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INTERACTION OF EXTREMELY LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS WITH HUMANS

T. S. Tenforde*
Biology and Medicine Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

and

W. T. Kaune**
Biology and Chemistry Department, Pacific Northwest Laboratories, Richland, WA 99352

Abstract—**The dosimetry and physical interaction mechanisms of electromagnetic fields with frequencies in the extremely low frequency (ELF) range (below 300 Hz) are described. The mechanisms through which ELF electric and magnetic fields induce electric currents in living organisms are summarized, with particular emphasis on humans. Topics that are discussed include: (1) sources and measurements of ELF electric and magnetic fields; (2) direct and indirect coupling of these fields to humans; (3) transient discharges and contact currents, and the thresholds for human response to these phenomena; (4) protective measures for the mitigation of potential ELF field effects on humans; and (5) mechanisms of interaction of ELF fields with cellular and tissue systems, with emphasis on field transduction mechanisms involving the cell membrane.**

I. INTRODUCTION

NUMEROUS sources of electromagnetic fields exist in nature and in the occupational and residential environments. In nearly all instances, these fields pose no obvious threat to human health or safety and are generally discussed as an inevitable by-product of modern technology. However, public awareness of the ubiquitous nature of these fields and the growing controversy over their potential effects on living systems have stimulated the research community to define more precisely the physical properties of these fields and to delineate the thresholds for their possible effects on human health and the environment.

In this paper, we discuss the physical nature and the measurement of electromagnetic fields in the extremely low frequency (ELF) range below 300 Hz, including the 50-Hz and 60-Hz frequencies used worldwide in power transmission and distribution systems. A detailed discussion is given of direct and indirect mechanisms by which these fields can couple to living systems. Tangible effects of ELF fields, such as human perception, annoyance and shock phenomena, are described in quantitative terms. Methods for mitigating the effects of these fields under conditions that pose a potential risk to human health and safety are described. Finally, a description is given of the mechanisms that have been proposed as a basis for the interaction of ELF fields with living systems at the cellular and tissue levels.

II. PHYSICAL QUANTITIES, UNITS AND MEASUREMENT TECHNIQUES FOR ELF ELECTRIC AND MAGNETIC FIELDS

II.1. *Electric field terms and units*

Any system of electric charges produces an electric field, **E**, at all points in space. **E**, a vector quantity, is defined so that an electric charge placed in it will experience a force, **F**, given by

$$\mathbf{F} = q\mathbf{E}, \tag{1}$$

where q is the magnitude of the charge placed in the field. In the International System of Units (SI), the unit of electric charge is the coulomb (C). The smallest quantity of electric charge that has been observed in nature is that of an electron or proton, 1.6×10^{-19} C. It appears that all observable quantities of charge are integral multiples of the electronic charge. The unit of electric field strength is volt per meter (V/m). It is usually easier to determine the electric potential, V, than the electric field because the potential is not dependent on the physical geometry of a given system (e.g. locations and sizes of conductors). The SI unit of electric potential is the volt (V).

The relationship between V and E can be calculated without difficulty in a few systems. The simplest example, and one of considerable practical importance, is that of

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* Address reprint requests to: T. S. Tenforde, Mailstop 74-157, Lawrence Berkeley Laboratory, No. 1 Cyclotron Road, Berkeley, CA 94720.

** Present address: National Bureau of Standards, Boulder, CO 80303.

two large parallel conducting plates. If an electric potential, V, is produced between the two plates, by removing a charge, $+q$, from one and placing it on the other, an electric field, **E**, will be established. Except near the edges of the plates, the electric field between the plates will be uniform and perpendicular to their surfaces. The magnitude, E, of this field is related to V by

$$E = V/h, \tag{2}$$

where h is the separation between the plates.

Electric fields exert forces on charged particles. In an electrically conductive material, such as a living tissue, these forces will set charges into motion to form an electric current. The unit of current is the ampere (A). The distribution of current in a three-dimensional volume is specified by the current density vector, **J**, the direction of which is the direction of current flow. The magnitude of **J** is equal to $\mathrm{d}I/\mathrm{d}A$, where $\mathrm{d}I$ is the current crossing an infinitesimally small surface element of area $\mathrm{d}A$, oriented perpendicular to **J**. The unit of current density is $\mathrm{A/m^2}$. **J** is directly proportional to **E** in a wide variety of materials:

$$\mathbf{J} = \sigma \mathbf{E}, \tag{3}$$

where the constant of proportionality, σ, is the electrical conductivity of the medium. The unit of σ is siemens per meter (S/m). (Before widespread use of SI units, the unit of conductivity was mhos/m). ELF conductivities of various living tissues are in the approximate range 0.01 to 1.5 S/m throughout the ELF range (Schw56; Schw57a; Schw57b; Ge67).

II.2. *Electric field measurements*

Standardized procedures exist for the measurement of power-frequency electric fields produced by transmission lines (IEEE78a). These procedures can, in most cases, be applied to the measurement of electric fields produced by other ELF sources.

The most common ELF measurement is of the magnitude and direction of an electric field at a point in space. Free-body meters (dipole meters) have been developed for this application. The typical free-body meter has a case that is divided into two electrically conducting halves. A current is induced between these two halves when the meter is placed in an electric field, and a measurement of this current, usually accomplished with electronics placed inside the case, is equivalent to a measurement of the electric field (actually, the time derivative of the electric field). Because these meters perturb electric fields in their vicinity, they cannot be used with accuracy when located close to a conducting surface. (Close, in this context, means that the distance from the conducting surface to the meter is less than about three times the largest dimension of the meter.) Commercially available meters, which are approximately the size of a conventional voltmeter, are adequate for electric field measurements near transmission lines or similar sources. However, such instruments may not be suitable for field measurements in laboratory systems (e.g. an electric field exposure system for laboratory rodents) because of their size. Much smaller meters have been developed for these measurements (Mis78).

Another potential source of error is field perturbations caused by the body of the person making the measurement. The presence of such an error can be detected experimentally by noting whether the reading on the meter is a function of its distance from the observer. Under transmission lines, it is recommended that the horizontal distance between the operator and the meter be at least 2.5 m (IEEE78a).

It is sometimes desirable to measure the electric field acting on a conducting surface (e.g. the surface of the ground or the surface of the body of a human). This measurement can be accomplished easily with the use of a small surface probe that can be located directly over, and very close to, the surface in question. The current induced in this probe is directly related to the average electric field acting on it (EPRI75; De77; Kau79).

II.3. *Magnetic field terms and units*

Magnetic fields are produced by electric charges in motion. Magnetic fields can exert forces on other charges, but, again, only charges in motion. The force, **F**, acting on an electric charge, q, moving with a velocity, **v**, through a magnetic field, **B**, is given by the expression

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}, \tag{4}$$

where the symbol "×" is the vector cross-product operator (Reit60). The work, W, per unit time, t, done by this force on the charge is $\mathrm{d}W/\mathrm{d}t = \mathbf{F} \cdot \mathbf{v}$, where the symbol "·" is the dot-product operator. According to eqn (4), **F** is perpendicular to **v** and $\mathrm{d}W/\mathrm{d}t = 0$, which means that the magnetic field does no work on the charge. However, magnetic fields can facilitate the transformation of one form of energy into another, as for example in an electric generator where mechanical energy is transformed into electrical energy.

Magnetic fields are specified by two vector quantities, the magnetic flux density, **B**, and the magnetic field strength, **H**. When using SI units, **B** and **H** have units of tesla (T) and ampere per meter (A/m), respectively. In air, in a vacuum and, to an adequate approximation, in all non-magnetic materials, **B** and **H** are related by the equation

$$\mathbf{B} = (4\pi \times 10^{-7})\mathbf{H}, \tag{5}$$

where the units of the constant are $\mathrm{T \cdot m \cdot A^{-1}}$. Thus, only one of the vectors, **H** or **B**, needs to be specified.

Unfortunately, there is currently no concensus on the reporting of magnetic field levels in the literature related to ELF biological effects; both flux density and field strength are in common use. An additional complication is that both the SI unit, tesla (T), and the cgs unit, gauss (G), have and are being used to express flux-density values.

In this paper, the primary specification of magnetic field levels will be in terms of the flux density vector (**B**) expressed in SI units. The conversion of flux densities from cgs to SI units is

$$B_{SI}/B_{cgs} = 1 \times 10^{-4}\,\mathrm{T \cdot G^{-1}}. \tag{6}$$

II.4. *Magnetic field measurements*

An alternating magnetic field induces an electric field and an electromotive force in any conducting circuit exposed to it. This fact is used in one type of magnetic field meter in which the voltage induced by a magnetic field in a "search" coil is measured. Meters of this type are simple, sensitive, prone to few errors, commercially available, and also easily fabricated in the laboratory. However, because the voltage induced in a search coil exposed to an alternating magnetic field is directly proportional to frequency, misleading results can be obtained with some meters when measuring fields containing significant amounts of harmonic distortion.

The second class of meters used for the measurement of ELF magnetic field uses the Hall effect [essentially an application of eqn (4)]. Meters in this class are also commercially available but are, because of lower sensitivities, less well suited for most ELF magnetic field measurements. (The exception is when a measurement with a very small sensor is required.)

Standard methods for measuring power-frequency magnetic fields under high-voltage transmission lines have been developed by the Institute of Electrical and Electronics Engineers (IEEE78a; IEEE79).

III. ENVIRONMENTAL SOURCES OF ELF ELECTRIC AND MAGNETIC FIELDS

III.1. *Electric field sources*

Electric fields with frequencies in the ELF range result predominantly from man-made sources. The strongest ELF fields to which humans are normally exposed are those produced by electric power generation, transmission and distribution systems. Considerable data have been published on measurements of the electric fields under high-voltage transmission lines (EPRI75; Di76; Bra76; De78; Bri81). Theoretical work has shown that it is possible to calculate accurately the electric fields produced by these sources (EPRI75; Bra76; Po77; De78; IEEE79).

Figure 1 shows electric field strengths measured under a 500-kV electric power transmission line. Table 1 gives field strengths for transmission lines at voltages ranging from 123 to 1200 kV (Hauf82). Similar data for substations are tabulated in Table 2 (Hauf82). These data show that the largest electric field strengths produced at ground level by transmission lines now in service are about 15 kV/m. Electric field strengths under even higher voltage lines, which may be built in the future, will probably not significantly exceed this value because of the need to limit shock hazards to personnel in their vicinity.

