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ELECTRIC AND MAGNETIC FIELDS

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BIOLOGICAL INTERACTIONS OF EXTREMELY-LOW-FREQUENCY ELECTRIC AND MAGNETIC FIELDS

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ABSTRACT

A description is given of the fundamental physical properties of extremely-low-frequency (ELF) electromagnetic fields, and the mechanisms through which these fields interact with the human body at a macroscopic level. The mechanisms through which ELF electric and magnetic fields induce currents in humans and other living objects are described. Evidence is presented that cell membranes play an important role in transducing ELF signals. Both experimental evidence and theoretical models are described that relate pericellular currents and electrochemical events at the outer membrane surface to transmembrane signaling pathways and cytoplasmic responses. Biological responses to ELF fields at the tissue, cellular and molecular levels are summarized, including new evidence that ELF field exposure produces alterations in messenger RNA synthesis, gene expression and the cytoplasmic concentrations of specific proteins.

INTRODUCTION

At a macroscopic level the interactions of ELF fields with humans and other living organisms can be described in a quantitative and relatively simple manner through the use of Maxwell's equations. The initial sections of this paper describe the nature of the fields and currents induced within the body by ELF fields applied through air, which is the typical human exposure situation. The final two sections of the paper describe the interactions of ELF fields with living tissues at the cellular and molecular levels.

PHYSICAL PROPERTIES OF ELF FIELDS

By definition ELF refers to the range of electromagnetic field frequencies below 300 Hz. In materials with the electrical and magnetic properties of living tissues, these fields have a long wavelength (~ 5000 m) and skin

depth (~150 m). As a consequence, in their interactions with humans and other living organisms ELF fields behave as though they are composed of independent electric and magnetic field components. This "uncoupling" of the orthogonal electric and magnetic components of an ELF field is commonly referred to as the "quasi-static approximation," which permits the radiating properties of the field to be neglected in describing its interactions with living organisms.

The units used for ELF electric and magnetic fields are defined by laws that describe the forces they exert on an electric charge, Q . In the case of an ELF electric field with intensity $\vec{E}$, the force $\vec{F}_e$ exerted on a charge at rest is given by Coulomb's law, $\vec{F}_e = Q\vec{E}$. An ELF magnetic field with flux density $\vec{B}$ is defined in terms of the force $\vec{F}_m$ exerted on a charge moving with velocity $\vec{v}$ (the Lorentz force law), $\vec{F}_m = Q(\vec{v} \times \vec{B})$. The term in parentheses is a vector cross-product equal in magnitude to $|\vec{v}||\vec{B}|\sin \theta$, where θ is the angle between $\vec{v}$ and $\vec{B}$. With $\vec{F}_m$ in newtons, Q in coulombs, and $\vec{v}$ in m/s, the MKS/SI unit for the magnetic flux density $\vec{B}$ is the tesla. One tesla is equal to 10^4 gauss, where the gauss is the CGS unit of flux density. It is important to note from the Lorentz force law that the maximum force is exerted on the moving charge Q when $\vec{v}$ and $\vec{B}$ are orthogonal, and no force is exerted when they are parallel. In addition, it should be noted that a magnetic field exerts no force (and hence does no work) on a charge that is not moving.

SOURCES OF HUMAN EXPOSURE TO ELF FIELDS

Natural phenomena such as thunderstorms and solar activity produce ELF electric and magnetic fields in the environment. These fields are generally of low intensity, and the predominant source of human exposure is from fields produced by man-made sources. Fig. 1 is a schematic depiction of the typical range of ELF electric and magnetic fields encountered in the home and near high-voltage transmission lines. The highest level of exposure to ELF electric fields occurs under high-voltage transmission lines and in substations, where the ambient field levels can reach intensities of 15-20 kV/m. In contrast, the highest levels of ELF magnetic field exposure occur in the home or workplace, rather than in the vicinity of power lines. For example, 50 or 60 Hz magnetic fields near the surfaces of appliances (e.g., hair driers) or electric tools (e.g., circular saws) can exceed the

field levels under transmission lines by two orders of magnitude. For this reason, research on the potential health effects of occupational or residential exposure to ELF fields has focused on the magnetic field component during the past several years.

INDIRECT COUPLING OF ELF FIELDS TO HUMANS

Indirect coupling occurs when a person either makes contact with an electrically charged object in an ELF field, thereby initiating contact currents, or comes into sufficiently close proximity to the object to initiate a transient discharge (often called a "spark discharge"). These phenomena are complex functions of the ELF contact voltage, stimulus duration, contact area, the degree of moisture in or on the skin, and the relative humidity and ambient temperature [1]. The reactions of both laboratory animals and humans to steady-state contact currents have been extensively studied during the past 60 years. Table 1 summarizes the threshold current levels that produce responses ranging in severity from perception to lethality in humans. In general, the thresholds are significantly lower in women than in men because of differences in the average body size. Regulations that limit steady-state contact currents to less than 5 mA are based in the United States on the National Electrical Safety Code [2].

DIRECT COUPLING OF ELF FIELDS TO HUMANS

The electric and magnetic components of an ELF field have several distinctly different features in their interactions with humans and other living organisms. Because of the quasistatic approximation and the uncoupling of the electric and magnetic components of an ELF field, the physical properties and biological interactions of these two field components will be treated separately in the following paragraphs.

ELF electric fields

The electrical conductivity of air is approximately 14 orders of magnitude less than that of living tissues at ELF frequencies. Consequently, the body behaves like a good electrical conductor in the presence of an ELF electric field. As a result, an electrical charge is developed on the surface of the body, and the electric field that penetrates into the body is very small compared to the external field in air. At ELF frequencies the ratio of the

intensity of the internal electric field induced in body tissue, E_i , to the intensity of the field in air immediately outside of the body surface, E_o , is given by the relationship [3,4]:

$$E_i \approx \frac{2 \pi f \epsilon_o E_o}{\kappa} \approx 10^{-7} E_o \quad (1)$$

In equation (1) f is the field frequency, ϵ_o is the permittivity of free space (8.85×10^{-12} F/m), and κ is the conductivity of tissue, which ranges from approximately 0.01 S/m (bone) to 1.5 S/m (cerebrospinal fluid and urine). In simple physical terms, equation (1) represents a boundary condition at the body surface which requires that the external displacement current (in air) is equal to the internal conduction current (in tissue). This boundary condition is formulated for the case where the external conduction current and the internal displacement current are negligible, which is the situation for a living body in an external ELF electric field.

As illustrated in Fig. 2, an ELF electric field is distorted significantly in the vicinity of the body's surface. Because the body is comparable to a good conductor immersed in an insulating medium, the electric field lines are aligned approximately perpendicular to the body's surface and the tangential field component is nearly zero. In regions of the body with small radii of curvature, such as the top of the head, the electric field lines become concentrated and the local field intensity is significantly greater than the intensity in air at a distance of several meters from the body. At the top of the head, for example, the local field is about 20 times greater than the field at a distance [4,5]. This phenomenon, which is usually called "field enhancement," greatly complicates the dosimetry of ELF electric fields in the proximity of the body.

One of the best known consequences of the surface charge developed on the body in an ELF electric field is the phenomenon of hair vibration (piloerection). Because of the charging of the shaft of a hair, it experiences a mechanical stress as a result of the electrical force exerted by the external electric field. This effect can be described quantitatively by the Maxwell stress tensor, $T = \epsilon_o E^2/2$. As illustrated in Fig. 3 the frequency of hair vibration is twice that of the applied ELF electric field, i.e., the rate of hair oscillation is 120 Hz if the applied field oscillates at 60 Hz. The

phenomenon of piloerection is generally believed to be responsible for perception of external ELF electric fields by humans and lower animal species. The threshold for field detection is quite variable among humans and between animal species, but nearly all humans can detect 60-Hz electric fields with intensities of 20 kV/m and above [4]. The threshold for detection can be lowered significantly by extending the finger tips in the direction of the electric field source, thereby causing field enhancement in the region of the fingers, hand and forearm. In furry laboratory animals such as rodents, the threshold for field perception is apparently lower than that for humans (see, for example, [6]).

