BIOLOGICAL EFFECTS OF ELECTROMAGNETIC FIELDS WITH EMPHASIS ON HEALTH AND SAFETY

INTRODUCTION

The biological effects of electromagnetic fields is a large and heterogeneous subject that spills over into biophysics, medicine, engineering, and, more recently, epidemiology, risk assessment, tort law, and public policy. Within this literature, the biological effects of electromagnetic fields comes up in a variety of contexts. More than 100 epidemiology studies have searched for possible associations between exposure to electromagnetic fields at either powerline or radiofrequencies and various health effects. Hundreds of other studies have, broadly, a toxicological focus (i.e., they were designed to identify effects of electromagnetic fields that may have some bearing on human health effects). Other studies have examined biological endpoints with potential significance to therapeutic applications of electromagnetic fields. Still other studies are basic in orientation and involve biological endpoints that have no direct relevance for health and safety. This vast literature, which includes hundreds of reports of biological effects of electromagnetic fields, is far too extensive to review here. (An Appendix will present selected references, available online, to recent reports of expert groups on the subject.)

EXPOSURE AND DOSE

In toxicology, exposure is the concentration in air, water, or food, or it is the intensity of a physical agent (an electromagnetic field, in this case) in the external environment of a subject. Dose is the amount of the agent delivered to the organ that is the target of toxicity. Appropriate measures of exposure include the following:

- External field strength, measured in volts/m (electric field) or amps/m (magnetic field). Most investigators cite the magnetic flux density in Tesla instead. Typically, field strengths outside of the exposed body (the external field E_o) are reported.
- Time dependence of the field, including frequency (Hz) and modulation parameters (for alternating fields) or pulsewidth, slew rate, and other parameters (pulsed fields). The frequency biological responses depend on the frequency or temporal characteristics of field pulses, both because of their intrinsic time responses, and because of the frequency-dependent coupling of external fields into the body.
- Incident power density (intensity), in W/m^2.

Typical measures of dose include the following:

- Internal field, E_i (i.e., the electric field induced within body tissues).
- Induced current density in A/m^2. The current density induced within the body is related to E_i by Ohm's Law

  $$J_i = \sigma E_i$$

  where σ is the conductivity (S/m) of the tissue. The current density within the tissue can be a better predictor of biological effects than the internal or external field strength.
- Specific absorption rate (SAR). For many effects reported from exposure to high frequency fields, the relevant measure of exposure is the SAR, defined as the rate of heat generation in watts per kilogram of tissue, in terms of the electric field E_i in the tissue,

  $$SAR = \sigma E_i^2/\rho \tag{1}$$

  where ρ is the tissue density (kg/m^3).

Sources of Exposure and Typical Exposure Levels

The interactions between electromagnetic fields and the body can be considered separately in three broad frequency ranges: static fields (0 Hz), low frequency fields (<3 kHz), and high frequency fields (3 kHz <f <300 GHz). The boundaries between these ranges are arbitrary. However, 3 kHz corresponds roughly to the upper frequency for nerve excitation: above 1kHz, the thresholds for nerve excitation increase rapidly with frequency. Below about 1–3 kHz, the most conspicuous hazards to humans from electromagnetic fields are associated with shock, and at higher frequencies they are associated with excessive heating of body tissues.

Static Fields. Technologies producing static magnetic fields include magnetic levitation trains, magnetic resonance imaging devices used in medicine, industrial processes using direct electric currents for materials processing in industry, and particle accelerators used in high energy physics. Static electric fields are commonplace in the environment because of naturally occurring electrostatic processes, and they are produced in some industrial processes. Human exposure to static magnetic fields varies widely. The Earth's magnetic field is approximately 50 μT. Some workers are exposed for prolonged times to static magnetic fields of tens of mT [aluminum workers (1)] to 1 T or more [physicists working on particle accelerators (2)]. Patients undergoing MRI imaging are briefly exposed to magnetic flux densities up to about 4 T. Static electric fields in ordinary room environments are several kV/m.

Low Frequency Fields (<3 kHz). Power distribution facilities and electrical equipment are ubiquitous sources of power–frequency (50–60 Hz) electric and magnetic fields in the environment. Other sources of strong low frequency fields include some industrial induction heaters and some specialized communications facilities.

In ordinary room environments, typical 50–60-Hz fields are about 0.1–0.2 μT (magnetic flux density) and 10–100 V/m (electric field strength). The strongest 50–60-Hz electric field strengths commonly found in the environment exist beneath high voltage transmission lines, where fields can exceed 12 kV/m at ground level [for a 765-kV transmission line located 12 m above ground (3)]. Field strengths of

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250 V/m have been measured 30 cm from an electric blanket. By contrast, the strongest power–frequency magnetic fields found in ordinary environments are associated with appliances. For example, the magnetic flux density near arc welders, soldering guns, and other high current devices can exceed 1 mT. Magnetic flux densities beneath high voltage power lines rarely exceeds 2 μT (all of these values are from Reference 4).

High Frequency Fields (3 kHz to 300 GHz). Many technologies produce electromagnetic fields in this frequency range, including industrial heating, radar, and communications applications.

Exposures to radiofrequency fields vary widely, depending on the proximity to transmitters. An Environmental Protection Agency survey published in 1982 reported a median exposure level of 50 μW/m^2 time-averaged power density for the population of the 12 cities, with approximately 1% of the population studied, or about 380,000 persons, potentially exposed to levels greater than $10^4 \mu$W/m^2 (5).

Sources of potentially hazardous radiofrequency fields are common in household and industrial environments. Devices operating in the industrial-scientific-medical bands at 27 MHz, 915 MHz, and 2450 MHz include microwave ovens and industrial heaters. Fields close to or within such devices can be clearly hazardous, although the systems are normally designed to prevent human exposure at levels above recommended limits. Medical diathermy units expose patients to radiofrequency fields (typically at 915 MHz or 2450 MHz) for purposes of heating.

