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ASSESSMENT OF BIOLOGICAL EFFECTS ASSOCIATED WITH MAGNETIC FIELDS FROM A SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

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April, 1986

Final report prepared for the Energy Storage and Hydroelectric Generation Program of the Energy Management and Utilization Division, Electric Power Research Institute, Palo Alto, CA, under Contract RP2572-5 with the Lawrence Berkeley Laboratory.

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ABSTRACT

The objective of this report is to provide a detailed evaluation of the potential biological effects of fringe magnetic fields associated with a superconducting magnetic energy storage (SMES) plant. The following aspects of magnetic fields are discussed: (1) mechanisms of interaction of static and slowly time-varying magnetic fields with living systems; (2) biological effects of magnetic fields on human and subhuman species, including the results of both laboratory studies and human epidemiological surveys; (3) physical hazards posed by the interactions of magnetic fields with metallic implants, e.g., aneurysm clips and prostheses, and with medical electronic devices such as cardiac pacemakers; (4) extant guidelines for occupational exposure to magnetic fields are summarized; (5) a summary and critique is given of topics (1) - (4); (6) recommendations are made for defining acceptable levels of exposure to SMES magnetic fields by occupational personnel and the population-at-large; (7) recommendations are made concerning several areas of research that would further our understanding of magnetic field interactions with living systems, and would provide additional elements of information required for the development of future exposure standards.

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BACKGROUND

The Electric Power Research Institute has completed a conceptual design and cost estimate for a 5500-MWh SMES plant that uses a 0.8-km-diameter NbTi superconducting coil operated at an average field strength of 4.25 T. The fringe magnetic fields at ground level above the buried solenoidal magnet approach 0.1 T and decrease to 0.001 T at a radial distance from the center of the SMES coil of approximately 2.5 km at ground level. The 0.001 T fringe field level is also reached at a vertical elevation of approximately 3 km above the SMES coil. The maximum field gradient occurs close to the coil and is approximately 0.1 T/m. The gradient decreases to less than 0.001 T/m at radial distances greater than 1 km from the geometric center of the SMES coil. These fringe fields also vary slowly with time as a result of variations in the field intensity that are required to achieve load leveling during peak and off-peak periods of energy utilization. The average time variation is anticipated to be 0.0002 T/s. This time variation could increase to 0.014 T/s during a quench of the superconducting magnet or an emergency power dump in response to some other system failure.

This report analyzes the possible biological effects resulting from the exposure of living organisms to the static and time-varying magnetic fields associated with an SMES plant. The analysis includes possible effects on workers at an SMES facility, on the general public in areas outside the boundaries of the facility, and on plants and subhuman animal species within the environment of the facility. Potential effects on implanted medical devices are also discussed quantitatively. Extant exposure guidelines are summarized, and recommendations are made for defining acceptable levels of exposure to SMES fields by occupational personnel and the population-at-large.

MECHANISMS OF MAGNETIC FIELD INTERACTIONS

Of the numerous mechanisms through which static magnetic fields can interact with biological processes, there are three major classes of interactions that have been documented in well-controlled laboratory research: (1) electrodynamic interactions with ionic conduction currents that lead to the induction of measurable electrical potentials in the major vessels of the circulatory system; (2) magnetomechanical effects that include the orientation of diamagnetically anisotropic macromolecular structures in strong uniform fields, and the translation of paramagnetic and ferromagnetic materials in strong magnetic field gradients; (3) Zeeman interactions with electronic spin states of radical pair intermediates involved in certain classes of electron transfer reactions, one example being the reduction in triplet state yield when the photo-induced charge transfer reaction in bacterial photosynthesis proceeds in the presence of a static magnetic field. The first two classes of interaction mechanisms have been shown to produce measurable biological effects in various living organisms. The third interaction mechanism occurs only under special laboratory conditions that do not occur in nature, and there is presently no evidence that static magnetic fields influence photosynthesis in plants or bacteria in their natural states.

The interaction of time-varying magnetic fields with living organisms results in the induction of faradaic electric fields and currents. Several lines of evidence indicate that these induced currents can exert effects on cellular biochemistry and functions when the current density exceeds the endogenous level present in living tissues, although the exact mechanisms through which such electrical signals are transduced have not as yet been elucidated. Several recent studies also suggest that magnetic resonance phenomena resulting from exposure to combined static and oscillating magnetic fields can influence biological functions, although the evidence is still of a very preliminary nature.