ELF magnetic fields

In contrast to the electric component, the magnetic component of an ELF field does not induce a surface charge and it penetrates the body with negligible attenuation since the magnetic permeability of tissue is nearly equal to that of air. The lack of distortion of an ELF magnetic field by the human body is illustrated in Fig. 4. As a consequence, the dosimetry of ELF magnetic fields in and near a living organism is relatively simple in comparison to the dosimetry of ELF electric fields.

Induced body currents

Another feature of the electric and magnetic components of an ELF field that differs significantly is the direction of currents that they induce in the body. The induced current density in tissue can be predicted from Ohm's law and is given by $\vec{J}_i = \kappa \vec{E}_i$, where $\vec{J}_i$ is the internal current density expressed in the MKS/SI unit of ampere per square meter. As illustrated by Fig. 5, in a homogeneous body with uniform electrical conductivity the induced currents resulting from the interaction of a vertical ELF electric field would be expected to flow predominantly in the direction of the long axis of the body. This expectation has been confirmed using saline-filled models of the human body [1]. However, it is important to recognize that local tissue electrical properties may be quite inhomogeneous, leading to significant distortions of the current pathways relative to those predicted from simple models.

ELF magnetic fields induce electrical currents in tissue that circulate in loops within planes that are orthogonal to the direction of incidence of the field, as illustrated in Fig. 6. This relationship between a

time-varying magnetic field and the circulating electric field that it induces is expressed formally by Faraday's law,

$$\frac{\partial \vec{B}}{\partial t} = - \nabla \times \vec{E} \quad (2)$$

where $\nabla \times \vec{E}$ is the curl of the electric field vector. As discussed above for ELF electric fields, the magnetically-induced electric field gives rise to currents that are predicted from Ohm's law. For a vertical magnetic field incident on an erect human subject, the induced current density is expected to circulate in planes that are orthogonal to the long axis of the body. Again, however, it must be borne in mind that inhomogeneities in tissue electrical properties will distort the induced current pathways. The magnitude of the magnetically-induced current density can be predicted easily for simple geometries. Consider, for example, a model of the human body as a uniformly conductive ellipsoid of revolution with the major axis, z , parallel to the long axis of the body. If a sinusoidal ELF magnetic field with an amplitude B_0 is incident along the z -axis, then the peak amplitude of the induced current density in a plane defined by the orthogonal x and y coordinate axes is given by,

$$J = \frac{2 \pi f B_0 \kappa}{a^2 + b^2} (b^4 x^2 + a^4 y^2)^{1/2} \quad (3)$$

where a and b are the semi-axes of the ellipsoid. The induced currents circulate in closed loops in the plane defined by the x and y coordinates (orthogonal to the z axis). For a prolate spheroidal model of a uniformly conductive object ($a = b$), equation (3) reduces to,

$$J = \pi f B_0 \kappa R \quad (4)$$

where $R [= (x^2 + y^2)^{1/2}]$ is the radius of the current loop in a plane orthogonal to the incident field. From equation (4) it is evident that the magnitude of the induced current density increases as a function of the loop radius. Hence the induced current density reaches its largest value in a loop defined by the perimeter of the body's surface.

Nonthermal interactions of ELF fields

An important aspect of the physical interactions of ELF fields applied to the body through air is their nonthermal nature. The specific absorption

rate (SAR) in tissue is related to the induced electric field by the equation,

$$\text{SAR} = \frac{\kappa E_i^2}{2\rho} \quad (5)$$

where ρ is the tissue density. Under typical conditions the highest electric field that can be induced in tissue by an applied ELF field in air is of the order of 1 V/m. Assuming an average tissue conductivity of 0.2 S/m, the SAR resulting from a 1 V/m field in tissue would be 10^{-4} W/kg. This value of the SAR is more than four orders of magnitude less than the basal metabolic rate of a resting subject. The rate of tissue heating by the induced field is given by SAR/C , where C is the heat capacity. Assuming an average value of the heat capacity of $3.5 \text{ kJ}\cdot\text{kg}^{-1}/^\circ\text{C}$, an SAR of 10^{-4} W/kg would cause the temperature to rise at a rate of approximately $3 \times 10^{-8} ^\circ\text{C}/\text{sec}$ in tissue. Because of the efficient heat loss mechanisms possessed by the body, this rate of heating would not lead to a measurable temperature increase. Although field levels exceeding 1 V/m in tissue can be induced magnetically by pulsed fields with large time rates of change of the magnetic flux density, these pulsed fields cannot be generated at a sufficiently high repetition rate to produce measurable tissue heating. In general, the interactions of ELF fields applied through air to humans or other living objects are therefore of a purely nonthermal nature.

BIOLOGICAL EFFECTS OF ELF FIELDS

Several extensive reviews of the published literature have demonstrated that the biological effects of ELF fields are correlated with the current density induced in tissue [7 - 13]. A few biological effects have been observed to result from induced current densities that are comparable in magnitude to the naturally occurring currents that flow in the body as a result of endogenous electrical activity of excitable tissues such as the heart and brain, i.e., 0.1 to $10 \text{ mA}/\text{m}^2$. These effects include the visual phenomena known as electrophosphenes and magnetophosphenes, and effects on the circadian rhythm in melatonin synthesis by the pineal gland. At higher levels of induced current density in the range of 10 to $100 \text{ mA}/\text{m}^2$, a variety of alterations in tissue and cellular properties have been reported to occur

in response to the application of ELF fields, including beneficial effects such as the facilitation of bone fracture reunion. With induced current densities in the range of 100 to 1000 mA/m², thresholds for neuronal and neuromuscular effects are exceeded. Finally, at levels above 1 A/m² the induced currents in tissue can produce severe, and potentially fatal, respiratory and cardiac effects. These biological effects, and the range of current densities required to produce them, are summarized in Table 2.

At high levels of induced current, approaching or exceeding 1 A/m² in tissue, significant effects on the membrane potentials of cells have been documented. In addition, polarization of the counterion atmosphere at the membrane surface occurs in strong ELF fields. These interactions have been implicated in many of the membrane-mediated biological effects that result from applying large electrical currents to living tissues [14]. The major challenge that faces us in ELF field research at the present time is the elucidation of mechanisms by which exposure to relatively weak fields, of the order of 1 V/m in tissue or less, can result in reproducible biological effects. To explain such effects, a large number of physical and electrochemical models have been proposed in which the cell membrane is viewed as playing a primary role in transducing the weak signals presented by induced ELF electrical currents in tissue [13,15,16]. A growing body of experimental evidence suggests that electrochemical events initiated at the membrane surface by circulating pericellular currents can alter ion binding to membrane macromolecules and influence ligand-receptor interactions at the cell surface (e.g., the binding of hormones, growth factors, etc.). These field interactions at the cell surface can trigger transmembrane phenomena involving alterations in ion transport and changes in the electroconformational states of membrane proteins. Events initiated at the inner membrane surface in response to these transmembrane signals can, in turn, influence the cytoplasmic concentrations of biologically important "second messengers" such as calcium ions and cyclic nucleotides that regulate macromolecular synthesis and control cellular growth and functional states. The molecular details of this cascade of transduction events that carry ELF field signals from the extracellular milieu into a living cell, as depicted in Fig. 7, remain to be elucidated by careful experimentation. However, the present state of knowledge strongly implicates the cell membrane as a site of ELF field transduction and signal amplification.

