defined as the "short-circuit" current, I_{sc}. Denoting the total induced surface charge by Q_s, then I_{sc} can be related to the average electric field at the body surface, E_o^{av}, and the total surface area, A, by the

following equation which uses the approximation given in equation (5) above:

$$I_{sc} = |dQ_s/dt| = \omega|Q_s| = \omega\int\int\sigma\, dS$$
$$\simeq \omega\varepsilon_o\int\int\hat{n}\cdot\vec{E}_o\, dS = \omega\varepsilon_o\, E_o^{av}\, A \qquad (6)$$

This relation between I_{sc} and E_o^{av} was shown by Kaune (1981) to provide a useful method for calculating the average electric field over the surfaces of humans and other animals in a high-voltage electric field. For a 70-kg man with a body surface area of 1.8 m^2, the short-circuit current in a 10-kV/m field is about 160 μA and the value of E_o^{av} predicted from equation (6) is 27 kV/m.

3.5 Contact Currents and Electric Shock Phenomena

Ungrounded metal objects within a high-voltage field can acquire a large surface charge and a high electrical potential relative to ground. Current flow is initiated when contact is made with the object by either a grounded or ungrounded person. The issue of electric shocks is a major practical concern in the vicinity of a high-voltage transmission line. Several classes of ungrounded or poorly grounded objects that represent a source of significant contact currents include large vehicles such as buses and tractor-trailers, large buildings with inadequate grounding of metal gutters and downspouts, wire fences and metal pipelines with long ungrounded sections, and farm equipment such as combines and tractors.

The severity of an electric shock depends upon a number of factors, including grounding conditions, magnitude of the contact current, duration of current flow and body mass. For adult humans insulated from ground by standing on a 0.3 m platform, the average body-to-ground capacitance was found to be approximately 275 pF and a shock sensation was observed at voltages exceeding 1 kV (Barthold et al., 1972). The threshold contact currents required to elicit both mild (perception) and severe (respiratory arrest and ventricular fibrillation) shocks have been well-studied in humans and in several species of animals with varying sizes. Early studies were conducted in the 1940's and 1950's by Dalziel, Kouwenhoven and others, and in recent years several summaries have been made of threshold currents for inducing electric shock phenomena in humans (Barthold et al., 1972; IEEE, 1978, 1984). Table 2 summarizes the body currents that elicit mild to severe responses. Currents above the 10 mA level represent a serious risk since the "let-go" threshold may be exceeded and the individual might not be able to release a charged object because of involuntary muscle contractions. In general, the contact currents that elicit reactions in 0.5% of adult human subjects are two to three times less than the levels which produce a 50% response. Also, the estimated level of the

TABLE 2 Human Reactions to 60-Hz Electric Currents

Reaction/Sensation	Average rms current (mA) to elicit effect at the 50% response level	
	Women	Men
Grip perception	0.73	1.10
Painful shock	6	9
Let-go threshold	10.5	16
Respiratory tetanus[a]	15	23
Ventricular fibrillation[a]	210	275

[a] Estimated values based on experimental animal studies and/or limited observations on humans.

let-go current in small children is approximately one-half as large as that for an adult man.

In order to limit hazards from contact currents, many states have adopted regulations based on the National Electrical Safety Code (NESC) prepared by the American National Standards Institute. The NESC requires utility companies to design transmission lines in a manner that limits the short-circuit current to ground from the largest anticipated vehicle (or other objects) to less than 5 mA. In practice, this limits the electric field over roadways to approximately 7 to 8 kV/m. It is important to realize that the NESC limit on I_{sc} will reduce contact currents between a person and a charged object to levels that are usually much below 5 mA because of impedance between the person and object, as well as person-to-ground and object-to-ground impedances.

3.6 Spark Discharges

Within a large electric field, capacitative spark dishcarges can occur between a person and a conductive object. A spark discharge can arise without direct contact if the person and object come close enough together (typically, <<1 cm) that the local electric field between them exceeds the dielectric breakdown level for air (3×10^6 V/m). Human reactions to spark discharges can be described either in terms of an

energy threshold given in millijoules (mJ) or a charge threshold given in microcoulombs (μC). A comparison of these thresholds is shown in Table 3 (data from IEEE, 1984).