Sources of electric fields typically consist of more than one charged electrode. For example, an alternating current (a.c.) transmission line has three conductors (for higher voltage applications, three bundles of conductors). The sinusoidal voltages of these conductors are approximately equal in magnitude, but are separated in time from each other by a nominal one-third of a cycle (i.e. by an electrical phase angle of 120°). The electric fields produced by the three conductors are therefore not in phase, which means that the three spatial components of the electric field vector produced by a transmission line will in general also have different electrical phases.

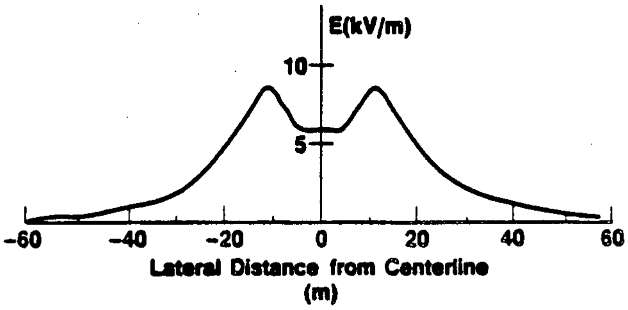


Fig. 1. Electric field (E) measured at ground-level under a 525-kV transmission line. The three electric phases (i.e. conductors) of the line were located in a horizontal configuration 10 m above the ground and with a phase-to-phase spacing of 10 m. The drawing gives electric field data as a function of lateral distance measured from the centerline of the transmission line. (Adapted from EPRI75.)

The terms linear polarization and circular polarization are occasionally used to describe two limiting cases of the phase relations discussed in the previous paragraph. An electric (or magnetic) field is said to be linearly polarized if all spatial components of the field have the same electrical phase. This is the approximate situation for electric fields produced by transmission lines at distances of more than about 15 m from the line's conductors (De78; De82).

The other limiting case—circular polarization—occurs when orthogonal components of the field vector are equal in magnitude but are 90° out of phase. This case can be detected with a field meter by noting if there is a plane in space within which the measured field strength is independent of direction.

Other electric field sources that have been studied include residences (Ca83) and electric blankets (Fl87). Figure 2 summarizes some of the results of these studies.

Studies are currently underway in the United States, Canada, the United Kingdom, Sweden and Japan, which are attempting to determine actual environmental exposures of humans to electric fields (De79; Lat82; Lo83; De84; Bra85; Cha85; Si85). These studies indicate that actual exposures are considerably smaller than those that would be predicted using only unperturbed electric field data.

III.2. *Magnetic field sources*

Natural phenomena, such as thunderstorms and solar activity, produce time-varying magnetic fields in the ELF range. Such fields are generally of low flux density,

Table 1. Maximum electric field intensities at midspan under electric power transmission lines operated at different voltages.*

Highest system voltage (kV)	Electric field intensity under line at midspan (kV/m)
123	1 - 2
245	2 - 3
420	5 - 6
800	10 - 12
1200	15 - 17

*From Hauf82.

approximately 0.01 μT. However, during intense magnetic storms, these fields can reach intensities of about 0.5 μT (Te85; Te86a).

Of greater importance in the context of possible biological effects are the numerous ELF magnetic fields arising from man-made sources. In the lowest intensity range, generally less than 0.3 μT, are fields found in the home (Ca83) and in office environments (e.g. near video display equipment) (Stu83). Magnetic fields from ELF communications and power transmission systems are somewhat higher and can approach a level of about 15 μT (Haub74; Na85).

Considerably higher flux densities can occur in the immediate proximity of industrial processes using large induction motors or heating devices. Lövsund and coworkers documented magnetic fields of 8 to 70 mT in the steel industry in Sweden (Lö82). Recent improvements in medical care include the use of time-varying magnetic fields for the treatment of bone fracture nonunions and the measurement of blood flow rates (Bas74; Mil77; Bas78; Bas82). Flux densities used in these techniques can range from 1 to 10 mT. The medical technique of magnetic resonance imaging also produces rapidly time-varying fields as a result of the switching of magnetic field gradients used for the localization of nuclei with magnetic moments, such as protons (Marg83; Bu84).

The ability of a magnetic field to induce an electric field in a biological body depends on the rate of change of flux density with time, d*B*/d*t*. Figure 3 gives maximum values of d*B*/d*t* for a representative sample of environmental and medical magnetic field sources.

IV. PHYSICAL INTERACTION OF ELF FIELDS WITH HUMANS

IV.1. *Direct and indirect mechanisms of interaction*

A number of ELF exposure mechanisms result in the application of electric and/or magnetic fields to the surfaces and interiors of the bodies of humans and animals. The more important of these mechanisms include:

(1) Electric fields produced by ELF sources act on an exposed human or animal, resulting in the application of (often intensified) electric fields to the

Table 2. Maximum electric field intensities in substations.*

Highest system voltage (kV)	Electric field intensity under busbars (kV/m)
123	5 - 6
245	9 - 10
420	14 - 16
800	14 - 16

*From Hauf82.

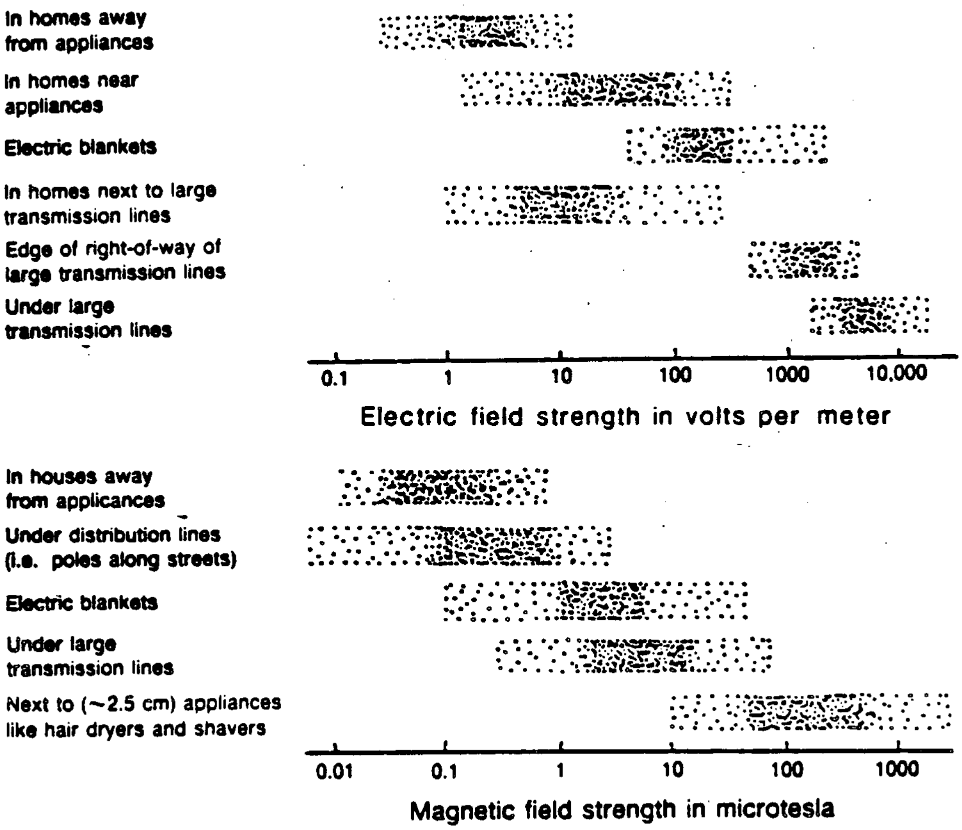


Fig. 2. Range of 60-Hz electric and magnetic field strengths frequently encountered in the United States. (Adapted from F185.)

outer surface of the body of the subject and the induction inside the body of electric fields and currents.

(2) Magnetic fields produced by ELF sources also act on an exposed human or animal, resulting in magnetic field penetration throughout the body, the induction of electric fields and currents inside the body, and the application of forces to moving charges within the body.

(3) Electric currents induced in a conducting object (e.g. an automobile) exposed to an ELF electric field can pass through a human or animal in contact with it.

(4) Magnetic field coupling to a fence line or other conductors can cause ELF currents to pass through a human or animal in contact with it.

(5) A human or animal, which is standing on earth that is carrying electric currents, may be exposed to a "step potential" that will cause currents to flow in the body.

(6) Transient (often called spark) discharges can occur when two bodies exposed to a strong ELF electric field come into very close proximity and/or at the instant of their contact.

It is useful to classify coupling mechanisms between humans or animals and ELF electric and magnetic fields into indirect or direct forms of coupling, depending on whether the presence of a second body, in addition to that of the exposed organism, is required for the coupling to occur. By this classification, the first two mechanisms listed above are examples of direct coupling between living organisms and ELF fields because they can occur when only the exposed organism is present. (However, the presence of other bodies may alter the strength or other details of direct coupling mechanisms.)

The latter four mechanisms listed above are examples of indirect coupling mechanisms because they can occur *only* when the exposed organism is in the vicinity of other bodies. These bodies can include the ground, other humans or animals, and/or objects such as automobiles, fences, etc.

The following sections discuss in more detail the most important forms of direct and indirect coupling between humans and ELF fields.