INTERACTIONS OF ELF FIELDS WITH CELL MEMBRANES

A substantial amount of experimental evidence obtained with in vitro cell and organ cultures indicates that the pericellular currents produced by ELF fields lead to structural and functional alterations in components of the cell membrane. These effects have been reported most frequently for pulsed fields with ELF repetition frequencies, but a significant body of evidence also indicates that sinusoidal ELF fields can influence membrane properties. Examples of ELF field effects on cellular membranes include the following: (1) altered Ca^{++} binding at the outer membrane surface [17, 18]; (2) suppression of T-lymphocyte cytotoxicity, which is dependent on cell-surface antigen recognition and binding [19]; (3) inhibition of lymphocyte activation by mitogenic compounds that bind to the cell surface [20]; (4) altered response of adenylate cyclase to exogenous hormones applied to bone cells [21] and to fibroblasts [22]; (5) altered distribution of cell-surface receptors and decreased lifetimes of ligand-receptor complexes [23]; (6) changes in the distribution of transferrin receptors in human tumor cells [24]; (7) altered release of insulin molecules from pancreatic cells [25]; (8) altered cellular partitioning in an aqueous two-phase system that is sensitive to changes in membrane composition [26]; (9) changes in glycosylation of cell-surface components [27].

Several innovative theoretical models have recently been proposed to explain the types of ELF signal transduction processes that might occur at cell surfaces and lead to the types of membrane changes described above. In one model, electric fields are postulated to change the intrinsic conformational equilibrium of membrane-bound proteins such as ATPases with resultant effects on enzyme kinetics [28]. Another model of electric field interactions focuses on electrical double-layer processes at the cell membrane, and describes the ionic fluxes that occur across excitable membranes in terms of electrodiffusion equations [29]. When the effects of a time-varying electric field are incorporated into these equations, it is predicted that ion concentration changes occur in the electrical double layers that surround charged groups at the outer and inner membrane surfaces. These concentration changes are predicted to influence ion transport through membrane channels, with the effects being maximal for imposed fields in the ELF range.

A generalized model of ELF field interactions with phospholipid bilayer membranes has been proposed on the basis of the observations that lipid domain structures exist in eukaryotic cell membranes at prephase transition temperatures [30]. These domain structures are susceptible to deformation by applied fields, thereby producing an alteration in the transmembrane diffusion of solutes. This model is supported by experimental evidence for the release of an encapsulated chemotherapeutic drug, cytosine arabinofuranoside, from liposomes exposed to either electromagnetic fields [31] or static magnetic fields [32].

Another model that has formed the basis for a number of experimental studies and theoretical efforts during the past few years is the "ion cyclotron resonance" model [33]. Several experimental studies have provided evidence that the combination of a weak static magnetic field, comparable in strength to the geomagnetic field, and a time-varying magnetic field in the ELF frequency range can produce resonance interactions that influence ion movements through membrane channels and other biological phenomena. The physical mechanism underlying this effect has been suggested to be ion cyclotron resonance [33 - 36]. In this process a resonant transfer of energy from a time-varying magnetic field occurs when its frequency matches the cyclotron resonance frequency of an ion moving within a static magnetic field. The resonance condition is formally expressed by the equation,

$$f_c = QB/2\pi m \quad (6)$$

where f_c is the ion cyclotron resonance frequency and m is the ion mass. For the typical range of the geomagnetic field over the surface of the earth (30 - 70 μ T), the resonant frequencies of many biologically important ions such as Na^+ , K^+ and Ca^{++} fall within the ELF range.

Several lines of experimental evidence suggest that ion cyclotron resonance interactions can influence biological processes. Four recent types of experiments have led to reports that certain combinations of static magnetic field flux density and time-varying magnetic field frequency can produce alterations in (1) the rate of calcium ion release from the surfaces of cells in brain tissue [37], (2) the operant behavior of rats in a timing discrimination task [38,39], (3) calcium-dependent diatom mobility [40,41], and (4) calcium ion uptake by human lymphocytes [42].

Although these experimental results suggest a resonance mechanism through which weak static and ELF fields could produce measurable biological effects, the interpretation of this work presents several theoretical difficulties. There are four major problems with the ion cyclotron resonance theory: (1) the collision frequency of ions undergoing cyclotron resonance motion in membrane channels is required to be orders of magnitude less than the typical collision frequency in an aqueous solution at physiological temperatures; (2) the interaction energy of the weak static magnetic field with biological ions is several orders of magnitude less than the Boltzmann thermal energy, kT ($= 4.28 \times 10^{-21}$ J at 310 K); (3) the thermally generated electrical noise (Nyquist noise) present in ion transport channels that traverse biological membranes is approximately two orders of magnitude greater than the electric field established in these channels by the resonant time-varying magnetic field [1]; and (4) for ion motion that is constrained to lie along a prescribed path, such as the helical path envisioned by Liboff [33] for ion transport through membrane channels, it follows directly from the equation of motion for the particle that a static magnetic field cannot influence the ion movement and establish a resonance condition [43]. The ion cyclotron resonance interaction is thus limited to unconstrained ion movements through membrane channels. All these factors would interfere with the establishment of ion cyclotron resonance conditions in combined static and time-varying magnetic fields. Obviously there is a need to refine the theoretical description of this phenomenon before it can form a plausible basis for weak field interactions with biological membranes.

CELLULAR AND MOLECULAR RESPONSES TO ELF FIELDS

In view of the large number of membrane processes that have been reported to be altered as a result of exposure to ELF fields, it would be expected that cellular biochemistry, physiology and growth patterns would also be affected. In this context, a number of literature reports have appeared which suggest that cellular and tissue responses to ELF fields do occur, and involve effects such as altered synthesis of RNA, DNA and proteins, changes in hormone production, modification of cell-mediated immune responsiveness, and changes in cell growth rate and differentiation. Rather than attempting to summarize this body of evidence (see [7] - [10]), selected

observations of cellular responses to ELF fields will be described with the intent of illustrating the types of changes in gene expression and macromolecular synthesis that have been reported to occur in cells exposed to ELF fields.

In studies with dipteran (Sciara and Drosophila) salivary gland cells, it has been demonstrated that exposure to either pulsed or sinusoidal electromagnetic fields leads to altered messenger RNA transcription patterns [44 - 46]. This effect is accompanied by a significant change in the spectrum of cellular proteins synthesized by the exposed cells relative to control cells [47]. As shown in Fig. 8, a total of 248 polypeptides in the control cells were resolved by two-dimensional electrophoresis, while 326 were observed in cells exposed to a 72-Hz pulsed magnetic field. The polypeptides synthesized in the dipteran salivary gland cells were specific to the characteristics of the ELF field to which these cells were exposed, with various polypeptides being either enhanced in quantity or suppressed relative to those observed for unexposed cells. Recent studies with cultured human cells have also demonstrated that an increased level of specific RNA transcripts occurs in response to ELF field exposure [48]. Using the technique of dot blot hybridization, it was observed that exposure to pulsed or sinusoidal ELF fields increased the levels of RNA with specific homology for β -actin, histone H2B and v-myc DNA. The observation that the number of transcripts of the v-myc oncogene were increased in cells exposed to ELF signals, including 60-Hz sine waves, deserves particular attention in future experiments.

Increases in the synthesis of specific proteins have also been observed in other studies on cells exposed to ELF fields. For example, it has been shown that ornithine decarboxylase levels are increased in several lines of cultured cells after exposure to a 60-Hz electric field [49]. The elevation in cytoplasmic concentration of this enzyme in cells exposed to a 60-Hz field for 1 h is transient, as illustrated in Fig. 9. Ornithine decarboxylase is essential for polyamine biosynthesis, and is activated by a number of chemicals that bind to receptors at the cell surface and stimulate cell proliferation. One example is the class of tumor promoters known as phorbol esters, and the results of the 60-Hz electric field studies described above

suggest that ELF field interactions may alter cellular biochemistry in a manner similar to these compounds. Phorbol esters have been shown to produce large elevations in ornithine decarboxylase activity via their binding to membrane-associated phosphokinase C receptors and the subsequent production of new messenger RNA specific for ornithine decarboxylase [50].

The recent experimental findings described in this paper provide a useful set of clues regarding the biochemical events that occur in response to ELF field signals transmitted from the cell surface into the cytoplasm. The further elucidation of these signal transduction mechanisms constitutes a major challenge for future research on ELF field interactions with living systems.