TABLE 3 Perception Thresholds for Spark Discharges

Reaction/Sensation	Threshold for reaction in 50% of adult men tested	
	Energy (mJ)	Charge (μC)
Fingertip touch perception	0.14	0.3
Fingertip touch annoyance	1.3	0.9

For small objects with capacitance less than approximately 600 pF, the energy criterion appears to give the best fit to data on human perception to spark discharges (IEEE, 1978). For larger objects (such as automobiles) with a greater capacitance, the charge criterion gives a better fit to the data than the energy criterion.

3.7 Internal Electric Fields Induced in Living Objects Within a High-Voltage Field

The relative magnitudes of the normal components of the electric field existing outside and inside the air/body surface can be calculated from equation (4):

$$|\hat{n}\cdot\vec{E}_i| \simeq (j\omega\varepsilon_o/\Lambda_i)|\hat{n}\cdot\vec{E}_o| \simeq 10^{-7}|\hat{n}\cdot\vec{E}_o| \qquad (7)$$

It follows from equation (7) that the magnitude of the internal field is exceedingly small. For example, the magnitude of E_o at the top of the head is about 200 kV/m for a man standing in a 10-kV/m field, and E_i is approximately 20 mV/m. Since $\Lambda_i \simeq 0.1$ S/m for brain tissue, the induced current density in the head $J_i = \Lambda_i E_i \simeq 2$ mA/m^2 = 200 nA/cm^2.

The values of E_i and J_i within different parts of the body exhibit large variations. Parts of the body with small cross-sectional areas, such as the neck, knees and ankles, have the largest current densities. These regions, in effect, "concentrate" the induced current density.

Two techniques have been applied to the direct measurement of

induced electric fields in different anatomic locations within electrically conducting scale models of man. Guy et al. (1982) used thermography to quantify the current distribution in homogeneous scale models exposed to a high-intensity 57.3 MHz field. The measured current densities were then corrected for frequency and for the difference in electrical conductivity at 60 Hz relative to 57.3 MHz in order to estimate the current densities induced by a power-frequency field. A second and more direct approach was taken by Kaune and Forsythe (1985), who used an electric field probe to estimate the induced fields and current densities in different regions of saline-filled human models exposed to a 60-Hz electric field. The results of current density measurements by Guy et al. (1982) and by Kaune and Forsythe (1985) in several anatomic locations within conducting scale models of man are summarized in Table 4. The measured and theoretically predicted current densities are, in most cases, in reasonable agreement.

TABLE 4 Calculated and Measured Current Densities in Human Models

	Average r.m.s. vertical J_i (nA/cm^2) for E_o = 10 kV/m		
Body location	Calculated	Electrical measurement[a]	Thermography[b]
Neck	550	375	410
Chest	190	260	380
Abdomen	250	330	---
Ankle	2000	---	1950

[a] From Kaune and Forsythe (1985).
[b] From Guy et al. (1982).

4. INTERACTION OF POWER-FREQUENCY MAGNETIC FIELDS WITH MAN AND OTHER LIVING ORGANISMS

A fundamental difference in the interactions of power-frequency electric and magnetic fields with living objects is the fact that the magnetic field is neither enhanced at the body surface nor attenuated

within the body. The magnetic flux density, $\vec{B}$, is related to the magnetic field intensity, $\vec{H}$, through the reationship $\vec{B} = \mu\vec{H}$, where μ is the magnetic permeability. Because the magnetic permeability of living tissue is nearly identical to that of air, it follows that the magnetic flux density external to the body, $\vec{B}_o$, is approximately equal to that within the body, $\vec{B}_i$, in an ELF field. At high frequencies, where the skin depth is comparable to or less than body dimensions and reflection losses cannot be neglected, this relationship between $\vec{B}_o$ and $\vec{B}_i$ will no longer hold. At power frequencies, however, the skin depth is greater than 50 meters and reflection losses at the surface can be neglected, so that the relation $\vec{B}_o = \vec{B}_i$ is valid to a high degree of accuracy.

The electric field induced within tissues exposed to an ELF magnetic field can be calculated from Faraday's law

$$\oint \vec{E}\cdot d\vec{l} = - d/dt \iint \vec{B}\cdot d\vec{S} \tag{8}$$

where $d\vec{l}$ is a vector element of length directed along the closed loop over which the line integral is calculated, and $d\vec{S}$ is a differential area vector normal to the surface bounded by the closed loop. For the specific case of a circular loop with radius R and a spatial orientation that is orthogonal to the external field $\vec{B}_o$, the magnitude of the induced internal electric field, E_i, is given by

$$E_i = R\omega B_o/2 \tag{9}$$

The induced current density, J_i, is equal to

$$J_i = \Lambda_i E_i = R\omega\Lambda_i B_o/2 \tag{10}$$

Both E_i and J_i are therefore linear functions of the field frequency and the radius of the loop.