Coupling Between External and Internal Fields

Static Fields. Body tissues are essentially nonmagnetic, and at low frequencies the magnetic field inside the body is essentially the same as that immediately outside it.

However, body tissues are conductive, with high permittivity at low frequencies (Table 1) (6), which means that an external DC electric field will not induce an electric field within the body in the absence of body contact to a conductor. The external field, however, will induce charges on the outer surface of the body, which can result in strong electric fields in the air near body edges (e.g., at the tips of hairs).

Low Frequency Fields. At low frequencies, the internal and external magnetic fields are virtually identical, because of the nonmagnetic nature of tissues.

However, alternating electric and magnetic fields will both induce electric fields within the body, which from a perspective of health and safety can be significant. These induced fields depend on numerous parameters including the frequency of exposure, geometry of the body, and so on.

The magnetically induced electric fields are determined by Faraday's Law

$$\partial \boldsymbol{B}/\partial t = -\nabla \times \boldsymbol{E} \tag{2}$$

(i.e., the induced electric field is proportional to the time rate of change of the magnetic field).

For a circular loop of tissue with radius R and an alternating magnetic field with (RMS) flux density B$_0$, the magnetically induced electric field E is given by

$$E = \pi\ f B_0 R \tag{3}$$

where f is the frequency (Hz).

Standards-setting organizations have used ellipsoids of revolution to model the body. If the ellipsoid is oriented with its longest semi-major axis along the z direction, which coincides with the orientation of the magnetic field, the induced current density J (RMS) is given by

$$J = \frac{2\pi\ f B_0 \sigma/\sqrt{2}}{a^2 + b^2}(b^4 x^2 + a^4 y^2)^{1/2} \tag{4}$$

where a and b are the two shorter semi-axes, which are assumed to be directed along the x and y axes (7). Thus, the magnetically induced electric field in this model is proportional to the distance from its center.

The electrically induced electric fields within the body depend on the shape of the body and whether it is grounded. For an ungrounded spherical object in air whose dielectric properties are typical of those of tissue, the electrically induced electric field E can be found by solution of Laplace's equation to be (8)

$$E = \frac{3\pi\ f E_o \epsilon_o}{\sigma} \tag{5}$$

where $\in_o$ is the permittivity of space (8.85×10^{-12} F/m) (all fields are RMS). For typical tissues, $\sigma \approx 0.2$ S/m at 60 Hz, and the electrically induced electric field is about 8 orders of magnitude weaker than E$_o$. The total internal electric field E$_i$ is the sum of the electrically and magnetically induced electric fields.

These calculations can be extended to more realistically shaped models of the body and to grounded objects. Figure 1 shows the induced fields in a grounded person standing erect in a vertical 60-Hz electric field. In these objects, the induced fields are greater than simple estimates based on a spherical model by about two orders of magnitude, a consequence of the shape of the body. The current density in the ankles is 10 times larger than in the trunk, because of the smaller cross-sectional area of the trunk and leg compared with the torso (9). Contact with ground results in an approximate doubling of the electrically induced electric fields in the body.

To summarize, inside the body of a person who is not in contact with the ground and exposed to an electric field in the air, at low frequencies:

1. The internal and external magnetic fields are essentially the same.
2. The electrically induced electric field in the body is proportional to the frequency and inversely proportional to the conductivity of tissue. At 50/60 Hz, it is about eight orders of magnitude smaller than E$_o$. These fields vary greatly throughout the body because of local variations in the electrical properties of tissue.
3. The magnetically induced electric field in the body is proportional to the frequency and to the size of the body. These electric fields are largest near the periphery of the body, and are nominally zero at its center.

Table 1. Permittivity ∈ (Relative to Vacuum) and Conductivity σ (S/m) of Tissues at 37°C (Adapted from Reference 6)[a]

Tissue	10 kHz		1 MHz		100 MHz		10 GHz	
	∈	σ	∈	σ	∈	σ	∈	σ
bone	640	0.01	87	0.02	23	0.06	50	0.5–1.7
fat	30000	0.02–.07	—	.02–.07	4.5–7	02–.07	4–7	0.3–0.4
blood	2800	0.7	2040	0.7	67	1.0	45	9–10
muscle (perpendicular to fibers)[b]	70000	0.085	$1–2\times10^5$	0.6–0.9	67–70	0.9–1.0	40–42	8–9
muscle (parallel to fibers)	80000	0.55						

[a] Considerable variability exists in the dielectric properties of tissue. Listed values are either typical values or ranges of reported data.

[b] No data exist for oriented muscle at high frequencies. However, anisotropy is less pronounced at high frequencies.

Table 2. Induced Current Density Associated with Biological Effects of Alternating Magnetic Fields

Induced Current Density (mA/m^2)	Order of magnitude flux density (50/60 Hz) needed to induce current density in human body	Effects (50/60 Hz)
1000	> 100 mT	stimulation of motor cortex in brain and peripheral nerves; possibility of ventricular fibrillation' definite hazards
100–1000	10–100 mT	stimulation of excitable tissue has been reported, other effects reported (changes in central nervous system excitability, reversal of visual evoked responses).
10–100	1–10 mT	magnetophosphenes, possible nervous system effects; reported enhancement of bone healing.
1–10	01–1 mT	endogenous current density; minor biological effects reported
<1	< 0.1 mT	absence of established effects

Adapted from References 15 and 16.