IV.2. *Direct electric field coupling*

Because the time rate of change of ELF electric fields is quite slow, it is useful to think first of a conducting object, such as an animal or a man, exposed to a static electric field, E_0. In this limit, the effect of E_0 is to induce an electric charge on the surface of the exposed object (Reit60). This charge produces its own electric field, E_1, on the surface so that the total electric field is $E_0 + E_1$. The magnitude and distribution of the induced surface charge is such that (1) $E_0 + E_1 = 0$ inside the object and

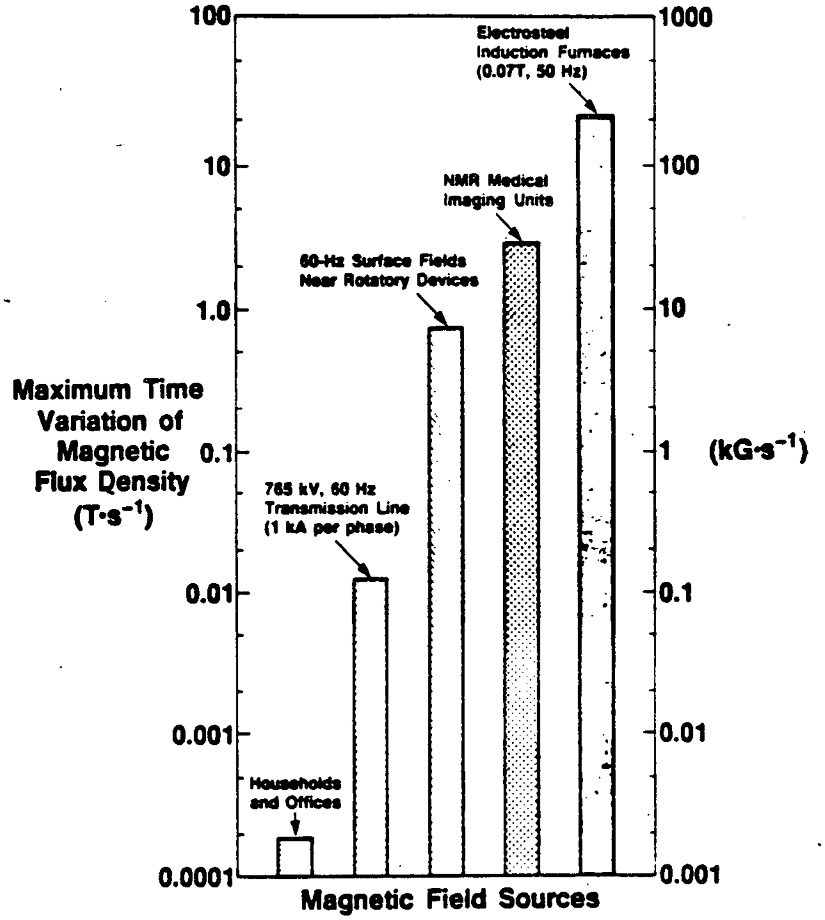


Fig. 3. Upper limits of the time rate of change of the magnetic flux density, dB/dt, for significant sources of extremely low frequency magnetic fields.

(2) $E_0 + E_i$ may be significantly larger than E_0 at some points on the exterior surface of the object.

Because the electric field inside the object is zero, the electrical properties and internal structure of the object cannot affect the exterior electric field or the induced surface charge density. Thus, the only important properties of the object are its shape and location relative to other objects and the ground.

Now suppose that the electric field oscillates at an ELF frequency. As the field oscillates, the induced surface charge density will oscillate correspondingly, thus requiring the presence of currents inside the object and, in general, currents between the object and any other conducting objects that are in electrical contact with it. Because living tissues have finite conductivities, internal currents cannot flow without the existence of electric fields. Thus, both currents and electric fields are induced inside a conducting object by an external ELF electric field.

In the ELF range, the variation in surface charge density with time is so slow that the currents and fields generated inside an object are very small in magnitude. Estimates show that the electric fields induced inside the bodies of humans and animals are generally less than about 10^{-7} of the field outside the body and probably rarely exceed about 10^{-4} of the external field (Kau81b). Because these internal fields are so small, the conclusion reached earlier for static electric field exposure is still valid to a very good approximation: the only properties of a living organism that affect the exterior field and induced surface charge density are the shape of its body and its location relative to other objects. Because currents inside the object have as their source induced surface charge, this conclusion can be generalized to total currents passing through any section of the body of a living organism (Kau81b).

The discussion presented in the preceding paragraph suggests that useful information can be obtained from experiments with conducting models that simulate the shapes of humans and animals. This technique has been used by Schneider and associates (Schn74), Deno (De77; De79), and by Kaune and Phillips (Kau80) and Kaune and Miller (Kau84).

IV.3. *Data on electric field coupling to living organisms*

A number of theoretical papers have been published in which exposure of animals and humans has been modeled. Most of these papers (Barn67; Sp76; Bay77; Ko78; Lat81; Sh81; Ha82) simulated the body of the exposed organism with a sphere, spheroid, or ellipsoid, but two used more refined models (Sp77; Sp81). The results of these investigations have been reviewed elsewhere (Kau85a; Kau85b; Kau85c; Kau86).

Considerable information can be obtained using models that simulate the conducting surfaces of the bodies of humans and animals. The following paragraphs summarize data obtained with the use of this technique.

Because exposure to electric fields often occurs when the subject is electrically grounded, a parameter of considerable importance is the short-circuit current, that is, the total current that passes between the subject and ground. Published short-circuit current data are summarized in Table 3 for humans (EPRI75; Bra76; De77), horses and cows (EPRI75), pigs (Kau78), guinea pigs (Kau84), and rats (Kau80). Most of these measurements were taken at only one frequency and body weight. They have been extrapolated to other frequencies, f, and body weights, W, assuming a $fW^{2/3}$ dependence (Kau81a). The human data were expressed by Deno (De77) in terms of body height rather than body weight. It was assumed that a body height of 1.7 m is equivalent to a body weight of 70 kg (ICRP75) in the preparation of Table 3.

The use of the formulae in Table 3 is illustrated by the following example. Consider a 70-kg human exposed to a 10-kV/m, 60-Hz electric field. The top line in Table 3 indicates that the short-circuit current induced in this person will be $(15 \times 10^{-8}) \times 60 \times 70{,}000^{2/3} \times 10{,}000 = 153\ \mu A$. At 50 Hz, this current would be decreased to 127 μA.

Deno (De77) published the first data on induced currents in anatomically detailed human models and, using these data, he estimated average vertical current densities in humans standing on the ground while exposed to vertical, 60-Hz electric fields (De79). Electric-field-induced current densities determined at one ELF frequency, f_1, can be extrapolated to other frequencies, f_2, by multiplying them by the ratio f_2/f_1 (Kau81b).

Deno (De77) also developed a simple technique for measuring the external electric fields acting on the surface of a body. Surface electric fields measured at one frequency can be extrapolated to any other frequency in the ELF range without scaling.

Kaune and Phillips (Kau80) used Deno's methods to measure surface electric fields and induced-current distributions in grounded rats and pigs exposed to a vertical electric field. Axial (i.e. along the long axis of the body) current densities were estimated from the induced current data.

Peak surface electric field and current density data, derived from Deno's human measurements and Kaune and Phillip's animal data, are presented in Fig. 4. In this figure, the magnitude and frequency of the unperturbed exposure electric field were assumed to be 10 kV/m and 60 Hz, respectively.

Figure 4 shows that the axial current densities induced inside the body of a human are considerably larger than the corresponding quantities induced inside rats and pigs exposed to the same external electric field. This conclusion is also true for induced electric fields because of the relationship between J and E given by eqn (3). [The conductivities of human and animal tissues are similar (Ge67).] These differences between species require that the external unperturbed fields, which are almost always used to specify exposure, must be scaled to equalize internal current densities and electric fields in order to extrapolate biological data from one species to another. This process is complicated by the fact that the actual value of

Table 3. Short-circuit currents induced in grounded humans and animals by vertical extremely low frequency electric fields.*

Species	Short-Circuit Current $I \times 10^8/fW^{2/3} E_0$* (μA)
Human	15.0
Horse	8.5
Cow	8.6
Pig	7.7
Guinea Pig	4.2
Rat	4.0

* Data from EPRI75, Bra76, De77, Kau78, Kau80 and Kau84.

** I = current (μA), f = frequency (Hz), W = weight (g), and E_0 = electric field intensity (V/m).

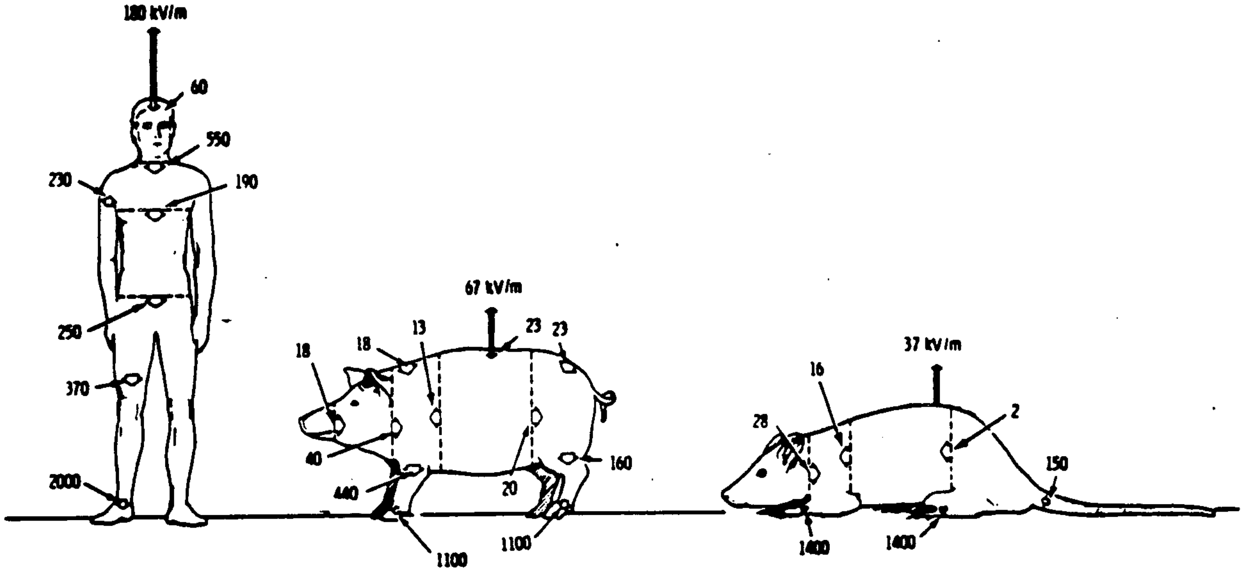


Fig. 4. Axial current densities and surface r.m.s. electric field intensities for a grounded man, pig, and rat exposed to a vertical 60-Hz, 10-kV/m electric field. Relative body sizes are not to scale. All values of the current density are in units of nA/cm^2. The internal current densities have been calculated along an axis parallel to the long axis of the body, and averaged over the cross-sectional areas shown as dashed lines. The calculated current densities shown at the surfaces of the man and the pig are perpendicular to the body surface. (Adapted from Kau80.)

the scaling factor depends on which internal quantity is being scaled. For example, a scaling factor for the peak electric field strength acting on the outer surface of the body would be about 4.9:1 for humans compared to rats, while the scaling factor for axial current density in the neck would be about 20:1 for the same species comparison. Evidently, knowledge must be obtained about the site of action for a particular biological effect before quantitative extrapolation of data across species can be performed.