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TABLE 1

Human reactions to 60-Hz electric currents

Reaction/Sensation	Average r.m.s. 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	15	23
Ventricular fibrillation	210	275

TABLE 2

Induced current density and biological effects*

Current density (mA/m ²)	Biological Effects	Projected health risk
<10	Magnetophosphenes Electrophosphenes Subtle tissue effects such as changes in pineal melatonin circadian rhythms (generally reversible)	Possibly none
10 - 100	Various tissue effects (including acceleration of bone fracture reunion)	Small (possibly none)
100 - 1000	Thresholds for neuronal and neuromuscular stimulation	Possible risk
>1000	Extrasystoles, ventricular fibrillation, muscular tetany, respiratory effects	Definite

*Typical range of endogenous current densities in the body is 0.1 - 10 mA/m².

FIGURE LEGENDS

- Fig. 1. Range of 60-Hz electric field levels that are frequently encountered in homes and under distribution and high-voltage (HV) transmission lines in the United States. The thick part of each bar represents the typical range of exposure, while the ends of the bar denote the low and high limits of exposure levels. The magnetic flux density is expressed in milligauss, which is equal to 0.1 microtesla. (Adapted from Fig. 2 of [1] and Fig. 8 of the final report of the International Electricity Research Exchange working group on "Epidemiological Studies Relating Human Health to Electric and Magnetic Fields: Criteria for Evaluation," issued June 22, 1988.)
- Fig. 2. Representation of the human body as a conducting object exposed to a vertical ELF electric field applied through air, which is a poorly conducting medium. The electric field lines are nearly perpendicular to the body's surface, and are concentrated in regions of the body with small radii of curvature such as the head.
- Fig. 3. Illustration of the charging of a hair on the body surface in the presence of a high-intensity ELF electric field. The mechanical stress resulting from electrical forces exerted on the charged hair cause it to vibrate. The hair vibration frequency is twice the frequency of the applied electric field.
- Fig. 4. Representation of the lines of flux from a vertical ELF magnetic field in the presence of a human body. The lines of magnetic flux are not distorted and pass through the body with negligible attenuation.
- Fig. 5. Lines of induced electric current in the body of an erect human exposed to a vertical ELF electric field. The induced current is predominantly in the same direction as the applied field, although significant horizontal components occur in regions such as the axilla and groin where the current path turns and enters the arms and legs. Deviations of the current pathway from the vertical direction are also expected to occur in regions of the body with anisotropic electrical properties.

- Fig. 6. Illustration of circulating electric fields and currents induced in the human body by an ELF magnetic field incident in the vertical direction.
- Fig. 7. Depiction of the proposed sequence of membrane-mediated events that lead to cellular and tissue responses to an applied ELF field.
- Fig. 8. Changes in cellular proteins of dipteran salivary gland cells exposed for 45 min to pulsed and sinusoidal ELF fields or subjected to heat stress. The total number of polypeptides resolved by two-dimensional gel electrophoresis of proteins extracted from cells exposed to the ELF fields was equal to or greater than the number observed in control cells. In contrast, heat shock suppressed the number of polypeptides relative to the control level. The response of the dipteran cells to ELF fields was signal-specific, with several new polypeptides being observed in the exposed cells relative to controls. (Adapted from Fig. 1 of [47].)
- Fig. 9. Changes in ornithine decarboxylase activity in cultured human and mouse cells exposed for 1 h to a 1-V/m, 60-Hz electric field applied to the culture medium by electrodes. The increased enzyme activity was transient, and peaked at 1 to 2 h following termination of the electric field exposure. (Adapted from Figs. 1 and 2 of [49].)

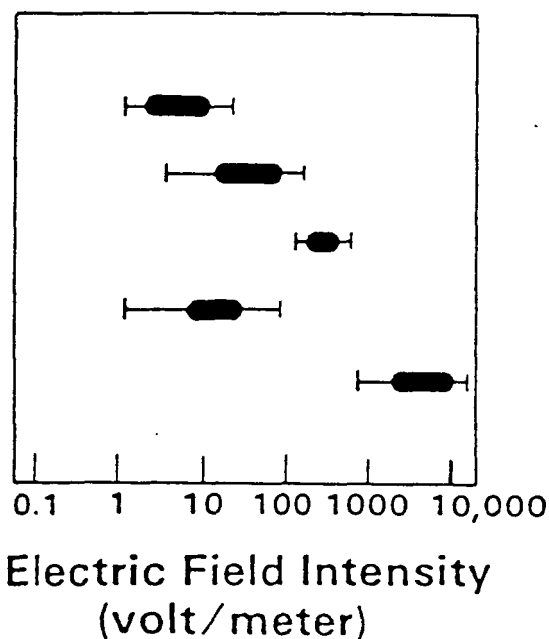
Range of 60-Hz Electric and Magnetic Fields Frequently Encountered in the United States

Within homes:

- Away from appliances
- Next to appliances
- Electric blankets

Under distribution lines:

Under HV transmission lines:



Within homes:

- Away from appliances
- Next to appliances
- Electric blankets

Under distribution lines:

Under HV transmission lines:

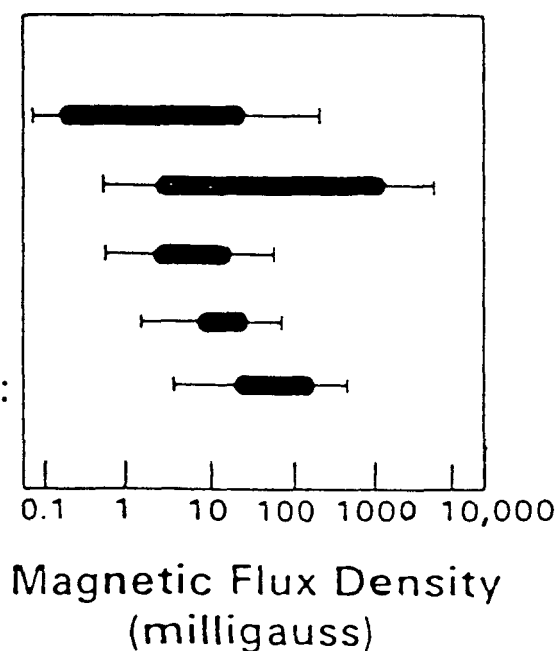


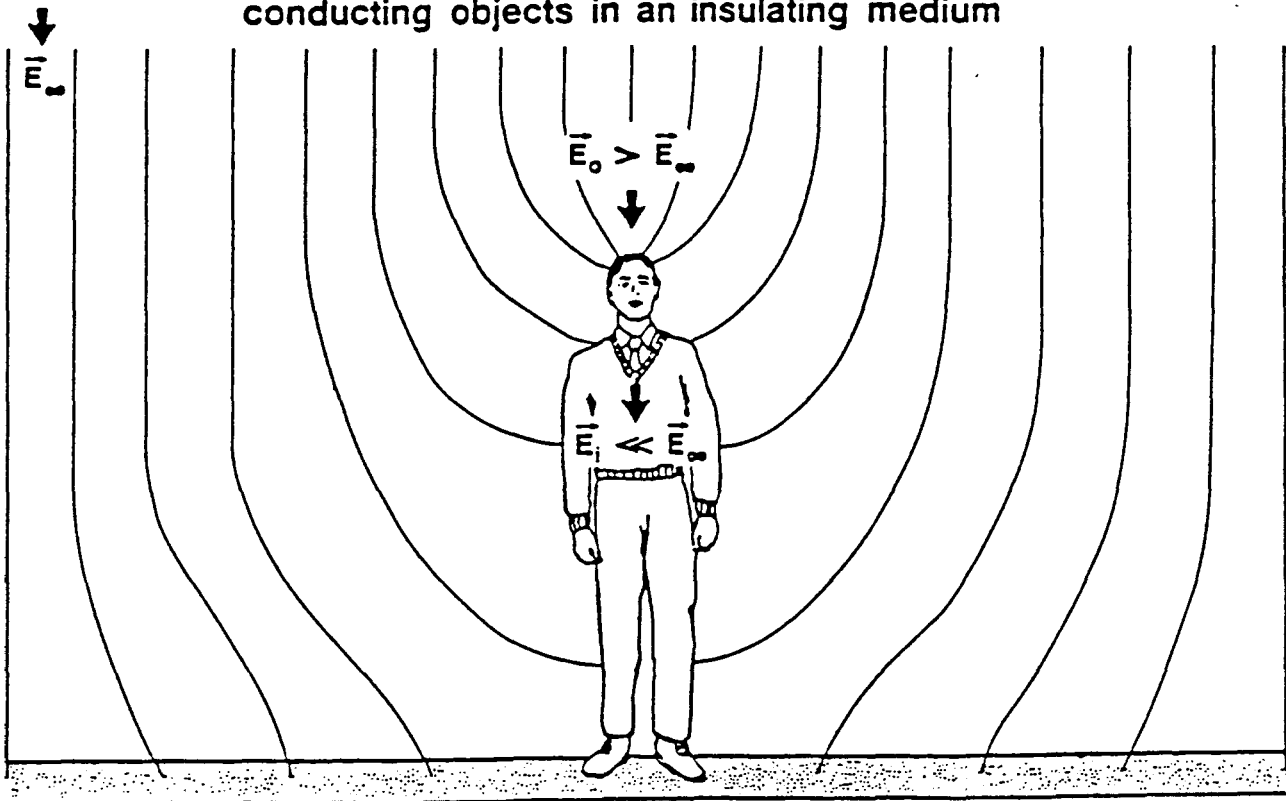
Figure 1

ELF Electric Field Near a Conducting Body

Conductivity of air $\kappa_0 \approx 10^{-14}$ S/m

Conductivity of tissues $0.01 < \kappa < 1.5$ S/m

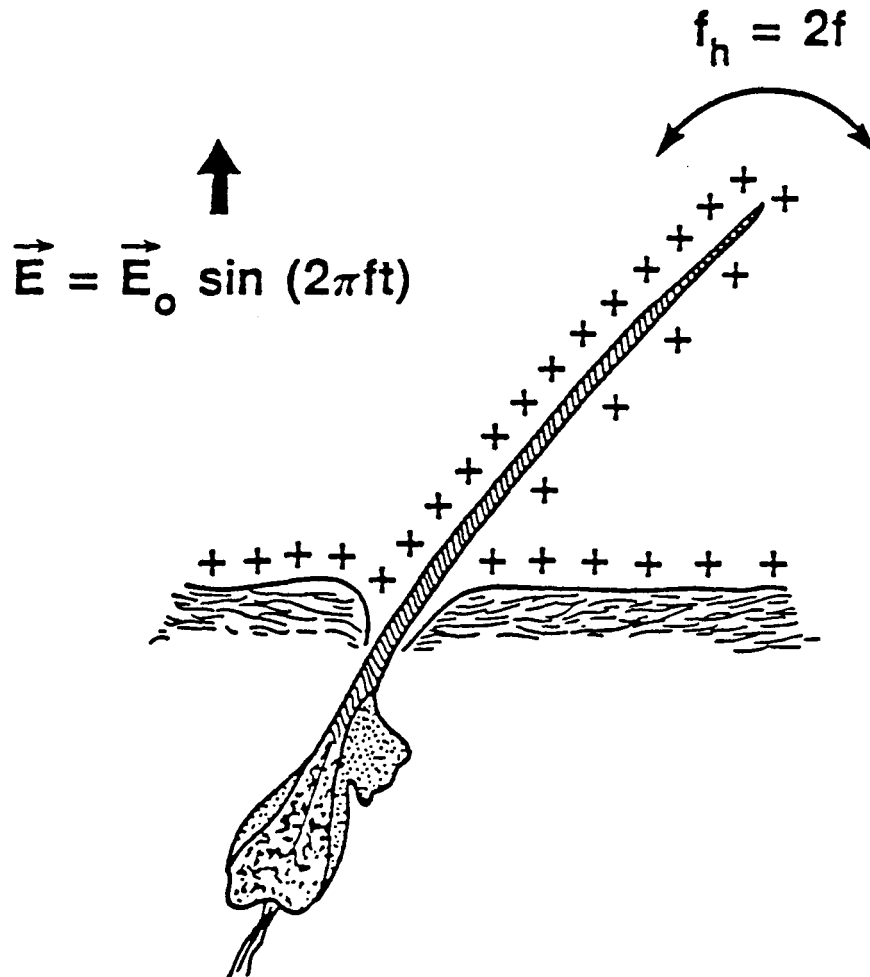
Animals within an ELF field can be modeled as conducting objects in an insulating medium



At body surface, tangential components of $\vec{E}_0$ and $\vec{E}_i$ are nearly zero, and so the field lines are approximately perpendicular to the body surface.

Figure 2

Hair Vibration in an ELF Electric Field



Mechanical stress on hair:

$$T = (\epsilon_0/2) E^2 = (\epsilon_0/4) E_0^2 [1 - \cos(4\pi ft)]$$

ϵ_0 = permittivity of air = 8.85×10^{-12} farad/m

f = electric field frequency (60 Hz)

$f_h = 2f$ = hair vibration frequency (120 Hz)

Figure 3

ELF Magnetic Field Near a Body

Magnetic permeability of tissue is approximately equal to that of air ($\mu_0 = 4 \pi \times 10^{-7} \text{ H/m}$)

- The lines of flux of an external ELF magnetic field pass through the body without significant attenuation