Table 3. Thresholds for Perception of Microwave Energy (50)

Frequency, GHz	Approximate energy penetration depth, m	Threshold for perception (10 s exposure, 0.024 m^2 exposure area),W/m^2
2.45	.02	660
10	.004	200
35	7×10^{-4}	90
94	2×10^{-4}	50

Table 4. Exposure Standards for 60-Hz Electric and Magnetic Fields

	IEEE 2002	ICNIRP 1998	ACGIH 2000
Occupational			
Electric field, kV/m	20	8.3	25
Magnetic flux density, mT	2.7	0.4	1.0
Contact current, mA	1.5	1.0	1.0
General public			
Electric field, kV/m	5	4.2	n/a
Magnetic flux density, mT	0.9	0.08	n/a
Contact current, mA	0.5	0.5	n/a

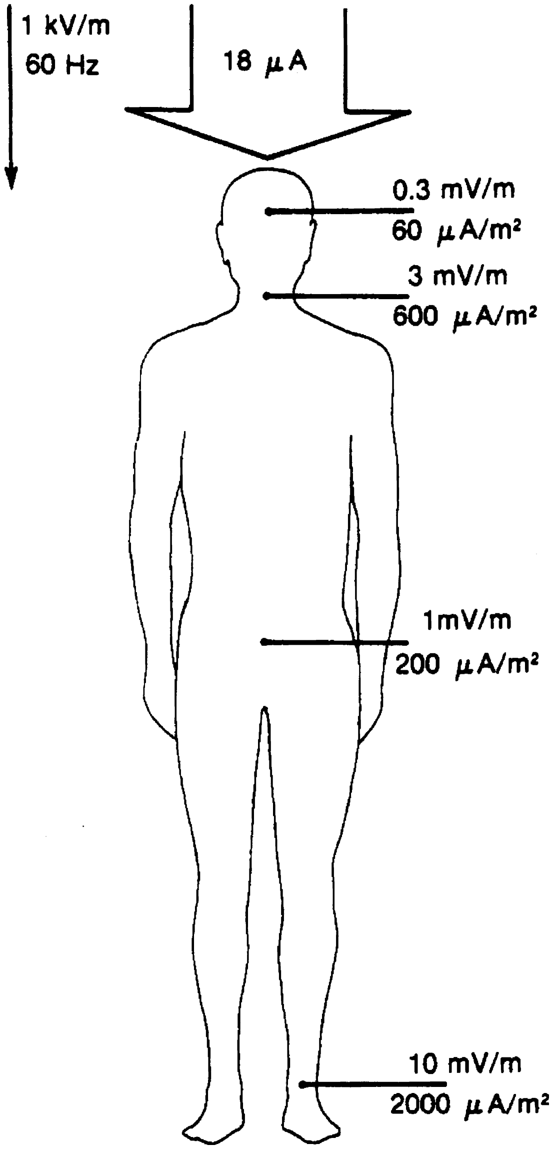

Figure 1. Fields induced in a grounded man standing in a kV/m-60 Hz electric field. The current entering the body (from capacitive coupling with the field) and current densities in the body are indicated. (From Reference 3 with permission).

4. A buildup of charge exists on the surface of the body, as with DC fields, which will lead to an enhancement of the field in the air near sharp objects such as tips of hair.

High Frequency Fields. At frequencies above tens of MHz (for bodies the size of an adult human), the simple calculations presented above become increasingly in error because of wave propagation effects. One must then calculate the induced fields in the body using the full set of Maxwell's equations, usually by numerical techniques (10). Reference 10 provides an extensive discussion of experimental and theoretical dosimetry.

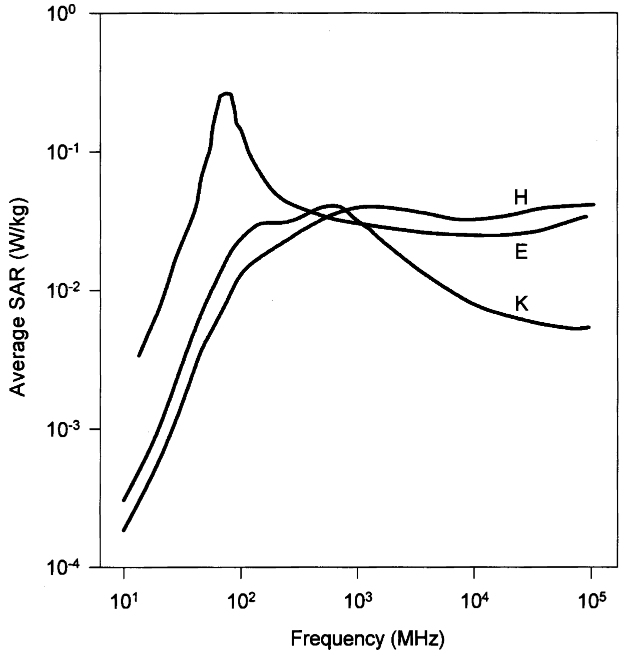

Figure 2. Whole-body average SAR in a prolate spheroidal model of man in a plane wave, as a function of frequency of the incident wave. The major semi-axis is 0.875 m, minor semi-axis 0.138 m, and volume 0.07 m^3. The SAR is given in W/kg, normalized to an incident power density of 10 W/m^2 (from Reference 10 with permission). Three curves are shown, for E (electric field vertical), H (magnetic field vertical), and K (wave propagating from the top) polarizations.

Figure 2 shows the whole-body average SAR in an ellipsoid modeling the body, subject to plane-wave irradiation at an incident power density of 10 W/m^2. At low frequencies, the SAR is proportional to the square of the frequency, as expected from equations 3 and 5. The whole body SAR exhibits a maximum near 70 MHz (for an ellipsoid modeling an adult human in a vertically polarized field) because of an electrical resonance resulting from the properties of the body as an antenna.