The surface electric field data given in Fig. 4 are limited in that measurements were made at only a few points on the body. A simple way to calculate electric field strengths averaged over the entire body surface of a grounded subject has been described by Kaune (Kau81a). This method requires only that short-circuit current, I_{sc}, and body surface area, A_b, be determined. In terms of these parameters, the average electric field, E_{avg}, acting on the surface of the body is

$$E_{avg} = \frac{I_{sc}}{2\pi f \epsilon_0 A_b}, \tag{7}$$

where f is the frequency and ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m). Table 4 gives approximate

Table 4. Peak and average electric field intensities at the surfaces of grounded humans and animals exposed to a vertical, 1-kV/m electric field.*

Species	Average E (kV/m)	Peak E (kV/m)
Human	2.7	18
Swine	1.4	6.7
Rat (resting)	0.73	3.7
Rat (rearing)	1.5	**
Horse	1.5	**
Cow	1.5	**

* Data are adapted from Kau84, and are valid for all frequencies in the ELF range.

** Not available.

maximum and average electric fields acting on the surfaces of the bodies of grounded humans, swine, rats, guinea pigs, horses, and cows exposed to a vertical, 1-kV/m electric field.

The current-density data given in Fig. 4 represent only one (the axial) of three components of the total current-density vector. This is a serious limitation in the animal data because it is certain that significant vertical current will also be present. Measurements in three-dimensional models of humans and animals are required to overcome this limitation.

Guy and associates (Gu82) and Kaune and Forsythe (Kau85b) measured induced electric fields and internal current densities in grounded homogeneous models of humans exposed to 60-Hz electric fields. Figure 5 summarizes Kaune and Forsythe's data for human models, assuming a frequency of 60 Hz and an exposure field strength of 10 kV/m. Note the enhancement in current density that occurs in the axillae (armpits). This enhancement was also observed by Guy and associates (Gu82).

One limitation of the current-density data given in Fig. 5 is that they pertain only to the exposure of electrically *grounded* humans. It is more usual for humans to be exposed when they are partially insulated from ground by their shoes. Deno (De77) and others (Kau87) have made measurements that enable grounded data to be extrapolated to ungrounded exposure situations. Figure 6 summarizes the results of the latter reference.

Data similar to those given in Figs. 5 and 6 are needed for laboratory animals to enable the determination of quantitative factors for scaling animal data to human exposure situations.

IV.4. *Direct magnetic field coupling*

In contrast to electric field exposure, the bodies of humans, animals and other living organisms do not measurably perturb an ELF magnetic field to which they are exposed. There are two reasons for this minimal interaction: (1) Excluding a few highly specialized tissues that contain magnetite, living tissues contain no magnetic materials and, therefore, have magnetic properties almost identical to those of air. (2) The modification in the applied magnetic field due to the secondary magnetic fields produced by currents induced in the body of the subject is small (Kau85a; Kau86).

Faraday's law of induction states that time-varying magnetic fields generate electric fields through induction. Therefore, a living organism exposed to an ELF magnetic field will also be exposed to an induced electric field from this source. The induced electric field causes current to flow in any conductive body. These currents, called eddy currents, circulate in closed loops that tend to lie in planes perpendicular to the direction of the magnetic field (Te86b).

A fairly useful model for a human or animal exposed to a uniform ELF magnetic field is a homogeneous ellipsoid (Ha82). An ellipsoid is defined by three parameters—the semi-major axes—which are the x, y, and z axes, respectively. (Assume that the symmetry axes of the ellipsoid coincide with the coordinate axes.) The electric field induced by a magnetic field of frequency f parallel to, for example, the z axis is

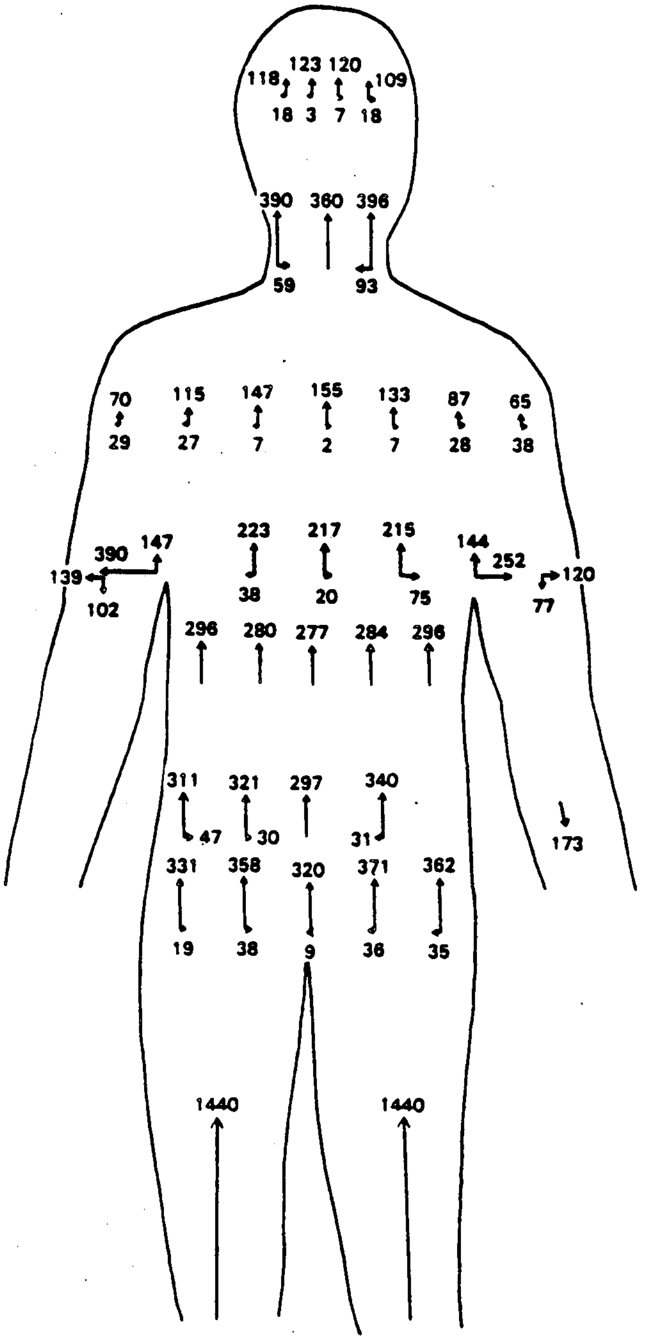


Fig. 5. Current densities measured in the midfrontal plane of a saline model of a standing man exposed to a 60-Hz, 10-kV/m electric field. Induced r.m.s. current densities are given in units of nA/cm^2. The model was grounded with equal currents passing through both feet. The vertical and horizontal arrows represent the axial and radial components of the induced current densities, respectively.

$$E_m = \frac{2\pi f B}{a^2 + b^2}\sqrt{b^4x^2 + a^4y^2}, \qquad (8)$$

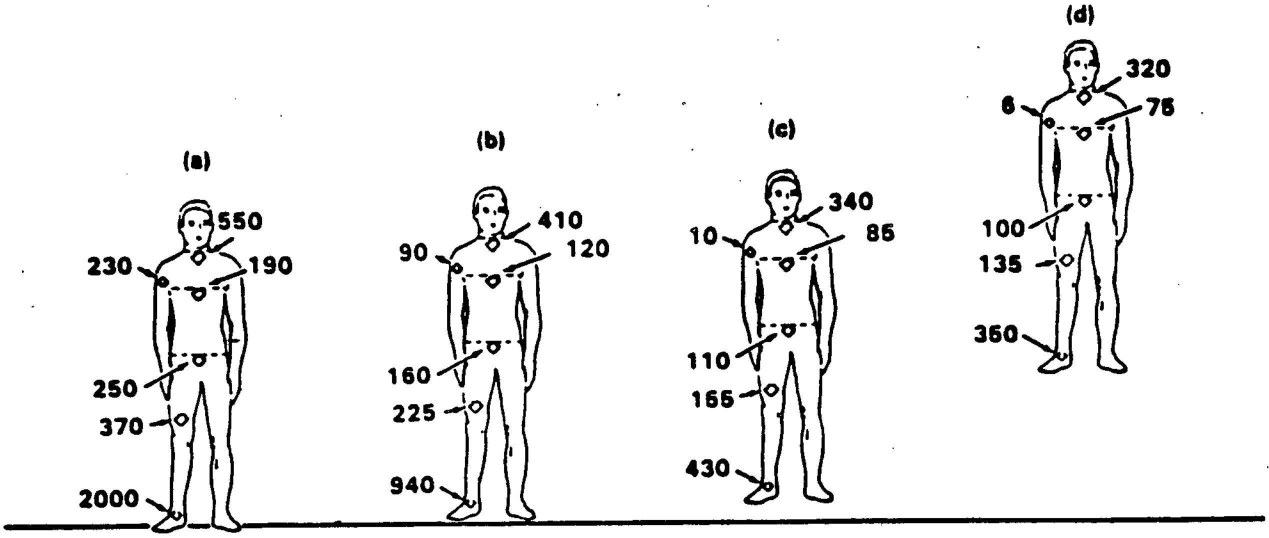


Fig. 6. Average axial current densities (nA/cm^2) induced in a 1.7-m-tall human exposed to a vertical 60-Hz, 10-kV/m electric field. Four positions of the body relative to ground are shown: (a) standing on, and in electrical contact with, the ground; (b) feet elevated 1.1 cm above ground to approximately simulate insulating footwear; (c) feet elevated 12.8 cm above ground; (d) feet elevated 123 cm above ground. (Adapted from Kau 87.)

where a and b are the semi-major axes of the ellipsoid in the x and y directions, respectively. The induced electric field lines circulate in closed loops in the plane defined by the x and y coordinates (orthogonal to the z axis).

IV.5. *Data on magnetic field coupling to living organisms*

Very little theoretical or experimental work has actually been carried out on the coupling of magnetic fields to living organisms. Spiegel (Sp76) published a paper describing ELF magnetic field (and electric field) coupling to spherical models. The magnetic field portion of this work essentially involved an application of eqn (8), where $a = b$ = radius of the sphere.

Gandhi and associates (Ga84) calculated induced current densities in the torso of a human exposed to an alternating magnetic field, using a technique that simulates the exposed object with a multidimensional lattice of impedance elements. These authors considered only a two-dimensional simulation, but there appears to be no fundamental problem in extending the method to three dimensions. The method offers a relatively simple and powerful way to analyze the coupling of humans and animals to ELF magnetic fields.