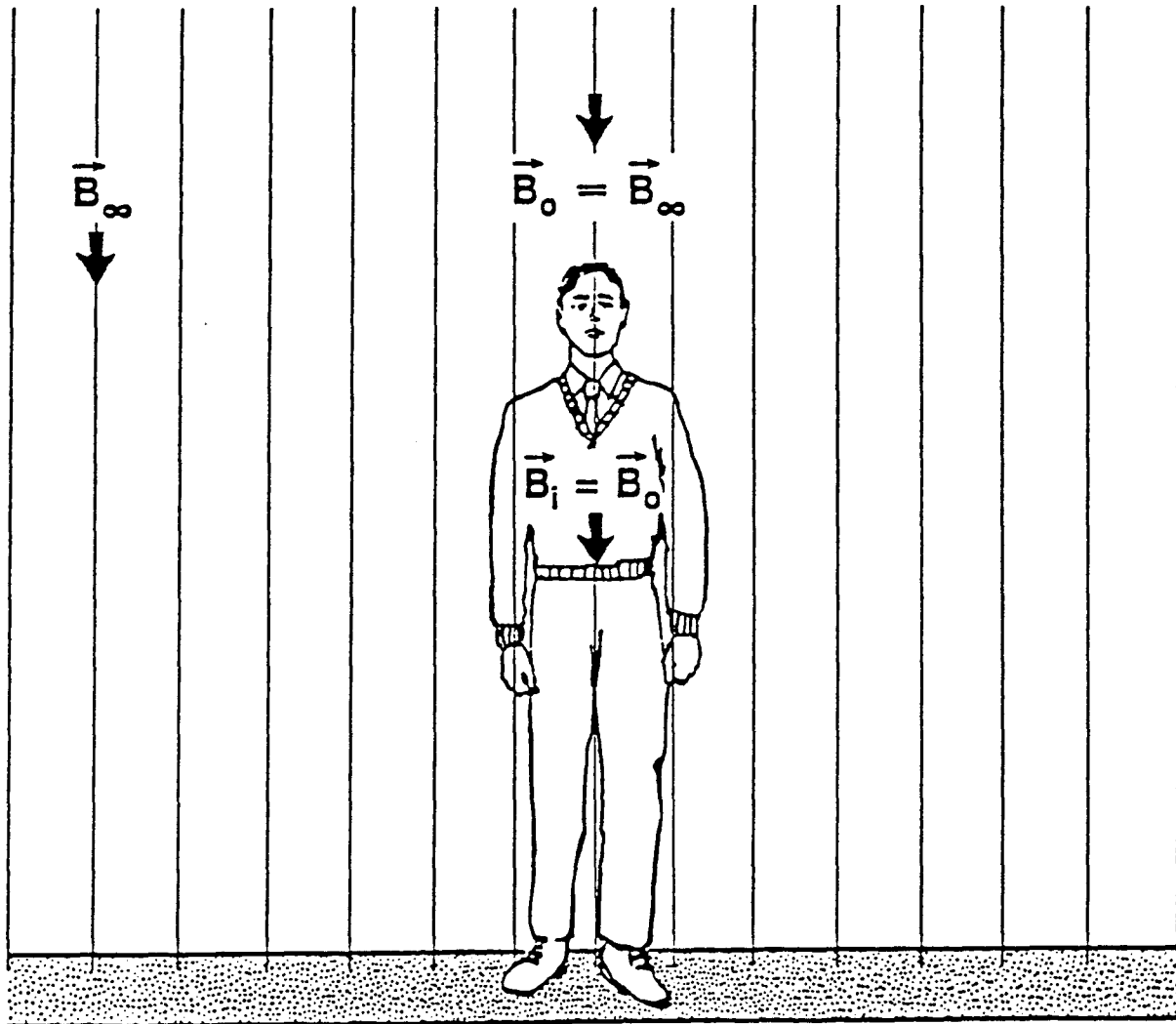


Figure 4

Induced Body Currents from ELF Electric Field

An external ELF electric field, $\vec{E}_o$, induces an internal field $\vec{E}_i \lesssim 10^{-7} \vec{E}_o$, and current density $\vec{J}_i = \kappa \vec{E}_i$.

If $\vec{E}_o$ is vertical, $\vec{E}_i$ and $\vec{J}_i$ are primarily in the vertical direction.

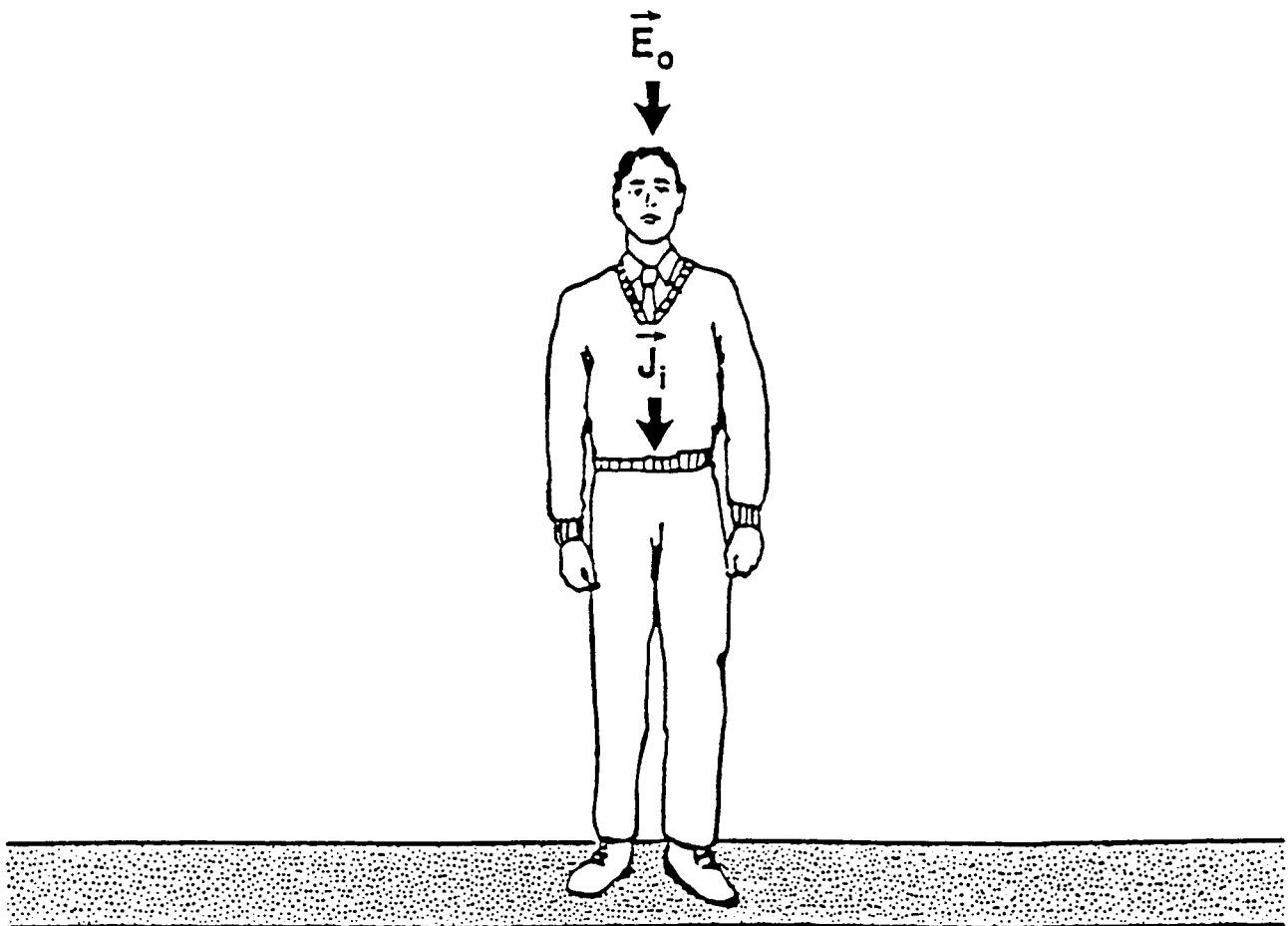


Figure 5

Induced Body Currents from ELF Magnetic Field

An ELF magnetic field induces a circulating electric field in accord with Faraday's law:

$$\frac{\partial \vec{B}}{\partial t} = - \nabla \times \vec{E}.$$

The circulating current density $\vec{J} = \kappa \vec{E}$.