LABORATORY STUDIES ON MAGNETIC FIELD BIOEFFECTS

Several organisms possess unique mechanisms for the detection of weak magnetic fields with intensities comparable to that of the geomagnetic field. Three well-documented examples described in this report are: (1) the electromagnetic detection system of elasmobranch fish (sharks, skates and rays), by means of which these animals derive directional cues from the weak voltages that are induced as they swim through the geomagnetic field; (2) the orientation of magnetotactic bacteria within the geomagnetic field; and (3) the effects of weak magnetic fields, including the geomagnetic field, on the migratory patterns of birds. Of these three examples, only the third is directly relevant to the potential environmental effects of SMES fringe fields.

In higher organisms, the one well-established biological effect of static magnetic fields is the induction of electrical potentials in the central circulatory system. The threshold flux densities for producing electrical potentials that can be detected in the electrocardiogram are 0.3 T for rats and 0.1 T for larger animals such as dogs and monkeys. Although these potentials exceed the millivolt level in large laboratory animals exposed to fields greater that 1 T, there is no evidence that they influence the hemodynamic properties of blood flow or other cardiovascular functions. Based on extensive laboratory studies conducted with magnetic fields of 1 T or higher, the following important biological processes also appear not to be influenced by static magnetic fields at high intensities: (1) cell growth and morphology, (2) DNA structure and gene expression, (3) reproduction and development (pre- and post-natal), (4) bioelectric properties of isolated neurons, (5) animal behavior, (6) visual response to photic stimulation, (7) cardiovascular dynamics (acute exposures), (8) hematological indices, (9) immune responsiveness, and (10) physiological regulation and circadian rhythms.

Laboratory studies on the biological effects of time-varying magnetic fields have demonstrated that several phenomena occur in high-intensity fields. These effects include: (1) neuromuscular stimulation by time-varying fields that induce current densities in excess of approximately 1 A/m^2; (2) magnetophosphenes and alterations in visually-evoked potentials are produced in humans exposed to pulsed and sinusoidal magnetic fields of sufficient intensity to induce current densities in the range of 1-10 mA/m^2 within the eye; (3) a number of alterations in cell and tissue biochemistry and functional properties have been reported to occur in response to time-varying magnetic fields that induce current densities exceeding approximately 10 mA/m^2, one example being the numerous reports of accelerated bone fracture healing in humans and laboratory animals exposed to pulsed magnetic fields. Because the maximum current densities induced in humans and wildlife exposed to the slowly time-varying fringe fields of an SMES plant would be less than 1 mA/m^2, none of the above effects would be expected to occur. There is some evidence that the navigational patterns of avians might be responsive to extremely weak, time-varying magnetic fields. However, at the present time there is no clear evidence to indicate that this sensitivity of migratory birds poses a significant environmental problem.

HUMAN HEALTH EFFECTS

Recent epidemiological studies in the United States have shown no adverse health effects associated with occupational exposure to static magnetic fields at National Laboratories and in chemical separation plants that use large electrolytic cells. Two studies on workers in aluminum plants have demonstrated an increased mortality from various types of cancer in comparison with the general population, but the possible influence of potentially carcinogenic factors other than magnetic fields were not adequately addressed.

Laboratory studies on human subjects exposed to time-varying magnetic fields have revealed no adverse clinical or psychological effects. However, recent epidemiological studies on individuals exposed residentially and/or occupationally to time-varying magnetic fields in the power-frequency range have led to 11 reports of an apparent correlation between exposure and cancer risk. The major type of cancer implicated in these studies was leukemia, although an elevated incidence of other forms of cancer was also reported in several studies. A majority of these studies did not adequately account for the influence of other carcinogenic factors in the home and workplace. There is a clear need for carefully-controlled epidemiological studies on large populations in order to clarify the issue of whether exposure to power-frequency fields increases cancer risk.