An interesting theoretical calculation involves the comparison of the relative magnitudes of the electric fields induced in a human by the electric and magnetic fields from a high-voltage electric power transmission line. For this estimate we will consider a transmission line that produces a 10-kV/m electric field and a 30-μT magnetic flux density (Fig. 2).

Reference to Figs. 4 and 5 shows that the maximum current density induced in the torso of a human grounded through both feet and exposed to a 10-kV/m, 60-Hz electric field is about 300 nA/cm^2 (3×10^{-3} A/m^2). Assuming an average tissue conductivity of about 0.2 S/m (Ge67; Kau81b), the approximate maximum electric field in the torso is about 15 mV/m.

Magnetic induction of ELF currents in standing humans can be modeled using a simple ellipsoidal approximation of a man. A typical man has a height of 1.7 m, a mass of 70 kg (ICRP75) and a ratio of the body width to thickness of about 2. An ellipsoid with semi-major axes of 85 cm, 20 cm, and 10 cm has the same body height, the same width-to-thickness ratio, and a body volume of 7.1×10^4 cm^3. The maximum electric field, E_m, induced in this model can be shown to occur when the magnetic flux-density vector, **B**, is horizontal and perpendicular to the front of the body. Using eqn (8) with $a = 0.20$ m and $b = 0.85$ m, the calculated value is $E_m \sim 1.2fB \sim 2.2$ mV/m, a value that is only about 15% of the maximum internal field resulting from induction by the electric field.

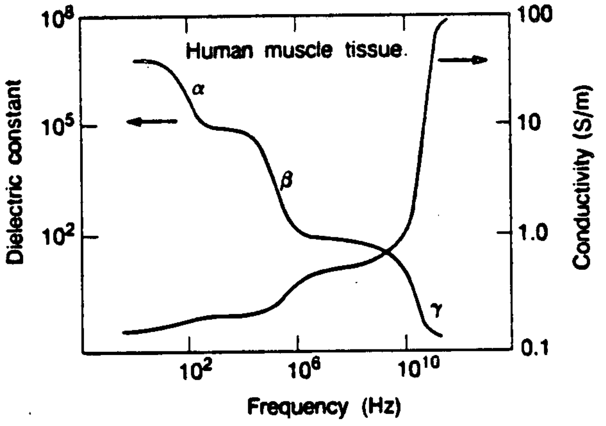
The estimate made in the previous paragraph led biologists and physicists to concentrate their efforts on electric field coupling to humans and animals for many years. However, beginning in the late 1970s, the subject of magnetic field coupling began to receive more attention, and it is currently believed by many that future research should place an increased emphasis on magnetic field coupling, or combined electric and magnetic field coupling, to humans and animals.

IV.6. *Indirect coupling: steady-state ELF contact currents*

In this section, the dielectric and conductive properties of cells and tissues exposed to ELF fields will be briefly described, and a summary will be given of the present state of knowledge of body impedance characteristics as a function of ELF contact voltage, stimulus duration, and contact area.

Dispersive electrical properties of cells and tissues. During the past five decades, an increased understanding has been achieved of the complex electrical properties of cells, cellular aggregates and organized tissues. Many of the major advances in this field are attributable to the pioneering research of Herman P. Schwan and his associates, which has been the subject of numerous review articles (see, for example, Sto82; Schw85; Fo86). Both the dielectric constant (ϵ) and the conductivity (σ) of tissues vary over orders of magnitude in the frequency range from ELF to extremely high frequency (EHF). As shown in Fig. 7 for human muscle tissue, there are three characteristic regions over which ϵ and σ exhibit dispersive properties characteristic of relaxation phenomena. These are denoted as the α, β and γ dispersions, and the fundamental cellular constituents responsible for these frequency-dependent properties are also indicated in the figure. These dispersive properties of cells and tissues are characteristic only of the electrical properties of living matter. The magnetic permeability of living tissue is nearly equal to that of a vacuum and shows little variation with frequency.

The α dispersion, which is of primary interest in the interpretation of ELF electric field effects, is thought to result primarily from electrical polarization of a diffuse counterion layer that surrounds the anionic fixed-charge groups that are present in great abundance at the surfaces of living cells. However, there are other possible contributions to the α dispersion from the frequency-dependent polarization of the membrane itself, as well as the polarization of intracellular membrane structures that are connected to the plasma membrane through reticular or tubular entities with finite resistivities in the ELF range. It should be noted that the α dispersion in tissue dielectric constant leads to a decrease in ϵ of nearly two orders of magnitude over the range from d.c. to 1 kHz, whereas the tissue conductivity increases by only a factor of 2 to 3 over the same frequency range. As a consequence of the very high values of ϵ in the ELF range ($\geq 10^6$), which result largely from the dielectric properties of cellular surface membranes, currents established in tissue through either contact voltages or external fields will have primarily an extracellular pathway. In effect, the interior (cytoplasmic) region of a cell is shielded from applied fields by the plasma membrane and its polarizable counterion layer.



Dispersion	Origin
Alpha	(a) Polarization of counterion layer at cell surface (b) Polarization of intracellular structures connected to the plasma membrane (tubular structures)
Beta	(a) Polarization of the cell membrane (b) Polarization of cellular organelles (mitochondria, nucleus)
Gamma	Polarization of tissue water

Fig. 7. Frequency dependence of the dielectric constant and conductivity of human muscle tissue. (Adapted from Schw85.)

Many advances also have been made towards understanding the origins of the β and γ dispersions, although again the state of knowledge is not complete. In brief, the β dispersion represents a region of frequencies extending from approximately 0.1 to 10 MHz in which the electrical polarization of the plasma membrane and intracellular organelles changes from a high value at the lower end of the frequency range to a low value at the higher frequencies. As a result, the cell membrane begins to pass electrical current and cytoplasmic resistance becomes an important parameter determining the passage of ionic currents through organized tissue structures.

In the very high frequency range above approximately 100 MHz, the γ dispersion effect occurs, with a resultant decrease in dielectric constant and a very large increase in tissue conductivity. This effect is primarily the result of polarization of tissue water, which occurs with a characteristic frequency of about 19 GHz. However, there are also contributions from the polarization of cellular proteins and bound water, which exhibit a broad spectrum of relaxation frequencies from less than 10 MHz to greater than 3 GHz. These dispersion effects broaden the tail of the β dispersion and overlap the region of the γ dispersion, which is associated primarily with contributions from unbound tissue water.

Body impedance. The impedance of the body, measured during contact with a wide range of both d.c. and 50/60-Hz stimulus voltages, has been studied by a number of investigators since the beginning of this century, as recently reviewed by Biegelmeier (Bi85). Because the electrical impedance of skin is significantly greater than that of tissues located within the body, the skin impedance is a major component of the total body impedance. The skin impedance, in turn, is influenced by a great number of factors related to ambient conditions, as well as the electrical stimulus that is delivered. These factors include the stimulus voltage, frequency, waveform, duration and path of current flow, surface area of the electrical contact, the pressure of the electrical contact, the degree of moisture in or on the skin, and the relative humidity and ambient temperature.

It has been established that the body impedance changes rapidly as a function of time following application of a voltage stimulus to the skin. During the initial current transient, lasting approximately 1 ms or less, the body impedance has a relatively low value of about 500–700

Ω (Bi85; Bri86). The impedance then rises dramatically due to electrical charging of the skin surface, i.e. the capacitative reactance of the skin becomes larger. The initial body impedance immediately following electrical contact is relatively insensitive to the stimulus voltage, waveform, frequency, contact area or moisture content of the skin. As indicated above, however, the larger steady-state body impedance is sensitive to these and other factors. During the initial transient the internal body resistance contributes to the total impedance, but its contribution to the final steady-state body impedance is negligible.

An extensive series of measurements of body impedance in human subjects exposed to 15-V and 25-V stimuli at 50 Hz was recently reported by Biegelmeier (Bi85). The body impedance of 100 persons (80 male and 20 female) were measured with a 25-V stimulus of 200-ms duration, and 52 persons (30 male and 22 female) were studied with a 15-V simulus of the same duration. Measurements of body impedance were also made with one additional person subjected to 100-ms stimuli at voltages up to 200 V. Although the range of measurements between individuals was large, with deviations exceeding ±30% of the mean value, the data had sufficient consistency that several general conclusions could be drawn. The basis of the observed variations between subjects was not discussed by Biegelmeier (Bi85), but was possibly related to differences in the skin moisture content because all of the other factors that influence body impedance (described above) were held constant. The results of Biegelmeier's measurements of body impedance during steady-state current flow with a hand-to-hand current path are illustrated in Fig. 8. Three conclusions that can be drawn from these data are the following: (1) For contact voltages less than 250 V, the body impedance varies inversely with the electrode contact area on the skin; recent research by Prieto and associates (Pr85) has shown that the body impedance varies as the contact area to the −0.32 power. (2) The impedance decreases rapidly as a function of the applied voltage, and most noticeably for small contact areas. (3) The body impedance asymptotically converges to a value of about 600–800 Ω for contact voltages greater than approximately 200–300 V. This effect is due to the physical breakdown of the skin in response to voltages greater than 200 V applied to a small contact area (i.e. the skin is punctured and its contribution to body impedance is reduced).

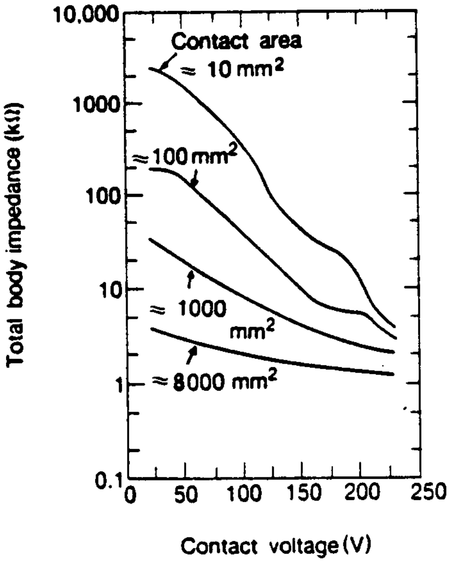


Fig. 8. Relationships between body impedance, contact voltage, and contact area for humans. (Adapted from Bi85.)