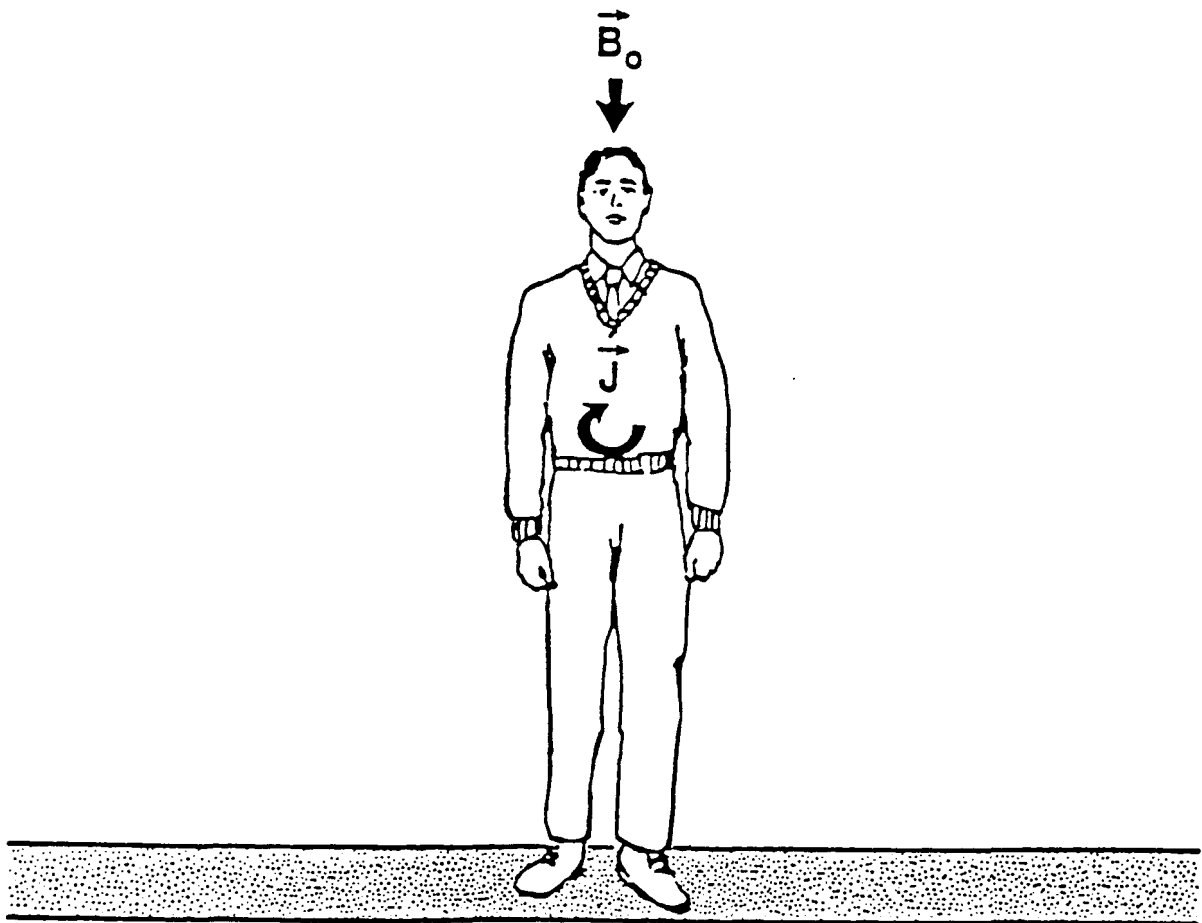


Figure 6

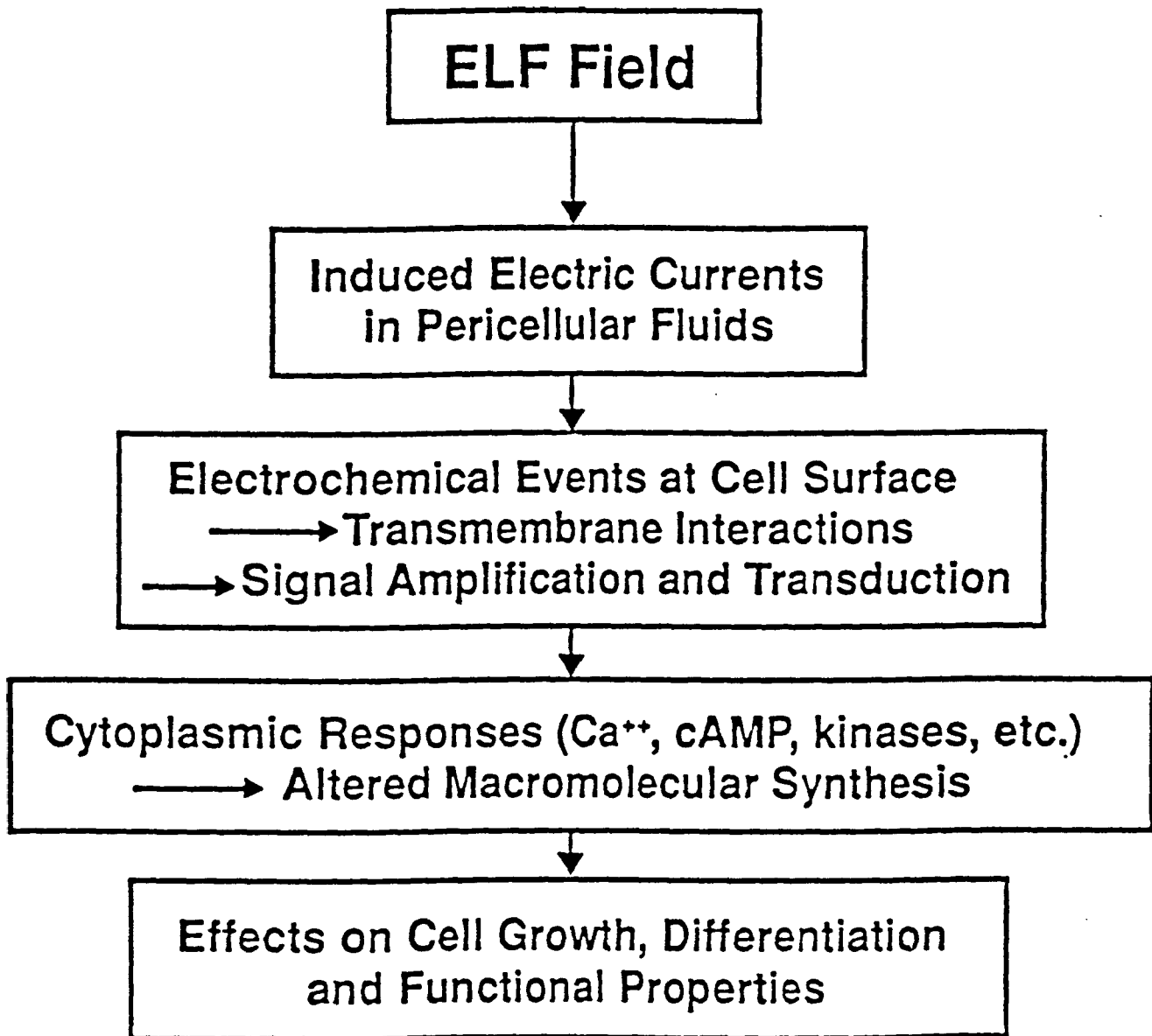
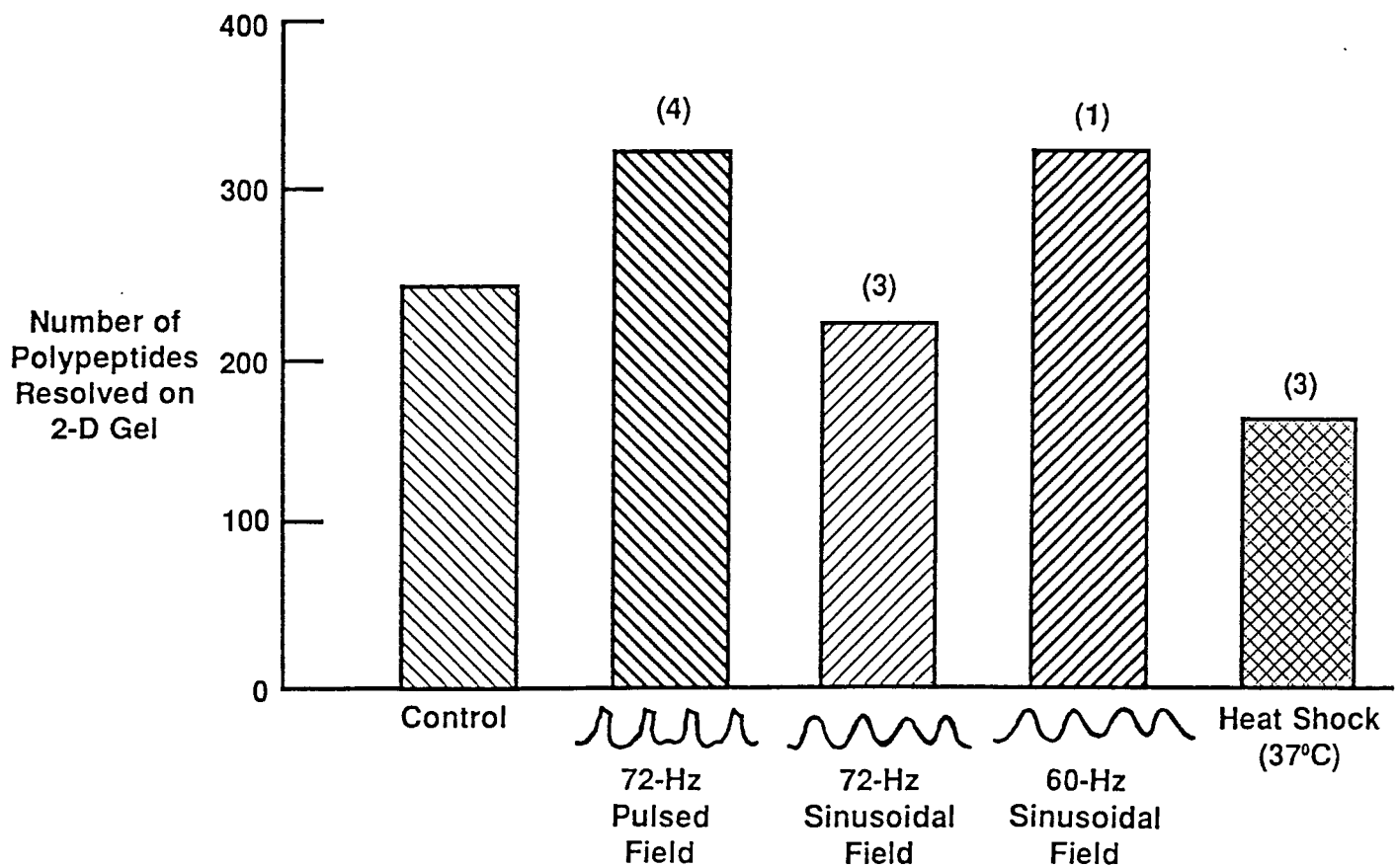