It is of interest to calculate the relative magnitudes of the current densities induced by the electric and magnetic fields associated with a 60-Hz high-voltage field. Consider, for example, a 10-kV/m, 0.5-G power-frequency field that is vertically incident on the head of a standing human (R = 0.08 m and Λ_i = 0.1 S/m). From equation (10), the magnetically-induced current density circulating around a loop at the perimeter of the head is equal to $J_{i,B}$ = 7.5 nA/cm^2. The electrically-induced current density, $J_{i,E}$, is directed along a vertical axis within the head and has a magnitude of ≈60 nA/cm^2. The electrically-induced current density is therefore about eight times as large as that induced by the magnetic field, and has a different spatial orientation within the head.

In terms of direct physical hazards from the magnetic fields associated with high-voltage, power-frequency systems such as transmission lines, the currents induced in long stretches of ungrounded metal conductors can present a risk of electrical shock. This situation could arise, for example, in the case of an ungounded

metal fence or a pipeline running parallel to a high-voltage transmission line. As in the case of shocks from electrically-charged conductors, this hazard can be avoided by adherence to proper grounding practices.

Another aspect of magnetic field interactions that should be noted is the inability of humans to perceive relatively large power-frequency magnetic fields, in direct contrast to the sensory stimulation provided by power-frequency electric fields with high intensities. In a careful study involving more than 200 human subjects exposed to 60-Hz magnetic fields with r.m.s. intensities up to 15 Gauss, Tucker and Schmitt (1978) found no evidence for field perception when they had successfully removed all sources of auxilliary clues such as vibration and audible noise associated with activation of the magnet coils.

5. CORONA AND RELATED PHENOMENA

Corona discharges occur at locations on high-voltage conductors where the surface fields exceed the dielectric breakdown level of air. Enhanced local fields that produce corona arise at surface irregularities caused by such factors as nicks in the conductor, attached insects, or hanging water drops. Corona energy loss occurs primarily as heat, but acoustic, electromagnetic and photic energy also result from a discharge. These modes of energy loss can result in audible noise, radio and television interference, and the production of oxidant gases such as ozone. A brief description of these secondary effects of corona are given in the following sections.

5.1 Audible Noise

Corona-generated audible noise covers the entire audio frequency spectrum up to 20 kHz, and is present as both discrete tones and as broadband noise. The most noticeable discrete tone is at 120 Hz, but the greatest annoyance to humans results from the broadband noise at frequencies above 500 Hz.

The audible noise level from corona on high-voltage conductors is strongly dependent on the moisture content of the air. Audible noise levels are normally expressed in decibels (dB) relative to a reference level of 20 micropascals (= 2×10^{-5} newton/m^2), and they are "A-weighted" to correspond to frequency-dependent variations in human auditory sensitivity. The A-weighted sound pressure levels above which complaints arise is approximately 52 dB, and levels above 58 dB are generally objectionable (Perry, 1972). For comparison, the normal conversation level between two individuals spaced two meters apart in an outdoor environment is about 55 dB. The Environmental Protection Agency has recommended that the average noise level from corona discharges should not exceed 55 dB in a rural environment. In addition, eleven states have established permissible audible noise limits that vary as a function of frequency and encompass a range of sound pressure levels from 40 to 70 dB.

5.2 Radio and Television Interference

Corona-generated electromagnetic noise in the low (30 to 300 kHz), medium (300 kHz to 3 MHz) and high (3 to 30 MHz) frequency ranges can interfere with amplitude-modulated radio signals. In the VHF range from 30 to 300 MHz, noise from corona and from discharges at mechanical gaps in transmission line conductors can interfere with AM television video signals. Frequency-modulated radio signals and television audio signals are both immune to this type of noise.

The electromagnetic noise produced by corona and gap discharges is expressed in dB relative to a reference field strength of 1 μV/m. The extent of radio and television noise interference is influenced by several factors related to transmission line design (e.g., the mechanical condition of conductors and their voltage, size, spacing and height above ground), and by meterological factors such as the moisture content of the air. In general, noise in the AM radio band produces little interference at levels below 54 dB, and noise in the VHF band that is less than 47 dB does not appreciably interfere with television video signals (IEEE, 1984).