Using the data of Biegelmeier (Bi85) and older data acquired in the 1930s by Freiberger (Fre34), who exposed corpses to 50-Hz voltages as high as 5000 V, the International Electrotechnical Commission (IEC) has recently compiled a table of body impedances as a function of contact voltages (Bri86). Because the body impedance of dead subjects is consistently higher than that of live subjects exposed to the same contact voltage under identical conditions, it was necessary to apply a scaling factor to Freiberger's data. This factor was derived by comparing values of impedance for live and dead subjects measured with a 50-Hz voltage of 25 V applied to a large contact area with a hand-to-hand current path. The factors derived for the 5-, 50- and 95-percentile ranks of the groups of live and dead subjects exposed to a 25-V stimulus were then used to "adjust" the data obtained by Freiberger with dead subjects exposed to voltages as high as 5000 V. The resulting estimate of impedance values for the 5-, 50- and 95-percentile ranks of live subjects exposed to contact voltages up to 1000 V are summarized in Table 5. As discussed by Bridges (Bri86), correction factors can be applied to these curves to obtain impedance values for current paths other than hand-to-hand. These factors are also summarized in Table 5. Biegelmeier (Bi85) has commented that, although the values of impedance presented in Table 5 were obtained with adult subjects, they should provide reasonable estimates for children as well. This speculation is based on the fact that the extremities of children are shorter in length than those of adults (e.g. the hand-to-hand path length), but the cross-sectional area of the extremities is also smaller. As a result, the impedance of children should be similar to that of adults for the same contact voltage and current path, although direct measurements are needed to verify this conjecture.

Biological effects of steady-state ELF contact currents. Steady-state ELF contact voltages can produce biological effects ranging in severity from perception to ventricular fibrillation and death. 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 high 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 (Bart72). 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

Table 5. Body impedance for hand-to-hand and hand-to-foot current paths.*†

Contact Voltage (V)	Body Impedance (Ω) 5th percentile	50th percentile	95th percentile
25	1750	3250	6100
50	1450	2800	5100
75	1250	2550	4500
100	1200	2400	4150
125	1100	2200	3800
220	1000	1800	3000
700	750	1100	1550
1000	700	1050	1500
Asymptotic value	650	750	850

* Adapted from Bri86.

† The initial contact impedance is approximately 500 Ω. For current paths other than hand-to-hand or hand-to-foot, the numbers in the table should be multiplied by the following factors: (1) hand to both feet: 0.75; (2) both hands to both feet: 0.50; (3) hand to trunk: 0.50; (4) both hands to trunk: 0.25.

during the two decades between 1930 and 1950 by Dalziel, Kouwenhoven and others, and in recent years several summaries have been made of threshold currents for inducing electric shock phenomena in humans (Bart72; IEEE78b; IEEE84). Table 6 summarizes the body currents that elicit mild to severe responses. Currents above the 10-mA level represent a serious risk because the "let-go" threshold may be exceeded, and the individual might not be able to release a charged object due to 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 that produce a 50% response. This range in human response to 60 Hz steady-state currents is illustrated in Fig. 9. It should also be noted that the estimated level of let-go current in small children is approximately one-half as great as that for an adult man.

An important aspect of the human response to high-voltage shocks is the duration of contact with the ELF current source. The relationship between stimulus duration and the current required to produce ventricular fibrillation has been extensively studied for nearly 50 y. Much of the early work in this field was carried out by Dalziel and his colleagues (Dal68), who derived an empirical relationship between the threshold current for ventricular fibrillation and the stimulus duration based on data from animal experiments and limited information on human responses to electric shocks. The Dalziel electrocution equation states that the threshold current is linearly proportional to the body weight of the subject and inversely proportional to the square root of the shock duration.

Several other investigators and committees have reviewed the available data on ventricular fibrillation thresholds as a function of shock duration and have proposed electrocution curves that differ markedly from the Dalziel equation (Os66; Ge75; Bi80; Sm85; Hauf85). The electrocution curves proposed by the Underwriter Laboratories and U.S. Consumer Product Safty Commission (Sm85) and by the current revision of the IEC's *Report* 479 (Hauf85) are shown in Fig. 10, along with the curves of Dalziel for adults and children having representative weights. The *Z*-shaped curve recommended by Underwriter Laboratories was based on an analysis of all available data on dogs, sheep and man. The curve lies a factor of 2 or more below the experimental data on 20 Hz and 60 Hz current thresholds for inducing ventricular fibrillation as a function of shock duration. The IEC curve is based on a consideration of cardiac physiology, and, in particular, on the duration of current flow relative to the vulnerable period of the cardiac cycle. The IEC curve also takes into account the fact that current flows of long duration will produce extrasystoles that lower the fibrillation threshold quite substantially. These factors have led the

Table 6. 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

* From Bart72, IEEE78b, IEEE84.

\+ Estimated values based on experimental animal studies and/or limited observations on humans.

IEC to propose the Z-shaped curve shown in Fig. 10, which is intended to represent the safe threshold for an adult with a current path from the left hand to the feet. However, Hauf (Hauf85) states that this curve is sufficiently conservative that it could be considered as a threshold curve for children as well.

Threshold voltage and current parameters for inducing ventricular fibrillation as a function of shock duration are also discussed in IEEE Standard 80 (IEEE76). This document uses the Dalziel electrocution equation and makes the simplifying assumption that the body impedance from both hands to both feet is 1000 Ω, irrespective of the contact voltage. The resulting curve for the current thresholds as a function of stimulus durations is accordingly quite different from the IEC curve shown in Fig. 10, with the IEEE Standard 80 curve being more conservative for stimulus durations in the range of 20 to 500 ms (the typical time required to clear a grounding

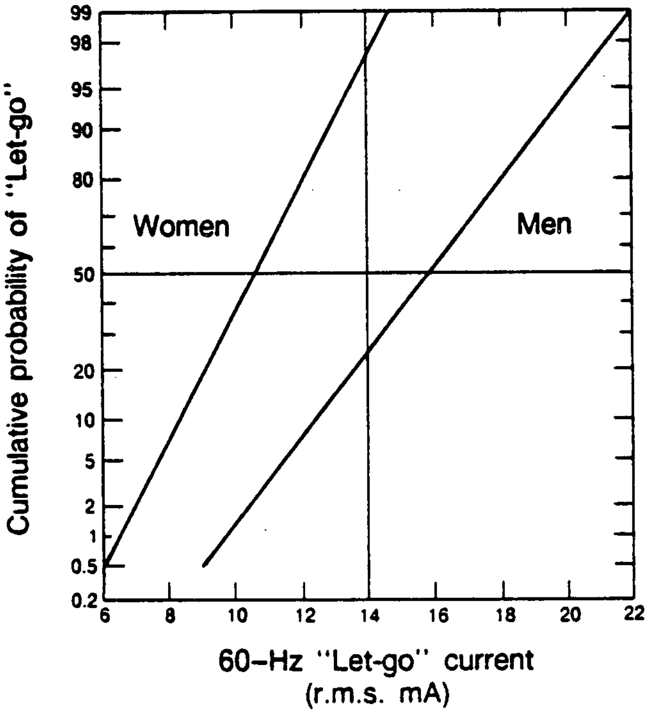


Fig. 9. Let-go current thresholds are shown for human adults. The data demonstrate significant differences between male and female subjects and the broad range of human response to 60-Hz currents. (Adapted from IEEE78b.)

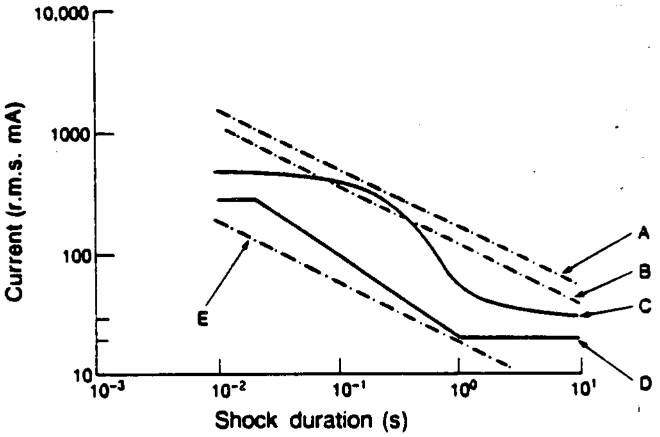


Fig. 10. Threshold 60-Hz currents that produce ventricular fibrillation in adults and children with a probability of 0.5% or less are plotted as a function of the shock duration. Curves A, B and E were derived from the model of Dalziel and Lee (Dal68) for an 80-kg man, a 50-kg man and an 8.4-kg child, respectively. In this model the ventricular fibrillation threshold current is assumed to be proportional to $M\tau^{-0.5}$, where M = body mass and τ = shock duration. Curve C is the human adult threshold curve established by the International Electrotechnical Commission (Hauf85). Curve D is the Underwriter Laboratories and Consumer Product Safety Commission threshold curve for an 8.4-kg child (Hauf85).

fault). The differences in these curves, and the underlying basis for their shapes, has been discussed in detail by Bridges (Bri86) and by Sverak (Sv85).

Regulations that limit hazards from steady-state contact currents are generally based in the United States on the National Electrical Safety Code (NESC) (NESC81). 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 short-circuit current will reduce contact currents between a person and a charged object to levels that are usually well below 5 mA because of the impedance between the person and object, as well as the person-to-ground and object-to-ground impedances.

IV.7. *Indirect coupling: transient discharges*

Physical characteristics of transient discharges. A transient capacitative discharge can occur between a person and a charged object either by direct contact or via a spark through an air gap. A spark discharge can arise without direct contact if the person and the charged object come close enough together (typically 1 mm or less) so that the local electric field between them exceeds the dielectric breakdown level for air (3×10^6 V/m). In the case of a contact discharge, it has been demonstrated by Reilly and Larkin (Reil83) that the stimulus delivered to the body surface consists of both a spark component and a contact component when the initial voltage is sufficiently high. This two-component discharge characteristic occurs only above a threshold initial voltage, as demonstrated in Fig. 11 for the case of a human subject tapping his finger on an electrode with a 1-mm-diameter tip. In the left panel, the initial electrode voltage and discharge capacitance were 405 V and 400 pF, respectively. The discharge consisted of a single contact current pulse centered at 100 to 200 μs following the initial electrode contact. In the right panel of Fig. 11, the initial electrode voltage and discharge capacitance were 586 V and 400 pF, respectively. In addition to the contact current pulse centered at 100 to 200 μs, there is an initial transient current of a large magnitude that discharges within the first 5 μs. This current pulse is associated with a spark discharge immediately prior to contact of the electrode with the finger. Under these experimental conditions, a threshold voltage of approximately 500 V was found to be required to initiate a spark discharge prior to the contact discharge (Reil83). A lower voltage is unable to initiate a spark discharge because of the dielectric protection of the skin (Mas76).