PHYSICAL HAZARDS OF MAGNETIC FIELDS

Two well-studied types of physical hazards are associated with exposure to static and time-varying magnetic fields: (1) forces and torques are exerted on ferromagnetic and paramagnetic materials by static magnetic fields, and (2) interference with the operation of medical electronic devices as a result of exposure to static and time-varying magnetic fields. In general, the first type of hazard should be present only for workers in the immediate vicinity of an SMES plant. The second class of hazard is of particular concern for workers and members of the general public in the vicinity of an SMES plant. Static magnetic fields exceeding 0.0017 T can produce closure of a reed relay switch used in modern cardiac pacemakers, thereby causing the pacemaker to revert to an asynchronous worn by individuals in high-intensity magnetic fields. Power-frequency fields with time variations greater than 0.075 T/s can also interfere with pacemaker operation, causing abnormal pacing characteristics and/or reversion to an asynchronous pacing mode. These effects indicate that persons wearing cardiac pacemakers should be excluded from regions surrounding an SMES plant where the static magnetic field level exceeds 0.001 T. Under this exclusion condition, no significant magnetic forces or electromagnetic interference with pacemaker operation would occur.

EXPOSURE GUIDELINES

At the present time, there are no official standards that limit human exposure to either static or slowly time-varying magnetic fields. Several sets of informal guidelines limiting human exposure to static magnetic fields in the workplace have been proposed during the past two decades. The most widely used guidelines are those established at the Stanford Linear Accelerator in 1970. These guidelines limit whole-body or head exposure to 0.02 T during the entire workday, and to 0.2 T for short intervals of several min duration. The limits for exposure of the arms and hands are 10 times greater than those for the whole body or head.

There is currently considerable interest in determining the safe limits of human exposure to both static and time-varying magnetic fields because of the rapid development of nuclear magnetic resonance techniques for medical imaging and *in vivo* spectroscopy. The health profiles of patients subjected to the relatively large static and time-varying magnetic fields associated with medical NMR devices are being followed, and this information may ultimately prove valuable for the establishment of safe limits of human exposure to magnetic fields. In addition, epidemiological surveys on human populations exposed residentially and/or occupationally to power-frequency magnetic fields are continuing, and the results of these studies should also be of value for the establishment of exposure guidelines. It is anticipated that by the early part of the next century, when the SMES technology becomes a commercial reality, there will be sufficient information available to establish formal regulations on human exposure to static and time-varying magnetic fields. Further laboratory-based research on the mechanisms through which these fields interact with living systems will also provide valuable information that is complementary to the results of epidemiological studies on exposed human populations. Several recommendations are made in this report on areas of future research that would extend the database required for the development of magnetic field exposure standards.

Section 1

INTRODUCTION

The Electric Power Research Institute has recently completed a two-phase study to provide a conceptual design and cost estimate for a 5500-MWh SMES plant. The results of this study demonstrated that the development of a large-scale SMES facility with reliable performance characteristics is technically feasible. Compared to other options for energy storage during off-peak hours, the SMES concept offers a high efficiency because no interconversion is required between the electric power and other forms of energy (thermal, mechanical or chemical energy).

In the recently-completed conceptual design of a 5500-MWh SMES plant, the 0.8-km-diameter NbTi superconducting coil carries a current of approximately 200 kA and has an average field strength of 4.25 Tesla ($1\ T = 10^4$ Gauss) at the coil midplane. The large magnetic fields that extend axially and radially from the circular coil necessitate a detailed analysis of several factors: (1) mechanical stresses in the coil and support structures; (2) environmental impact of the fringe fields; (3) human health and safety factors, both for operational personnel exposed to high field levels and for the population-at-large exposed to low-intensity fringe fields extending beyond the perimeter of the SMES facility.

This report addresses the second and third of these issues. It is anticipated that both issues will have an impact on the eventual licensing of a commercial SMES facility, and on the total land procurement that will be required in order to reduce the magnetic field level at the perimeter of the facility to an acceptable level. A summary and analysis is given in this report of the mechanisms of interaction and the bioeffects of static and slowly time-varying magnetic fields. Several reviews of these subjects have been published in recent years (1 - 8). The objective of this report will be to summarize the existing literature on magnetic field bioeffects within the context of established physical interaction mechanisms, and to relate this body of information to the specific issue of the potential effects of SMES magnetic fields on human health and the environment.

Section 2

FIELDS ASSOCIATED WITH SMES FACILITIES

The superconducting magnetic energy storage (SMES) system is a technique for storing electric power during periods of low utilization, and for supplying power during times of peak demand to achieve "load leveling." The theoretical energy storage and dispatch efficiencies of SMES devices are about 90 percent, and they offer promise as a method for effective electric power utilization in the future. During the last decade a prototype SMES device with a 4 T field and a 30 MJ storage capacity was built and tested at the Tacoma Substation, which is under the jurisdiction of the Bonneville power facility in the United States. This was a ground level facility with fringe fields up to 0.05 T at operator accessible locations (9).