Radio and television noise interference associated with transmission lines is currently not regulated at the state or federal levels. Thirty-two states require utilities to perform an environmental assessment for new high-voltage lines, and to limit noise levels in compliance with the Federal Communication Commission code which states that 24 dB is a satisfactory signal-to-noise ratio for radio broadcasting.

5.3 Ozone and Other Oxidants

Corona discharges from high-voltage conductors produce ozone (O_3) and other oxidants such as nitrous oxides (Roach et al., 1978). From theoretical considerations, the maximum possible concentration of corona-generated ozone near a 765-kV line under worst-case conditions (rain and a low wind velocity) is about 7 to 9 p.p.b. Actual measurements under worst-case conditions indicate that ambient ozone concentrations attributable to transmission lines do not rise above 2 p.p.b. This level is well below the Environmental Protection Agency Ambient Air Quality Regulation which limits ozone to a maximum one-hour concentration of 80 p.p.b. (not to be exceeded more than once per year).

Other oxidants produced by corona discharges such as oxides of nitrogen are present near high-voltage lines in concentrations that are 5 to 20 times less than the concentration of ozone. The concentrations of these oxidants produced by corona are also far below the permissible limits prescribed by the EPA Ambient Air Quality Regulations.

6 PHYSICAL HAZARDS ASSOCIATED WITH POWER-FREQUENCY ELECTROMAGNETIC FIELDS

Studies during the past decade have demonstrated several physical phenomena associated with high-voltage electromagnetic fields that are potentially hazardous to humans and to various other life forms. In this section a brief summary will be given of electromagnetic interference (EMI) effects on cardiac pacemakers, as well as various direct effects of high-voltage fields on animals and plants.

6.1 Pacemaker Interference

Certain types of modern cardiac pacemakers exhibit malfunction in response to EMI produced either by endogenous myopotentials or by external sources such as high-voltage systems. The modern implantable pacemakers are microprocessor-controlled and function in a "demand" mode in which stimulatory pulses are delivered to the heart only if it fails to exhibit intrinsic electrical activity. The endogenous cardiac activity is detected by a signal sensing circuit in order to avoid competitive pacing between the pacemaker's stimuli and the heart's intrinsic activity. The modern pacemakers also contain a noise detection circuit that can discriminate electric fields with different frequencies and waveforms than those associated with the heart's bioelectric activity. When EMI is sensed, the demand pacemaker reverts to a fixed-rate pacing mode which may be asynchronous with the normal cardiac activity. This pacing mode is frequently referred to as the "reversion" or "noise" mode of operation, and can be undesirable if the pacemaker signals are competitive with the intrinsic cardiac electrical activity.

Two different configurations of electrode leads are used in pacemakers, and these have very different sensitivities to EMI. In one style, termed the "bipolar" design, both leads are implanted within the heart at a typical separation distance of 3 cm. In the second style, termed the "unipolar" design, the cathode lead is implanted in the heart and the pacemaker case serves as the anode. Because of the considerable physical separation of the anode and cathode leads in the unipolar design, this type of pacemaker provides a large antenna for the reception of EMI. Of the two designs for pacemaker electrode configurations, only the unipolar type has been found to be sensitive to EMI. Among the 350,000 to 500,000 individuals in the U.S. that have implanted pacemakers, approximately 50% have models with the unipolar electrode design.

During the past decade several laboratory tests and studies on pacemaker patients have been conducted to assess the response of different pacemaker models to power-frequency electric and magnetic fields (Jenkins and Woody, 1978; Butrous et al., 1982, 1983 a,b; Griffin, 1985). Two types of pacemaker malfunctions have been observed in response to EMI: (1) an aberrant pacing rate, with irregular or slow pacing, and (2) reversion to fixed-rate (asynchronous) pacing. The

probability that a malfunction will occur in the presence of an external electromagnetic field is strongly dependent on the pacemaker model, since some manufacturers have incorporated a feature into their pacemakers that automatically decreases the sensitivity of the amplifier circuit when EMI is sensed. These specific brands of pacemaker thereby avoid reversion to an asynchronous mode in response to EMI.