Several other features of the two-component discharge process have also been described by Reilly and Larkin (Reil83). From Fig. 11, it is evident from the voltage traces that different plateau voltages exist for the spark and contact phases of the discharge. The spark and contact voltage plateaus are approximately 400 V and 100 V, respectively. The existence of these plateaus indicate that as the discharge voltage declines, the impedance becomes very large in both phases of the discharge. The major site of this impedance is in the corneous layer of the skin, since stripping successive layers of the stratum corneum with cellulose tape progressively lowers the discharge impedance. Reilly and Larkin (Reil83) have also demonstrated that the discharge waveforms for stimulation at different body locations can differ significantly, with the variation in minimum impedance being as great as a factor of two. They have attributed this variation to differences in hydration of the stratum corneum at various anatomic locations as a result of differences in the distribution of sweat ducts. The extent of hydration of the skin significantly influences its electrical conductivity, which in turn affects the local transient discharge characteristics.

Perception and annoyance levels. The relationship between the initial discharge voltage and human reaction to transient electric shocks has been shown to depend in a complex manner on the capacitance of the discharging object. An extensive series of experiments on human reactions to capacitative discharges were conducted at the high-voltage research facility of project UHV in Pittsfield, MA (IEEE78b). The results of tests on the voltage corresponding to the median peception levels in subjects exposed to transient discharges under a variety of environmental conditions are shown in Fig. 12. Two major observations made in this series of experiments were: (1) Below a discharging object capacitance of approximately 600 pF, the median perception curve exhibits a threshold that is proportional to a constant value of the energy

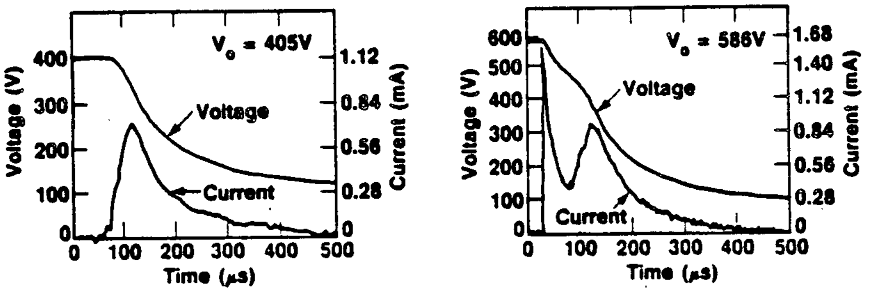


Fig. 11. Stimulus waveforms are shown following fingertip contact with an electrode that has a 1-mm-diameter tip. The discharge capacitance was 400 pF, and the initial discharge voltage (V_0) was adjusted to 405 V (left panel) or 586 V (right panel). The initial spark (right panel) can be distinguished from the contact discharge by the presence of a spike at the onset of current flow. (Adapted from Reil83.)

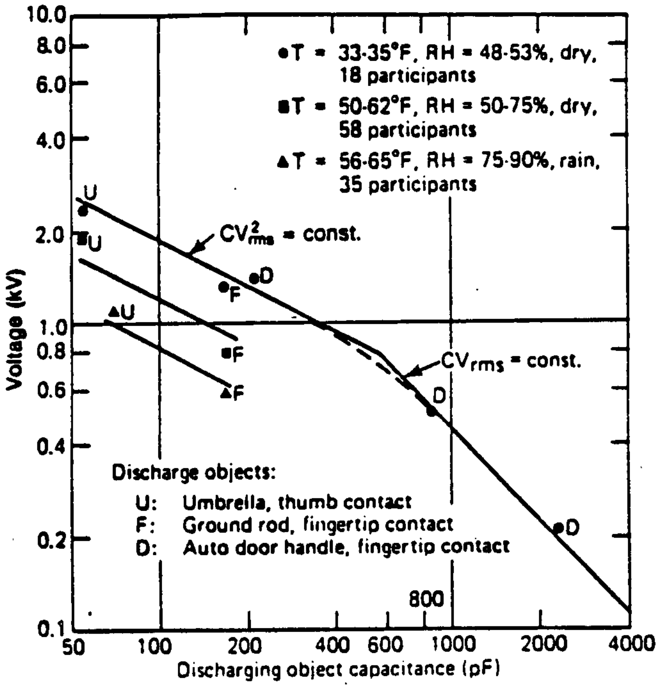


Fig. 12. Voltage corresponding to median perception level as a function of discharge capacitance for fingertips of adult males in contact with discharging objects. (Adapted from IEEE78b.)

transferred in the spark discharge (i.e. $CV^2_{r.m.s.}$ = constant where C = capacitance and V = voltage); above 600 pF, the threshold curve is proportional to a constant value of the charge transferred (i.e. $CV_{r.m.s.}$ = constant). (2) The threshold for perception is highly sensitive to the moisture content of the air, as indicated by the significant shift of the threshold curves in the capacitance range below 200 pF when the relative humidity was varied.

Based on these findings, subsequent research has attempted to characterize human reactions to transient discharges either on the basis of an energy threshold in millijoules (mJ) or a charge threshold in microcoulombs (μC). A summary of recently published data on the thresholds for fingertip touch perception and annoyance are summarized in Table 7. Shock phenomena experienced when a person touches a small object such as a short rod are best characterized by the energy-threshold criterion, whereas the charge-threshold criterion is more appropriate for characterizing transient discharges from a larger object such as an automobile. As indicated by the data in Table 7, the threshold for perception lies considerably below that for annoyance regardless of the relevant threshold criterion. A recent study by Larkin and his associates (Lar86) has clearly demonstrated that the sensitivity of individuals to transient discharges has a linear dependence on body mass. Other factors such as sex, age or skin hardness have no correlation with the threshold sensitivity of an individual to transient electrical discharges.

IV.8. *Protective measures for electric field coupling*

Protection from direct electric field exposure can be achieved relatively easily with the use of shielding. At ELF frequencies, virtually any conducting surface will provide substantial electric field shielding. One practical approach for personnel working in high field strength regions is to provide them with clothes that are electrically conductive. This practice is used commonly in the electric utility industry by linemen who work on high-voltage transmission lines using "bare-hand" techniques. Deno and Silva (De84) used such a fabric to make a conductive vest for their research effort. Another method to obtain protection from electric field exposure is to limit the access of individuals to areas where electric field strengths are large.

Personnel protection from the effects of indirect coupling to ELF fields can often be obtained by appropriate grounding practices. For example, humans who are reasonably well grounded may be exposed to possibly significant ELF currents if they touch a truck or bus that is located in an ELF electric field. The solution, in many cases, can consist of insuring that the bus or truck is electrically grounded and, perhaps, equipping individuals who might be exposed with insulating footwear.

IV.9. *Protective measures for magnetic field coupling*

There is no practical way to shield against direct ELF magnetic field exposure. Thus, the only protective method, if such is deemed necessary, is to limit exposure, either by limiting access of personnel to areas where magnetic flux densities exceed whatever safety standard is set or by limiting magnetic flux densities in areas where humans could be exposed.

Table 7. Perception thresholds for transient electrical 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

* From IEEE84.

As in the case of electric fields, ELF field exposure resulting from indirect modes of coupling to magnetic fields can be limited in many cases by appropriate grounding procedures. Consider, for example, magnetic coupling to a barbed-wire fence. Barbed wire is commonly strung on wooden posts to make fences. Thus, an individual strand of wire may be reasonably well insulated from the ground over most of its length. Suppose, however, that this strand is grounded at some point, for example, at a metal gate, and suppose that a person touches this strand at some point. A conducting loop is thus formed, consisting of that portion of the fence between the gate and the person, the person's body, the ground, and the gate. An electromotive force will be induced in this loop if an ELF magnetic field is present, and currents will flow as a result.

It is easily shown, for environmental sources of ELF magnetic fields, that rather large loops are required for the generation of significant voltages (i.e. >10 V). This fact suggests that mitigation can be obtained, if necessary, by grounding a fence at multiple intervals along its length to break any large conducting loops into a number of smaller loops.

V. MECHANISMS OF BIOLOGICAL INTERACTION BETWEEN ELF FIELDS AND LIVING SYSTEMS

In contrast to the reasonably detailed experimental and theoretical understanding that has been gained on the macroscopic interactions of ELF electric and magnetic fields with humans, relatively little is known about the mechanisms through which weak ELF currents induced within the body interact with molecular and cellular structures. As a result, increased emphasis has been given in recent years to research on the mechanisms through which ELF fields interact with biological structures at the microscopic level and produce functional alterations in living cells and tissues.

A growing body of experimental evidence has implicated the cellular membrane as a primary target of biological interactions with ELF fields. For example, electromagnetic fields in the frequency range below 100 Hz have been demonstrated to alter the release of Ca^{++} from cell-surface binding sites in chick brain and various other forms of tissue (Baw76; Bl85a), to suppress T-lymphocyte cytotoxicity which is dependent on cell-surface antigen binding (Ly83), to inhibit human lymphocyte activation by mitogenic compounds that bind to the cell surface (Gra85), to alter the response of adenylate cyclase to the binding of parathyroid hormone molecules at receptor sites on bone cell surfaces (By84), to alter the distribution of cell-surface receptors and the lifetimes of ligand-receptor complexes (Chi84), to influence the release of insulin molecules from pancreatic cells (Jo83), and to alter cellular partitioning in an aqueous two-phase system that is sensitive to changes in membrane composition (Marr83).

Although these alterations in cell membrane properties clearly implicate this structure as a responsive target for ELF field interactions, the precise mechanisms through which this interaction takes place have not been identified. As discussed earlier in this paper, both the electric and magnetic field components of an externally applied ELF field induce electrical potentials and resultant current flows in the aqueous medium that surrounds living cells. Because the membranes of these cells form a dielectric barrier to the passage of current in the ELF frequency range (see the earlier discussion of α dispersion and tissue dielectric properties), only a small fraction of the induced current penetrates the cell surface. For this reason, it is generally believed that the pericellular currents induced by an ELF field produce electrochemical alterations in components of the cell membrane surface. These events, in turn, send signals across the cell membrane barrier that produce alterations in intracellular biochemical and physiological functions. This hypothesized scheme of transductive coupling between induced electric currents in the extracellular medium and the intracellular events occurring in living cells is illustrated schematically in Fig. 13.