Several other designs of SMES systems involving a significantly larger energy storage capacity have been developed through support of the U.S. Department of Energy and the Electric Power Research Institute (10, 11). All of these new designs have incorporated a trench in which the solenoidal superconducting magnet is buried in order to provide cost-effective mechanical support for the coil. A mechanical support frame imbedded in granite or other types of rock is required in order to oppose the transverse magnetic forces that are present when the magnet is operating at a peak field level (typically 4 to 5 T). Even with a buried SMES design, however, the fringe magnetic fields at ground level above the solenoidal magnet are anticipated to approach 0.1 T for a plant operating at or above 5000 MWh. This is demonstrated by the fringe magnetic field profile shown in Figure 2-1 for a conceptual 5500 MWh SMES unit that has a 4.25 T field level at the coil midplane (11). The fringe field decreases to the 1 mT (10 Gauss) level at a radial distance from the center of the SMES coil of approximately 2.5 km at ground level. The 1 mT fringe field level is also reached at a vertical elevation of approximately 3 km above the SMES coil. The static magnetic field spatial gradients are large only within the SMES trench and its immediate vicinity. At distances beyond 1 km from the geometric center of the SMES coil, the spatial gradients are less than 1 mT/m.

The magnetic fields associated with SMES plants also vary slowly with time as a

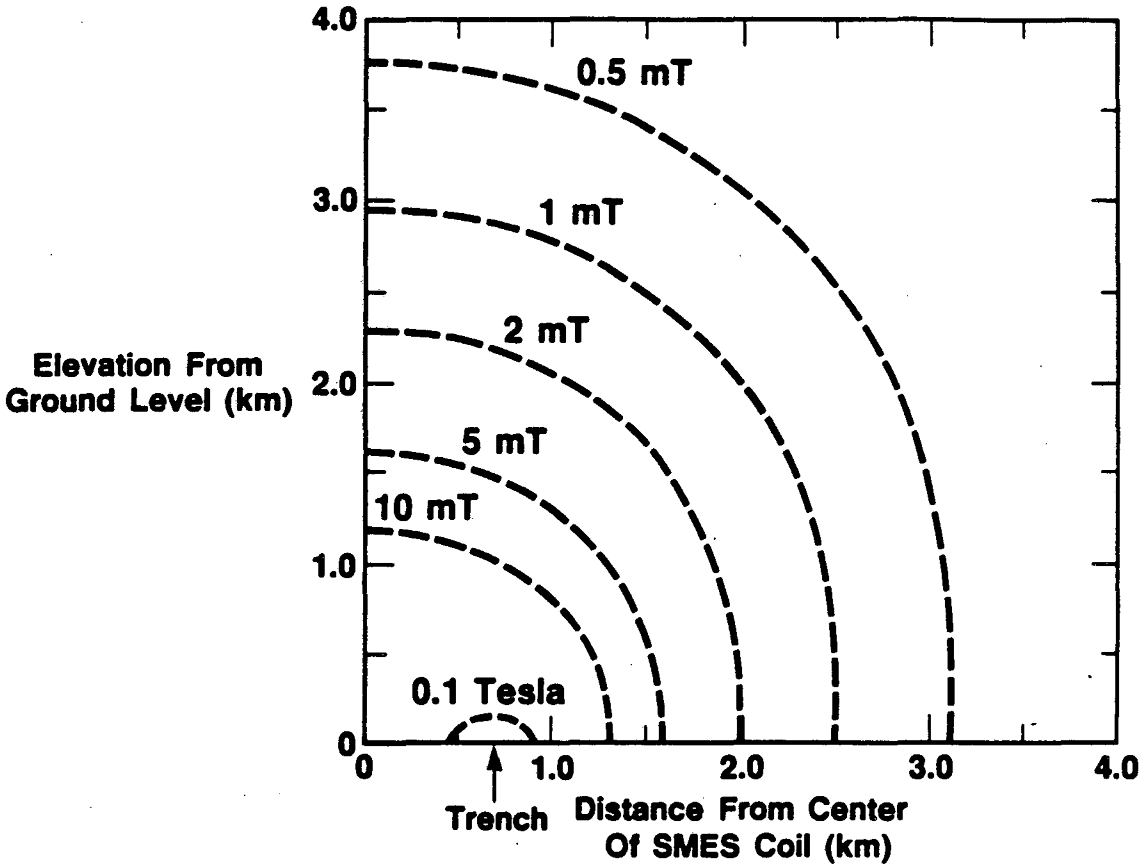


Figure 2-1. SMES Magnetic Field Contour

Calculated magnetic field profiles are shown for a conceptual design of a buried 5500-MWh superconducting magnetic energy storage system. [Adapted from Figure 4-3, p. 4-6 of ref. 11.]