When irradiated with waves whose frequency is near or above the resonant frequency, the SAR within the body becomes nonuniform. Close to the resonant peak, the SAR is maximum in the center of the object. At frequencies above about 10 GHz, the exposure comes to resemble plane-wave irradiation of a tissue plane. In that case, the energy penetration depth (6) is given by

$$\delta = \frac{3.38 * 10^5}{f\sqrt{\epsilon}} \frac{1}{\sqrt{1-\sqrt{1-(\tan(\delta))^2}}} \tag{6}$$

where f is the frequency in Hz and

$$\tan(\delta) = \tan(\frac{\sigma}{2\pi f \epsilon \epsilon_o}) \tag{7}$$

is the loss tangent of the material. The SAR as a function of depth x into the tissue is given by

$$SAR = \frac{I_o e^{-x/\delta}}{\rho\delta} \tag{8}$$

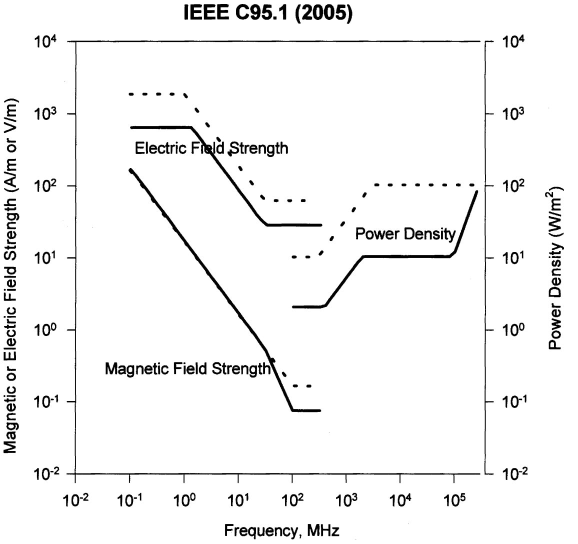

Figure 3. Maximum permissible exposure for persons in controlled (dashed line) and uncontrolled (solid line) environments. These correspond approximately to occupational and general public exposure limits.

At frequencies above about 10 GHz, the energy penetration depth of the incident wave is less than a few mm and the energy is absorbed very close to the surface.

Mechanisms of Interaction

Fields in the frequency range considered here are nonionizing (i.e., their photon energy is too weak by orders of magnitude, for the fields considered here to disrupt chemical bonds), which is in sharp contrast to ionizing radiation such as X-rays, which damage tissue by disrupting chemical bonds and creating highly reactive free radicals. It should also be noted that power–frequency fields are not properly considered to be radiation, because the exposure occurs in the near fields of the sources that for all practical purposed do not radiate.

Numerous mechanisms exist by which nonionizing electromagnetic fields can interact with biological systems, (for reviews, see References 12–14. Each mechanism is characterized by an intensity and frequency threshold for producing observable effects. These mechanisms can be classified as thermal or nonthermal, depending on whether the mechanism is directly associated with tissue heating or some other mechanism.[1] They can be further classified as first or second order in the field strength. This distinction is important because mechanisms that are quadratic in field strength are generally weaker than first-order mechanisms, but can be effective at higher frequencies.

Thermal Effects. Thermal effects are produced by Joule heating (a quadratic effect in electric field), as given by the SAR. A useful benchmark for assessing the threshold for thermal effects is the basal metabolic rate of man, about 1 watt per kg of body mass. Whole–body average or local SAR values substantially higher than 1 watt/kg are likely to be thermally significant, either because of the total thermal load on the body or because of localized temperature rise. With typical values for the conductivity of tissue (Table 2 (15, 16)), it corresponds to internal electric field strengths ranging from 100 V/m (50/60 Hz) to 30 V/m (1 GHz). Thus, internal field strengths above 30–100 V/m will cause significant heating if the exposure persists long enough.

Thermal effects can be observed from microwave fields (typically pulsed fields) in the absence of large (or even measurable) temperature increases. Pulsed microwaves of high peak but low average power can elicit auditory sensations in people by generating sounds in their heads. Each microsecond pulse raises the tissue temperature by a few microdegrees, but the acoustic waves that are produced (by thermal expansion of tissue fluids) can exceed 100 dB sound pressure (17) The sensations arise from perception of these acoustic transients by normal hearing mechanisms.

At a higher level of exposure, a variety of responses can be elicited by brief exposure to intense microwave fields. Mice exposed in the head to intense microwave pulses, sufficient to heat their brain temperatures by a few tenths of a degree within one second, exhibit a variety of involuntary body movements and other stun phenomenon (18). The effect is related to the high rate of heating of the brain tissue, which results in changes in membrane potentials (19), not to the magnitude of the temperature rise itself. Such exposures require specialized equipment (associated with military weapons systems) and do not occur in normal environments.

Nonthermal Mechanisms. Numerous nonthermal mechanisms are known, although in many cases the required field strengths are too high to result in observable biological effects under realistic exposure conditions. These effects include:

Membrane Excitation. Low frequency electric fields can excite membranes, causing shock or other effects. At 50/60 Hz, the threshold current density in tissue for producing shock is very roughly 10 A/m^2, which corresponds to an electric field strength of about 100 V/m in the tissue. Thus, at 50/60 Hz, the internal electric field strength needed to produce shock is comparable with that needed to produce significant heating.

As the frequency is increased above about 1 kHz, the threshold field strength needed to excite cellular membranes increases rapidly. By contrast, the internal field strength to produce significant heating increases slowly with frequency, being determined instead by the frequency dependence of the conductivity. Thus, at low frequencies (<1 kHz), the obvious hazards are generally related to shock or other membrane excitation phenomena, whereas at higher frequencies, the obvious hazards generally are a result of burns or other effects of heating body tissues. This distinction is not absolute; for example, low frequency

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[1] "Thermal" and "nonthermal " are used inconsistently in the bioeffects literature, at times referring to mechanism for producing an effect, and at times (even in the same paper) referring to the presence or absence of what the investigator considers to be a significant change in temperature. Some investigators use the term athermal to indicate a biological effect that occurs in the absence of noticeable heating, but which is still produced by thermal mechanisms. An example of an athermal effect might be a physiological response caused by thermoregulation, although no noticeable change in body temperature occurs.

currents can produce serious burns, which might be more serious, under some hazard scenarios, than electric shock.