The range of power-frequency field strengths that cause reversion to an asynchronous mode of operation has been characterized for unipolar pacemaker models that are vulnerable to EMI. Power-frequency electric fields with intensities in the range of 3 to 20 kV/m (producing body currents of 26 to 203 μA) have been found to cause reversion or an aberrant pacing rate in 15 of 16 models that were tested (Butrous et al., 1983b). With all but two of the pacemaker models, both of which were produced by the same manufacturer, fields greater than 5 kV/m were required to produce a malfunction. Power-frequency magnetic fields ranging from 1.1 to 4 G were found to produce reversion in 77% of the pacemakers tested, with the average threshold field level for an effect being 2.1 G (Jenkins and Woody, 1978). The levels of power-frequency electric fields that were observed to produce pacemaker malfunction are within the range of field levels associated with high-voltage power lines and other types of electrical systems. The occurrence of EMI effects on the pacemakers of workers at electrical substations has recently been described by Butrous et al. (1983a). In contrast, pacemaker malfunctions produced by power-frequency magnetic fields require field intensities that are greater than those associated with high-voltage transmission lines and most other types of electrical systems.

Griffin (1985) has estimated the total population of pacemaker patients in the U.S. who might be at serious risk to the effects of EMI. He assumed that (1) 350,000 to 500,000 individuals wear pacemakers, (2) that 50% are of the unipolar design, (3) that 10 to 20% of the unipolar pacemakers are highly sensitive to EMI, and (4) that 20 to 25% of the patients with sensitive pacemakers are totally dependent on the pacemaker to sustain their cardiac rhythm. With these assumptions, it can be calculated that approximately 3,500 to 12,000 pacemaker wearers might be at serious risk to EMI. However, it must be borne in mind that only a small fraction of the individuals at risk are likely to encounter a source of EMI such as a high-voltage transmission line during the time periods when their cardiac function is totally dependent on an implanted pacemaker. The above estimate of the population at risk must therefore be regarded as an upper bound that perhaps greatly overestimates the actual probability for the occurrence of a potentially fatal pacemaker malfunction in response to EMI.

There are at the present time no federal or state regulations requiring manufacturers to use procedures that would ensure pacemaker immunity to EMI. However, as discussed earlier some pacemaker manufacturers have used state-of-the-art technology to provide immunity from the effects of EMI, and it would clearly be advisable if other

pacemaker suppliers were to follow this example.

6.2 Physical Hazards to Animal and Plant Life

Three types of power-frequency electromagnetic field effects on living systems that are well understood in terms of the relevant physical interaction mechanisms will be discussed in this section. These three phenomena are (1) step potentials in beehives, (2) stray voltage effects on livestock, and (3) corona discharges on the tips of plant leaves.

Beehives in strong electric fields can develop significant electrical potential differences over dimensions that are comparable to the length of a bee's body. This potential difference is called a "step potential" since the bee experiences a shock each time it takes a step. The threshold field level is in the range of 1.8 to 4.1 kV/m for inducing physiological and behavioral changes in the honeybees such as weight loss and adnormal deposition of propolis at hive entrances (Greenberg et al., 1981). At a field level of 7 kV/m, which produces a total hive current of 90 μA, there is a significant decrease in foraging by the bee colony, a loss of queens, and a greatly reduced survival rate. The solution to this problem is straightforward, since a grounded metal cage or screen placed over a hive that is located in the vicinity of a high-voltage transmission line will reduce the field within the hive to a level that is not harmful.

Another direct effect of power-frequency electric fields on animals results from "stray voltages" that can cause microshocks upon contact with metallic surfaces on devices such as automatic feeders, etc. (Gustafson and Albertson, 1982). These stray voltages arise from small potential differences that develop between a grounded neutral conductor and the true earth ground (neutral-to-earth voltages). Livestock such as dairy cattle can perceive low-level shocks from stray voltages, with a resulting effect on productivity and health. Stray voltage sources are in the electrical distribution system rather than the primary electrical supply lines, and these voltages are not a problem directly associated with high-voltage transmission lines. The mitigation of neutral-to-earth voltages can be achieved by various methods which include modification of the neutral voltage system, altering the total electrical load, or modifying the conducting surfaces present in areas where stray voltage problems are encountered.

The sharp tips of leaves on certain species of plants can be damaged by corona discharge when the plants are in high-voltage fields at intensities exceeding 20 kV/m (Johnson et al., 1979). However, as recently reviewed by Graves et al. (1985b), a number of studies have failed to detect any adverse effects of power-frequency fields up to 30 kV/m on plant life. The plant parameters that were found to be unaffected by high-voltage fields include growth rate, seed production and germination, and physical characteristics such as height, mass and leaf area.

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