result of variations in the field intensity to achieve load leveling during peak and off-peak periods of energy utilization. The largest average field variation for the EPRI 5500 MWh SMES design would be approximately 4 T over a 5 h period (12), corresponding to an average time variation (dB/dt) of 0.2 mT/s. During a magnet quench or an emergency power dump in response to some other system failure, a 5 T field reduction is anticipated to occur in a 6 min interval (12). The resulting average dB/dt would be 14 mT/s, which is 70 times larger than the anticipated diurnal fluctuation in field strength associated with load leveling.

Three options have been considered for shielding humans and other life forms from the large fringe fields associated with SMES devices (10). These options, alone and in various combinations, include (1) passive shielding with iron, (2) active shielding with a compensating magnetic coil, and (3) substantial land procurement around an SMES facility. The first two options are generally not economically feasible, whereas the third option is economically attractive in regions where land procurement costs are low. However, in some cases this option could ultimately lead to licensing difficulties because of the intrinsic and/or projected value of land, even in relatively undeveloped areas. Also, the siting of an SMES system within a large exclusion zone addresses only the issue of shielding the radial fringe fields. The vertical fringe fields in the atmosphere and their potential impact on avian species would remain as an environmental issue if land procurement were the only shielding option that was implemented. For this reason a combination of the second and third options may need to be considered in certain special circumstances. However, the construction of a shield coil would represent a substantial capital investment, and the feasibility of using this option must be weighed carefully against the perceived risk of not shielding the SMES fringe field.

Section 3

MAGNETIC FIELD INTERACTION MECHANISMS

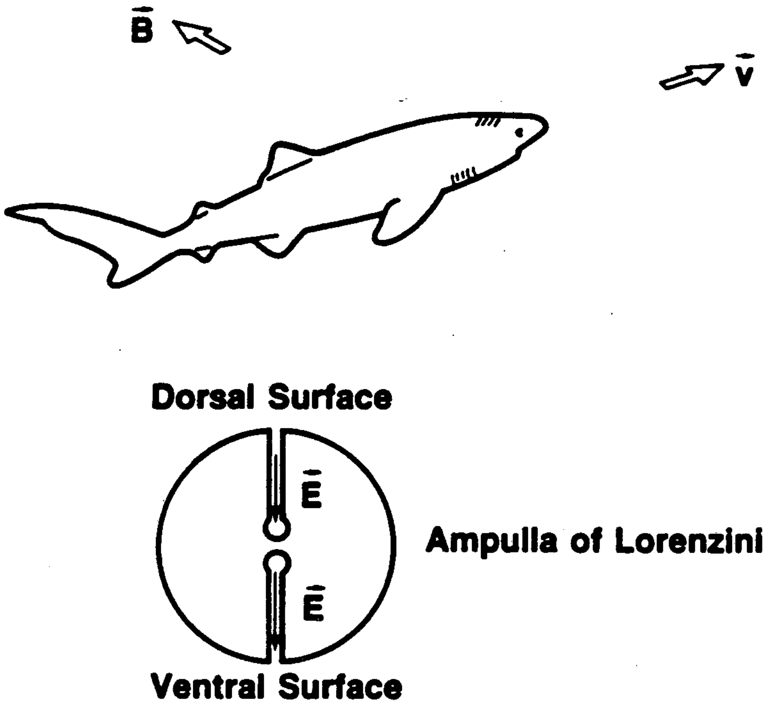
STATIC MAGNETIC FIELDS

Although numerous mechanisms have been proposed through which static magnetic fields could potentially influence biological functions (5), only three classes of physical interactions are well established on the basis of experimental data: (1) electrodynamic interactions with ionic conduction currents; (2) magnetomechanical effects, including the orientation of magnetically anisotropic structures in uniform fields and the translation of paramagnetic and ferromagnetic materials in magnetic field gradients; (3) effects on electronic spin states of the reaction intermediates in charge transfer processes. Each of these physical interaction mechanisms, along with relevant experimental data, will be described in this section.