The key element in the sequence of events through which externally applied ELF fields influence cellular properties is the transductive signalling event within the cell membrane. Numerous theoretical models have been proposed for the transmembrane signalling process (or processes) that are triggered by induced pericellular electric currents (Ad81). In the broadest sense, these hypothesized mechanisms can be grouped into two general classes: (1) long-range cooperative phenomena established within the matrix of glycoproteins and lipoproteins that constitute the cell membrane, and (2) localized events occurring at specific ligand binding sites (receptors) at the outer membrane surface, or events occurring within ion-selective channels that span the membrane and electrically couple the intracellular and extracellular fluids. These classes of phenomena are depicted by the boxes at the left and right sides of Fig. 13, and they will be discussed separately.

Long-range cooperative phenomena in cell membranes. The electric fields induced in tissue by externally applied, ELF electromagnetic fields are many orders of magnitude less than the voltage gradient that exists across the living cell membrane. It has been proposed, therefore, that the cellular response to external ELF fields may involve an amplification process in which a weak electric field induced in the extracellular fluid acts as a "trigger" for the initiation of long-range cooperative events within the cell membrane (Ad79; Ad81). The basic premise underlying this theoretical concept is that the cell membrane exists in a metastable, non-equilibrium state that can be significantly perturbed by a weak electrical stimulus. Various physical models of such interactions have treated the cell membrane as a lattice in which nonlinear oscillations are established by weak electrical (or electrochemical) stimuli. These oscillations are amplified by the collective excitation of patches of membrane molecules that extend over a significant portion of the cell surface. The stored

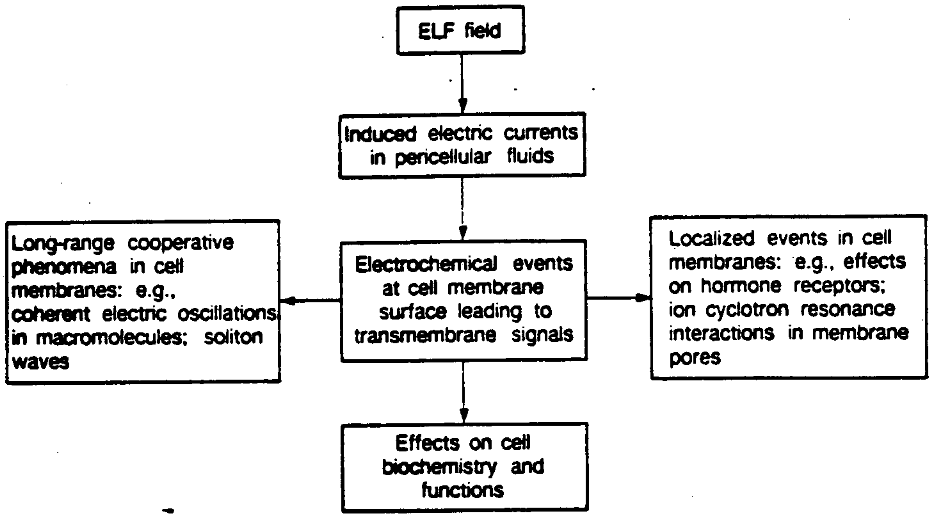


Fig. 13. Schematic representation of various hypothesized mechanisms through which ELF fields could couple with living cells. The induced electric currents in the extracellular fluid are proposed to interact with membrane structures either in a long-range coherent manner, or at localized sites on the cell surface.

energy resulting from this collective mode of molecular excitation is then released via molecular reorganization within the membrane, or it is released as metabolic chemical energy through the activation of ion pumps or enzymatic reactions within the membrane.

Several models that have been proposed of nonlinear membrane phenomena triggered by weak ELF fields are described below:

(1) Fröhlich (Frö68) has proposed that weak electrical stimuli can excite the coherent oscillation of membrane molecules that have electric dipole moments. His theory predicts that dipolar modes of longitudinal oscillation in membrane molecules can be channeled into a single mode by a small energy input that exceeds a critical threshold level. This event would amplify the ELF signal in a highly nonlinear manner predicted by the well-known Lotka-Volterra equations.

(2) Kaczmarek (Kac77) has proposed a similar model involving nonlinear kinetics in which the energy states of membrane proteins move between the ground state and excited states in a limit-cycle behavior. This type of nonlinear oscillation is formally similar to the behavior of a Van der Pol oscillator, and it can be described by analogous mathematical equations.

(3) Grodsky (Gro76) has devised a model of the cell membrane in which the phospholipid polar groups are treated as a two-dimensional crystal lattice of electric dipoles, among which negatively charged glycoproteins that possess a large cation binding affinity are interspersed. By modeling the two-dimensional lattice as a ferroelectret, Grodsky argues that a weak external electric field imposed on this system can force a phase transition in which the dipolar sheet of phospholipid headgroups changes its configuration. This transition occurs in a resonant manner that releases a significant amount of stored energy within the membrane.

(4) Another type of nonlinear excitation of transmembrane proteins that has been proposed as a mechanism for the transductive coupling of weak ELF fields to living cells is the formation of "solitons." The soliton represents a type of collective oscillation in which a slowly dissipating wave moves through a biological structure such as an array of peptide groups in an alpha-helical transmembrane protein. The transfer of energy from soliton excitations occurs in metabolic processes such as the hydrolysis of ATP. Because the soliton results from nonlinear interactions, it represents a possible mechanism for the amplification of weak stimuli presented to cellular structures by externally applied ELF fields. The theory of soliton excitations in biological systems was first proposed by Davydov (Dav79), and it has been applied to the interaction of ELF fields with cell membranes by Lawrence and Adey (Law82).

Localized interactions of external ELF fields with cell membrane structures. Recent experimental evidence has given support to the concept that the interaction of ELF electromagnetic fields with living cells occurs at specific loci on the cell membrane, as reviewed earlier. In many ways, this concept is more attractive than the hypothesized long-range membrane interactions described above. Apart from the abstract nature of such theories, the concept of long-range interactions that involve a large fraction of the cell membrane surface is generally feasible only for electromagnetic fields with frequencies well above the ELF range. Recent theoretical efforts have focused, therefore, on the possibility that weak ELF field interactions could significantly alter either ligand-receptor interactions at the membrane surface, or the transmembrane movement of electrolytes. Two recent theoretical developments in this area are the following:

(1) Chiabrera and his associates (Chi84) have proposed a model of membrane interactions in which a microelectrophoretic motion induced in the cell membrane by weak ELF electric fields influences the average distance between charged ligands and the cell-surface receptors to

which they are bound. In this theoretical model, the effect of the imposed electric field is to decrease the mean lifetime of the ligand-receptor complexes on the membrane surface. They propose that this effect could influence various biological phenomena such as the activation of lymphocytes by antigens and lectins. An ELF field interaction of this type could also influence the gating mechanisms that control the membrane transport of various types of cations such as Ca^{++}.

(2) Several lines of recent experimental evidence have indicated that ion cyclotron resonance effects could occur between ELF fields and static magnetic fields with intensities comparable to that of the geomagnetic field. Briefly summarized, it has been reported that magnetic resonance conditions influence the dielectric properties and growth rate of yeast cells (Ja82), the rate of lysozyme reaction with a cell membrane substrate (Ja82), the behavior of rats in a timing discrimination task (Li85a), and the rate of Ca ion release from brain tissue exposed *in vitro* to low-intensity electromagnetic fields (Bl85b). The first two of these biological effects were claimed to occur in response to conventional nuclear magnetic resonance conditions in which the static field intensity and the frequency of the electromagnetic field were related by the Larmor relationship for various nuclei, including ^1H, ^{23}Na, ^{31}P, ^{35}Cl and ^{39}K. In the third study (Li85a), reversible changes in rodent timing behavior were observed when rats were simultaneously exposed to a 60-Hz magnetic field and a magnetostatic field with a flux density of 26 μT. This combination of static-field intensity and oscillating-field frequency satisfies the cyclotron resonance condition for Li ions, which are thought to exert neuropharmacological effects. In the fourth study (Bl85b), a generalized heuristic relationship was derived between the biological effective electromagnetic field frequency and the static magnetic field flux density. This relationship established a proportionality between the frequency of the oscillating field and the static magnetic field flux density multiplied by an index, $(2n + 1)$, where $n = 0$ or 1.

Liboff (Li85b) has proposed that these weak interactions, which involve an energy transfer from the external field that is eight orders of magnitude less than the Boltzmann thermal energy (kT), could nevertheless impart kinetic energy to ions such as calcium moving through transmembrane channels. The argument was made that ion channels provide an environment in which collisional damping effects on ion motion may be reduced relative to the high collision frequencies that exist in bulk aqueous media (Li85b). Nevertheless, a simple calculation indicates that the induced electric field within ion transport channels under the various experimental conditions described above is on the order of 10^{-10} V/m. This field level is two orders of magnitude less than the Nyquist thermoelectric noise present in membrane channels (Baw76). Overall, the experimental data that suggest a possible role of cyclotron resonance effects on ion transport through cell membranes are intriguing, but there is a clear need for refinements in the theoretical description of this phenomenon.

VI. SUMMARY AND CONCLUSIONS

Considerable advances have been made during the last decade in characterizing the numerous sources of ELF electromagnetic fields to which humans are exposed and in defining the interaction of these fields with living systems. Both theoretical and experimental dosimetry research have made significant advances in describing the distribution and strength of the electric fields and currents induced in various parts of the body by ELF fields. The nature of both direct and indirect coupling of these fields to living systems and the thresholds for human response are now reasonably well defined. In addition, various methods for avoiding the aversive effects of electric shock phenomena are understood and widely practiced.

The fundamental challenge that remains is to unravel the complex mechanisms by which ELF fields interact with cellular and tissue structures that possess nonlinear, frequency-dependent electrical properties. A large number of innovative ideas have been advanced to explain the basis for coupling of ELF fields to living cells, many of which involve transduction and amplification phenomena occurring at the cell membrane. There is little doubt that induced electric currents in living tissues are the "trigger" for ELF field interactions. However, the cell membrane constitutes a formidable dielectric barrier that opposes the transmission of ELF currents to intracellular structures. Several new avenues of research concerned with membrane-related phenomena that could possibly transmit extracellular signals to the intracellular environment have been initiated. With persistence and insight, an understanding of the mechanisms by which external ELF fields can influence intracellular events may be gained.

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