Electroporation. Electric fields can create pores in cell membranes (electroporation) by inducing electrical breakdown, which requires potential differences across the membrane of 0.1–1 V, which in turn requires high field strengths in the surrounding medium (typically 10^4–10^5 V/m). However, electroporation may occur in the absence of thermal damage if the exposure is brief enough, and it may be a factor in electrical injury (20).

Perception of Weak Fields. At an opposite extreme, some animals are sensitive to very small electrical fields; for example, some sharks and rays can detect electric fields in the surrounding sea water below 1 μV/m (21). This extraordinary sensitivity involves specialized electrical sense organs (the ampullae of Lorenzini) that depend on the salt water environment of the animal, and is unrelated to biological effects in humans.

Electric Field—Charge Interactions. DC currents introduced into the body can produce electrochemical changes through iontophoresis and electro-osmosis, which can lead to hazards including electrochemical burns (22). These effects require DC currents to be introduced into the body, which in turn requires contact with external conductors.

Electric Field—Permanent Dipole Interactions (Force Linear in E). Electric fields can exert torques on permanent dipoles, which range from dipolar molecules to cells and larger tissue structures. However, the rotational response is damped by viscous forces from the surrounding media, and the alignment is disrupted by thermal agitation. A tradeoff also exists between the threshold field strengths needed to produce a significant alignment and the cutoff frequency of the response. Very high fields (above 10^6 V/m) are needed to produce a significant alignment of globular protein molecules, but the cutoff frequencies are high ($\approx$ 1 MHz). Larger structures, such as cells, can be oriented by weaker fields, but the cutoff frequencies are lower. To produce a biologically significant effect by such a mechanism would normally require field levels that are thermally damaging.

Electric Field–Induced Dipole Interactions (Force Quadratic in E). An electric field can exert mechanical forces on cells and other structures through its interaction with induced electric dipoles, a phenomenon called dielectrophoresis. This effect has important applications in biotechnology, such as manipulating cells or to studying their electrical properties (23). Such effects require high fields, typically thousands of volts per meter or more.

Effects of Magnetic Fields.

Magnetic Force Effects. With few exceptions, biological tissues are diamagnetic (i.e., their magnetic susceptibilities are very close to that of vacuum). Nevertheless, it is possible under some circumstances to detect magnetically induced forces on biological materials, either through magnetic field-permanent dipole or magnetic field-induced dipole interactions. These mechanisms can be first or second order with the field.

Magnetic fields will induce a torque on a magnetic dipole, which is a linear function of the field strength. One biological effect developing from such forces is the orientation of magnetotactic bacteria by the Earth's magnetic field (50 μT) (24). These bacteria contain chains of small magnetite particles, and it is the interaction between the Earth's field and these particles that aligns a bacterium. Similar particles have been found in other species, including human brain tissue, and some investigators have suggested that it might provide a mechanism for magnetic field sensitivity in some animals (25).

Much smaller forces can be exerted by inhomogeneous magnetic fields on ordinary biological materials, which is a quadratic field effect analogous to dielectrophoresis. Investigators have levitated (magnetically suspending in air) saline droplets containing fertilized frog eggs, using inhomogeneous magnetic fields of about 13 T (26). Very strong fields (generally $>$ 10 T) can orient cells and lipid membranes (27).

Other Effects of Magnetic Fields. Various subtle effects can be observed in humans and animals exposed to strong DC magnetic fields. At flux densities generally $>$ 1 T, changes can be observed in the electrocardiogram, typically an increase in the amplitude of the T wave. These changes result from electric potentials that are induced in blood as it flows through the aorta, which give rise to an additional voltage superimposed on the normal electrocardiogram (28).

Effects of DC magnetic fields on rates of bimolecular reactions with nonzero-spin intermediates are well documented, typically at levels of at least 1 mT, and generally over 10 mT (29). Some investigators have proposed that low frequency magnetic fields can cause biological effects through a similar mechanism (30). However, other scientists have argued that such mechanisms are unlikely to result in biological effects from 50/60-Hz magnetic fields at typical exposure levels (31).

BIOLOGICAL EFFECTS OF ELECTROMAGNETIC FIELDS IN HUMANS

This subject is large, and particularly as it relates to possible chronic health effects from low levels of exposure, very contentious. We will first consider the effects that underlie major exposure standards for electromagnetic fields, and then comment about possible effects of chronic exposure to electromagnetic fields in humans.

Static Fields

The strongest DC magnetic field that a human is likely to encounter is in the low-Tesla range (e.g., during imaging by MRI). No biophysical reason exists to anticipate pronounced effects in humans at such levels, and limited testing with animals has disclosed only subtle effects. One investigator noted mild sensory effects in humans exposed to 4 T fields in an MRI system (32). One group reported a change in the permeability of the blood–brain barrier permeability in rats from exposure to 1.5-T magnetic fields (33). This effect (which is so far unconfirmed by independent studies) remains poorly understood and its implications for health and safety are unclear. Blondin et al. reported the threshold for human perception of DC electric fields to be 40–45 kV/m (34).

Low Frequency Fields

The threshold for human perception of 50/60-Hz electric fields is in the range of 2 to 10 kV/m, because of the movement of the hairs on the subject's skin. The threshold for perceiving spark discharges corresponds to field strengths outside the body of about 3 kV/m, when a person can perceive mild shocks when touching a conductive object located in the field. At about 8–10 kV/m, painful shocks can be felt by finger contact with vehicles or other large objects in the field (35). Above about 20 kV/m, annoying shocks are felt at the shoe level (36). Exposure to 50/60-Hz electric fields at still higher levels is very unpleasant because of transient shocks. These effects are a result of currents that are passed into the body by touching a conductive object; the fields induced within the body from such exposures, in the absence of contact with conductive objects, is generally far below the thresholds for inducing shock (Fig. 1).