Figure 7

Proteins in *Sciara coprophila* Salivary Gland Cells
Exposed to ELF Magnetic Field Signals



(Numbers in Parentheses are the Numbers of Signal-Specific Polypeptides)

Figure 8

Effects of 60-Hz Electric Fields on Ornithine Decarboxylase Activity

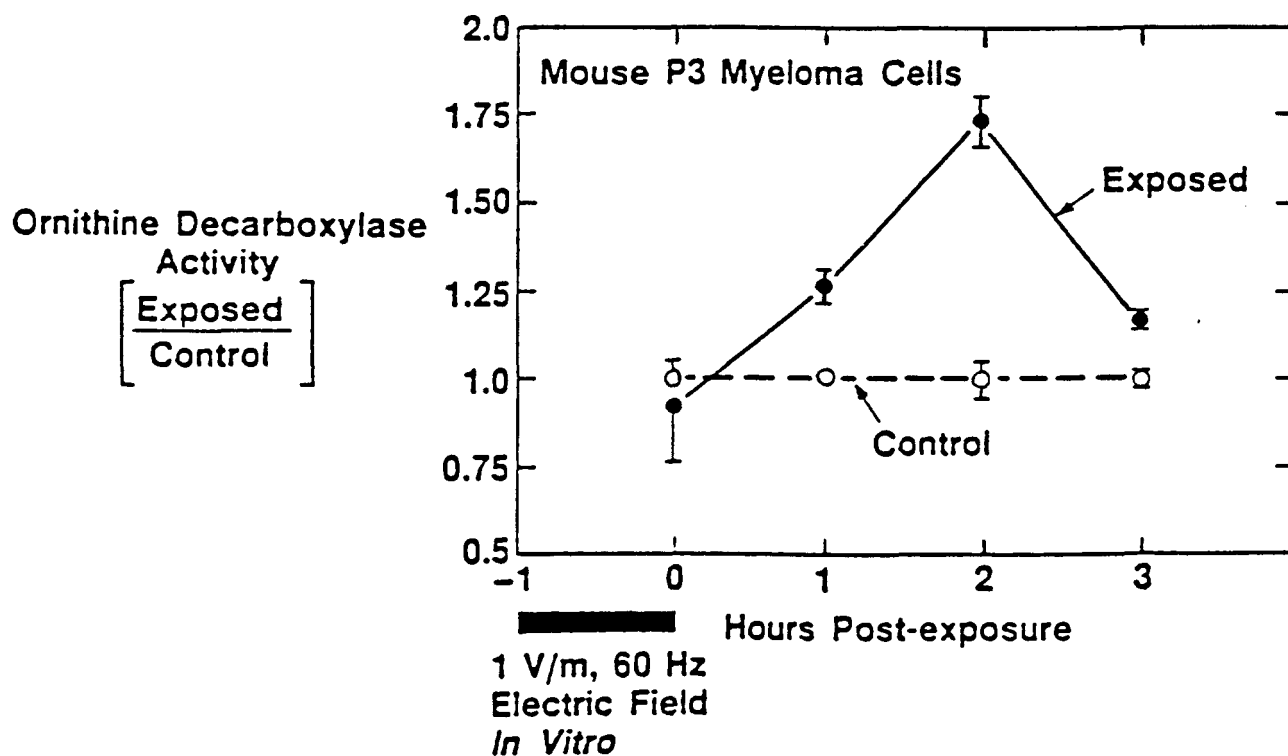
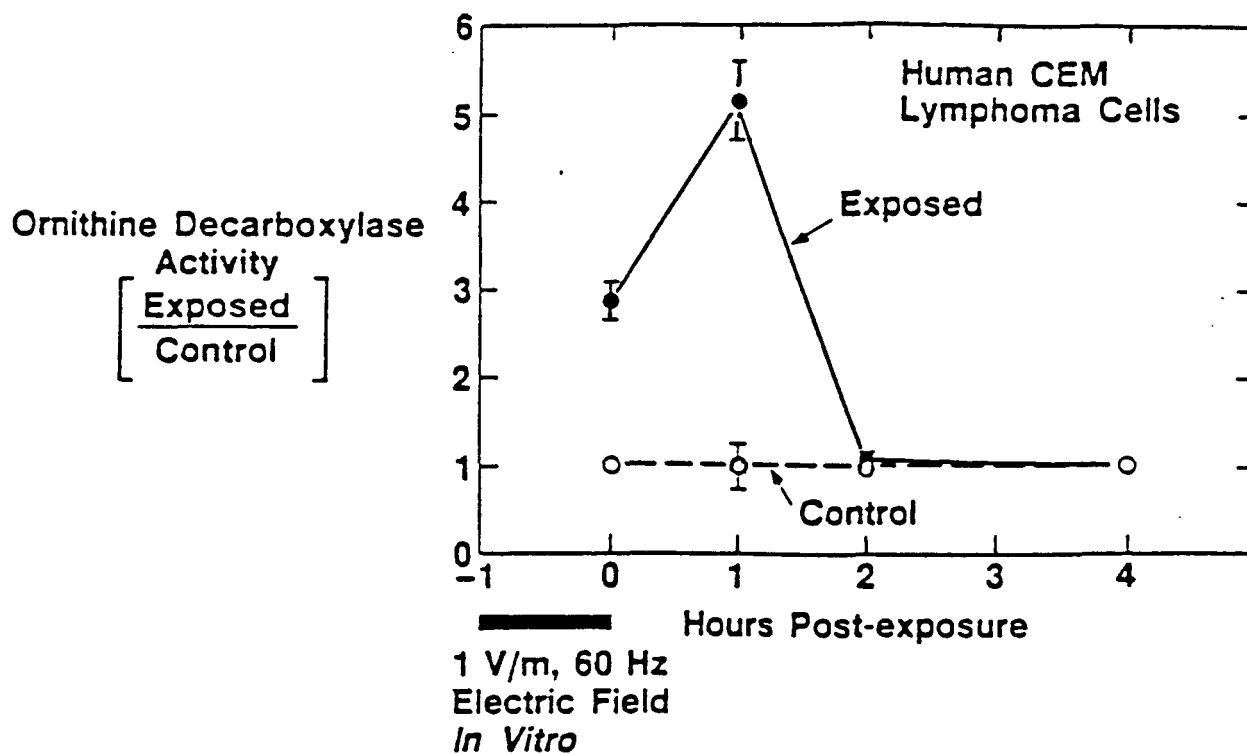


Figure 9