Cardiac Excitation and Fibrillation

Various effects have been reported or can be anticipated from low frequency alternating magnetic fields at sufficient flux densities, which are associated with induced electric currents (Table 2) (37–39). One potentially lethal effect is cardiac fibrillation from induced electric fields in the chest. Reilly estimated that the threshold current density in the human heart for causing electrical stimulation is about 1 A/m^2 (60 Hz), with thresholds for inducing fibrillation being about 2–3 times higher. Current densities in excess of 2 amp/m^2 (60 Hz), if applied directly to the heart, can induce fibrillation in dogs (40). The National Radiological Protection Board (NRPB) estimated the threshold induced current that would produce cardiac fibrillation in the human to be 3 A/m^2 (41). To produce such currents in the human chest would require magnetic flux densities above 100 mT at 60 Hz (42).

Nerve Stimulation by Pulsed Magnetic Fields

Some clinical devices use pulsed magnetic fields to stimulate nerve and muscle tissues (43, 44), which typically employ pulsed magnetic fields, usually of millisecond duration and with magnetic slew rates (dB/dt) of tens of T/s, and peak magnetic fields ranging from several hundred mT to several T.

Other effects such as headache and general discomfort (45) have been reported in humans at flux densities > 60 mT (50/60 Hz) and may involve neurological effects. However, the literature on these effects is sparse and variable in quality, and the mechanisms for the effects are not well understood.

Bone Repair Stimulated by Pulsed Magnetic Fields

An often-reported effect of magnetic fields that remains poorly understood is the stimulation of fracture repair in bones. Magnetic bone stimulators have been approved for sale in the United States since the late 1970s. These devices employ a variety of pulsed fields, and they induce electric fields in the body with peak levels of the order of 0.1 V/m (46). The corresponding peak current densities are of the orders of tens of mA/m^2 in soft tissue, which are above the level of naturally occurring (endogenous) fields but are well below anticipated thresholds for eliciting action potentials in excitable tissue.

Magnetophosphenes

A well-established effect, first observed by d'Arsonval in 1896, is the production of visual sensations, called magnetophosphenes, when the head is exposed to alternating magnetic fields (10–20 mT, 50 Hz). These effects are caused by small currents (20–200 mA/cm^2) that are induced in the retina of the eye (47,48), and are the most sensitive responses observed in humans from exposure to low frequency electric or magnetic fields. The effect has not been considered to be a hazard by the expert committees that have examined the literature.

Endogenous Electric Fields

Naturally occurring (endogenous) electric fields exist in the body because of bioelectric phenomena such as the electrocardiogram, electromyogram, and electroencephalogram. Such fields generally have most of their spectral density below 100 Hz and correspond to current densities of 1–10 mA/m^2; but current densities of 1000 mA/m^2 can develop during brief periods of electrical activity (action potentials) on the surface of nerve or muscle cells (49). The ubiquitous presence of such fields in body tissues would seem to place a lower limit on the strength of externally induced fields that would be biologically significant.

High-Frequency Fields. As the frequency of the applied field is increased above 1–3 kHz, cell membranes become progressively less sensitive to stimulation, and thermal phenomena predominate. A variety of effects, some hazardous, have been reported from high frequency electromagnetic fields (mostly at radiofrequencies and above).

Perception and Pain

The thresholds for perception of microwave energy have recently been measured by Blick et al. for brief (10-second) exposure to microwave energy over an area of 0.024 m^2 on the backs of human volunteers (Table 3) (50). A thermal model, which takes into account the reflection of energy from the skin and heat conduction, shows that the temperature rise at the skin surface at the threshold for perception is about 0.07°C over this entire frequency range (51).

The threshold for perception decreases with increasing frequency, because of the shorter penetration depth into tissue (and corresponding increase in SAR near the skin surface), modified by thermal conduction effects.

The threshold for painful stimulation under similar exposure conditions would be 50–100 times higher for these exposure conditions. However, the thresholds for perception and pain are likely to vary greatly, depending on the location of the exposed surface, duration of exposure, and other variables.

Burns

At still higher exposure levels, or for longer exposure times at these exposure levels, burns may it result. Despite the many high power sources of radiofrequency and microwave energy that exist in modern society, the incidence of serious burns from radiofrequency energy is low (a handful of incidents have been reported of burns from defective microwave ovens, some of them disputed (52), and occasional industrial accidents occur that involve exposure of workers to high levels of radiofrequency fields).

The thresholds for producing thermal damage in tissue depend on the magnitude and duration of the increase in temperature. Tissues can tolerate heating to temperatures below about 43°C almost indefinitely, whereas higher temperatures will lead to thermal damage at progressively shorter times at higher temperatures (53). Thus, the microwave exposure needed to produce thermal damage depends on several factors, including the time over which irradiation persists, the size of the heated region, and the rate at which heat is transported from the heated region. Despite the fact that burns are an unequivocal potential hazard from exposure to RF energy, the incidence of such injuries is very low. Reasons include the general inaccessibility of high powered sources of RF energy to the general population and the fact that overexposure will lead to severe pain before thermal damage occurs, forcing the subject to withdraw from exposure. Incidents of serious injury to exposure to RF energy are typically associated with industrial accidents (for example, one case involved a tower climber who was suspended in front of a high powered broadcast transmitter and could not escape) or in military environments in which a person comes into contact with very intense RF beams.

Thermoregulatory Effects

If the heat load to the body is comparable with, or even below, rates of heat generation by metabolism, biological effects can occur as a result of the normal operation of the thermoregulatory mechanisms. Characteristic thermoregulatory changes include alterations in blood flow, respiration, sweating, and many more subtle physiological responses. Various subtle physiological effects observed in animals after moderate exposure to microwaves can be interpreted as normal thermoregulatory responses, and various reported synergistic interactions of drugs and microwave exposure might likewise have a thermoregulatory component (54). The basal metabolic rate in man is about 1 W/kg of body mass, and whole-body exposures somewhat above and below this level can be expected to produce thermoregulatory responses.

Other Thermal Effects

A wide variety of thermal effects have been demonstrated in animals that can be anticipated to occur in humans as well. Some of the more significant include the following:

- Cataract is an established hazard of microwave energy, which has been reported occasionally in humans exposed to high intensity microwaves. Cataracts can be produced in animals at high exposure levels, generally > 1000 W/m^2, and are associated with temperature increases of several degrees in the eye. Exposures at such levels would be acutely hazardous to personnel because of the likelihood of thermal injury to the body (and not just in the eye). Occasional claims of cataract produced by low level microwave exposure have not been substantiated by animal studies (55).
- Reproductive effects (birth defects and other adverse effects) are well established in mammals exposed to microwave energy sufficient to raise body temperature [e.g., (56)]. The exposure required to produce such effects is quite high (tens of W/kg), and the effect can be presumed to be thermal in nature. High exposures, far above present exposure safety limits, would be required to produce such effects.
- Behavioral disruption has been observed in several species of animals exposed to microwaves at whole-body exposures of 4–6 W/kg, at several frequencies above 100 MHz (57). In such studies, the animals are trained to carry out a task (for example, pressing a lever to obtain food pellets) and exposed to microwave energy. At some exposure level, the animals stop performing the assigned task and begin a different behavior, typically one associated with thermoregulation (for example, spreading saliva on the tail in rats). Major standards-setting committees have considered behavioral disruption to be the effect of radiofrequency energy that has been reliably demonstrated at the lowest whole-body exposure level. Behavioral disruption can be interpreted as a normal response of the animal to the excessive heat load to its body, and is not, strictly speaking, an adverse effect at all; however the thermal burden to the body in such cases is undoubtedly close to hazardous levels.

Consequences of Long-Term Exposures

All of the scientific results discussed so far pertain to effects produced by short-term exposures to electromagnetic fields, usually at high levels. A very different body of literature has emerged since the late 1970s pertaining to possible health effects from long-term exposures to environmental fields, either at power line (50/60 Hz) or radiofrequencies, based on epidemiological studies that focus on possible statistical correlations between exposure and a health endpoint.

The epidemiology literature is far too large to review here. The following paragraphs provide citations to major recent reviews and indicate the nature of their conclusions.

Powerline Fields. Most epidemiology studies related to power line fields have focused on a possible link between exposure to 50/60-Hz magnetic fields and childhood leukemia, first suggested in a 1979 paper by Wertheimer and Leeper (58). A variety of other health endpoints have been examined as well.

By now, more than 100 epidemiology studies have been reported related to power frequency fields and human health; for recent reviews, see Kheifets and Shimkhada (59) and Feychting et al. (60). A definitive review of the literature, focusing primarily on epidemiology literature but considering relevant animal studies, was published in 2002 by the International Agency for Research on Cancer (IARC) (61). The IARC review classified power frequency magnetic fields as "possible" human carcinogens (Group 2B in its classification scheme), based on limited epidemiological evidence together with limited or inadequate animal evidence (other 2B carcinogens, as determined by IARC, include coffee, automobile exhaust, and pickled vegetables). IARC judged the evidence for other health effects to be inadequate to draw conclusions.

Radiofrequency Fields. Public concerns that use of mobile telephones might cause brain cancer were triggered by a story broadcast on a United States television show in 1993 by a man whose wife had used a mobile telephone and subsequently developed brain cancer, which he attributed to the effects of the phone. Such observations have obvious weaknesses for documenting cause-and-effect relationships: many millions of people use mobile telephones and an incidence of the disease in the United States is 15–20 new cases per hundred thousand people per year, and consequently many users of mobile phones will develop brain cancer every year even if no causal link to the phones exist. In the intervening decade, more than a dozen large-scale epidemiology studies, and numerous animal studies, have been undertaken (for recent reviews, see Ahlbom et al. (62) and Moulder et al. (63). Several massive epidemiology studies are nearly completed and much more data will become available on this issue in coming years; present results are generally negative but insufficient to persuade most health agencies that no hazards (cancer or otherwise) are associated with use of mobile telephones. The problem is complicated by the largely unknown cause of brain cancer in its various forms, by the long latency (time between initiation of the tumor and its clinical detection in a patient), and by the rapidly changing technology of wireless communications.

EXPOSURE LIMITS

Several government and nongovernment agencies have established guidelines for human exposure to electromagnetic fields. The standards are complex, and the reader is referred to the original documents for authoritative information about the standards and how they would be applied.

DC Fields

Few standards exist for exposure to DC electric and magnetic fields. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) set a limit for occupational exposure of 2T, with a time-weighted-average of 0.2 T over a workday (64). Similar limits have also been set by the National Radiation Protection Board (NRPB) in the United Kingdom and the American Conference of Governmental Industrial Hygienists (ACGIH), as well as other agencies. Exposure limits set by various agencies for static electric fields are in the range of 25–60 kV/m. It should be noted that these limits are designed to protect against possible health effects of the fields; protection of patients with implantable devices undergoing MRI examination (for example) is a different matter entirely.

Low Frequency Electric and Magnetic Fields

Several agencies have established exposure standards for both power–frequency electric and magnetic fields. Most are designed to limit magnetically induced current densities within the body to 10 mA/m^2 at 50/60 Hz, on the assumption that induced currents below the levels of endogenous currents are unlikely to be hazardous. Other limits apply to contact current, which is introduced into the body by contact with an external conductor in a field. Exposure limits set by U.S. and European agencies are in the range of 0.5–7 mT for magnetic flux density and 10–30 kV/m for electric fields of 50/60 Hz (Table 4).

Radiofrequency Energy

The exposure standard for RF fields that is most widely adopted around the world is that of the International Commission for Non-Ionizing Radiation Protection (ICNIRP); another and quite similar standard is IEEE C95.1-2005 (65).

The ICNIRP and IEEE C95.1 exposure guidelines provide two sets of limits: basic restrictions and reference levels. Basic restrictions are limits based on health effects and specify the maximum fields or SAR that exist within the body from exposure to fields. As the induced field or SAR within the body is not practical to determine in most practical settings, both ICNIRP and IEEE C95.1 also provide a set of reference levels. These levels are the strengths of the fields outside the body, or incident power density, that would ensure compliance with the basic restrictions. The guidelines allow exposures above the reference levels, but in that case, a detailed exposure assessment would be needed to ensure that the basic restrictions are satisfied. In addition, ICNIRP and IEEE C95.1 have two tiers of limits that correspond to limits for occupational groups and the general population (ICNIRP) or for persons in "controlled " and "uncontrolled" environments (IEEE C95.1). A "controlled" environment in the IEEE limits is one in which occupancy of a person is subject to control and accountability as established by an RF safety program.

Both the ICNIRP and IEEE C95.1 limits have been criticized at times as being "thermal" and not protective against "athermal " hazards. Indeed, they are designed to protect against hazards of RF energy (e.g., burns, shock, excessive heat load to the body), which are characteristically associated with short-term exposures to fields at high levels. Both ICNIRP and IEEE C95.1 acknowledge that “athermal” biological effects have been reported by some scientists from low level exposures to RF energy, but the standards-setting committees considered the evidence that is presently available about athermal effects to be insufficient to use to develop exposure guidelines. Thus, “overall, the literature on athermal effects of AM electromagnetic fields is so complex, the validity of reported effects so poorly established, and the relevance of the effects to human health is so uncertain, that it is impossible to use this body of information as a basis for setting limits on human exposure to these fields” (ICNIRP).

Controversies and Unresolved Issues

The biological effects of RF and microwave energy has been remarkably contentious for many years, which is a common situation with environmental health issues of all sorts, in part because of the inevitable gaps and ambiguities in the data, and in part because of different perceptions by different stakeholders about the interpretation of the data. In common with other environmental health issues, the scientific literature in this field includes many studies that are highly variable in relevance to health and scientific quality. People who are inclined to worry can pick and choose data to support their fears even as health agencies review the broader literature and fail to find persuasive evidence for a health problem.

Particularly intense controversies have swirled for decades over concerns expressed by many people that exposure to electromagnetic fields, of some sort, might be linked to some form of cancer. Specific concerns have developed about the following: power frequency magnetic fields and childhood leukemia or brain cancer, police radar detectors and testicular cancer, mobile telephone handsets and benign or malignant brain tumors, and living near radio transmitters and childhood leukemia. Despite these concerns, careful reviews by health agencies (some of which are cited in the Appendix and are readily available on the Internet) have consistently failed to find persuasive evidence for any health effects from exposure to electromagnetic fields below IEEE or ICNIRP exposure limits.

DISCUSSION

In virtually all ordinary environments in modem society, the field levels that are present are very far below recommended (ICNIRP or IEEE) exposure limits. Limits, for radiofrequency energy, are generally exceeded only very close to high powered transmitters, which are hardly ever present in ordinary environments but may occur in some occupational settings. Few injuries are reported from exposure to radiofrequency fields, and still fewer from exposure to low frequency fields. The electrical accidents that are reported more commonly involve contact with charged conductors. For example, construction workers near AM broadcasting facilities can suffer electrical bums from radiofrequency currents induced in cranes or other large metal objects near the transmitters. In the United States, accidental electrocution claims the lives of about 1000 individuals every year. No doubt exists that electricity is dangerous, but it seems that exposures to fields is not a major source of injury.

APPENDIX:

Recent Assessments of Possible Health Risks of Electromagnetic Fields by National Expert Groups (Most of these focus on radiofrequency fields; others include discussion of possible health effects of power frequency fields. Several of these agencies release yearly updates; only the most recent report is included below.)

National Radiation Protection Board (UK)

Documents of the National Radiation Protection Board (UK): Volume 14, No. 2 Health Effects from Radiofrequency Electromagnetic Fields: Report of an independent Advisory Group on Non-ionising Radiation. http://www.hpa.org.uk/radiation/publications/documents_of_nrpb/abstracts/absdl4-2.htm

UK Independent Expert Group On Mobile Phones

Mobile Phones and Health, UK. May 2000. http://www.iegmp.org.uk/index.htm

Health Council of the Netherlands

Elektromagnetische Velden: Jaarbericht 2005 / Electromagnetic Fields: Annual Update 2005. The Hague: Health Council of the Netherlands, **2001**, 2001 / 14. http://www.gr.nl/pdf.php?ID=1281&p=l

New Zealand Ministry for the Environment

National guidelines for managing the effects of radiofrequency transmitters, December 2000. http://www.mfe.govt.nz/publications/rma/radio-freq-guidelines-dec00.pdf

The Royal Society of Canada

Expert Panel on Potential Health Risks of Radiofrequency Fields from Wireless Telecommunication Devices 2004 update report: Recent Advances In Research On Radiofrequency Fields And Health: 2001–2003. http://www.rsc.ca//files/publications/expert_panels/RF//expert_panel_radiofrequency_update2.pdf

Swedish Radiation Protection Authority

Recent Research on Mobile Telephony and Health Risks Recent Research on EMF and Health Risks. Third annual - report from SSI’s Independent Expert Group on - Electromagnetic Fields. - SSI’s Independent Group on Electromagnetic Fields, 2005. http://www.ssi.se/PdiUpload/SSI_EMF_2005.pdf#search='electromagnetic+fields’

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11. ibid.
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