Electrodynamic Interactions

Ionic currents interact with static magnetic fields as a result of the Lorentz forces exerted on moving charge carriers. Under steady state conditions this electrodynamic interaction gives rise to an electric field $\vec{E} = -\vec{v} \times \vec{B}$, where $\vec{v}$ is the velocity of current flow and $\vec{B}$ is the magnetic flux density. This phenomenon is the physical basis of the Hall effect in solid state materials, and it also occurs in several biological processes that involve the flow of electrolytes in an aqueous medium.

One example of electrodynamic interactions with weak magnetic fields is the electromagnetic guidance system of elasmobranch fish, a class of marine animals that includes sharks, skates and rays (13 - 15). The heads of these fish contain long jelly-filled canals with a high electrical conductivity, known as the ampullae of Lorenzini. As an elasmobranch swims through the lines of flux of the geomagnetic field, small voltage gradients are induced in its ampullary canals (Figure 3-1). These induced electric fields can be detected at levels as low as 0.5 μV/m by the sensory epithelia that line the terminal ampullary region (16). The polarity of the induced field in an ampullary canal depends upon the relative orientation of the geomagnetic field and the compass direction along which



$$\vec{E} = -\vec{v} \times \vec{B} \cong 5 \times 10^{-7} \text{ V/m (detection threshold)}$$

Figure 3-1. Electromagnetic Guidance System in Elasmobranch Fish

A shark swimming through the earth's magnetic field induces weak electric fields in the ampullary canals that protrude into the heads of these marine animals. The ampullary canals are lined by sensory epithelia that can detect exceptionally small electrical potential differences, thereby signaling the compass direction along which the animal is swimming. [Adapted from Figures 1 and 2 of ref. 15.]

the fish is swimming. As a consequence, the $-\vec{v} \times \vec{B}$ fields induced in the ampullae of Lorenzini provide a sensitive directional cue for the elasmobranch fishes. A second example of electrodynamic interactions is the electric field resulting from blood flow in the presence of a static magnetic field. It is a direct consequence of the Lorentz force exerted on moving ionic currents that blood flowing through a cylindrical vessel of diameter, d, will develop an electrical potential, ϕ, given by the equation (5):

$$\phi = |\vec{E}|\, d = |\vec{v}||\vec{B}|\, d \sin\theta \qquad (3\text{-}1)$$

where θ is the angle between $\vec{B}$ and the axial velocity vector, $\vec{v}$. This equation, which was first derived by Kolin, describes the physical principle upon which the electromagnetic blood flowmeter operates (17 - 19). The induced blood flow potentials within the central circulatory systems of several species of mammals exposed to large static magnetic fields have also been characterized from electrocardiogram (ECG) records obtained with surface electrodes (20 - 26). As demonstrated by the data shown in Figure 3-2 for a *Macaca* monkey exposed to static fields up to 1.5 T, the primary change in the ECG is an augmentation of the signal amplitude at the locus of the T-wave. Based on its temporal sequence in the ECG record, this change in T-wave amplitude has been attributed to the electrical potential that is induced within the aortic vessel during pulsatile blood flow in the presence of a magnetic field (21 - 26). The opening and closing of the aortic heart value have been shown to be correlated with the timing of the appearance and disappearance of the magnetically-induced potential at the locus of the T-wave (27). In small animal species such as rats, the aortic blood flow potential can be detected in the ECG when the magnetic flux density exceeds 0.3 T (25). For larger animal species such as dogs, monkeys and baboons, the threshold field level that induces a measurable potential is approximately 0.1 T (23, 26, 27). For all of these animal species, the change in T-wave signal amplitude observed during magnetic field exposure has been shown to be completely reversible upon removal of the field. In addition, the linear dependence of the aortic blood flow potential on magnetic field strength and its variation as a function of animal orientation within the field (see Eq. 3-1) have been experimentally confirmed (23, 25 - 27).

The linear dependence of a magnetically-induced blood flow potential on vessel diameter, as shown in Eq. 3-1, leads to the prediction that these potentials should have greater magnitudes in humans than in the smaller animal species that have been studied in the laboratory. This prediction is supported by a calculation based on Eq. 3-1 that the maximum magnitudes of the induced aortic blood flow potentials in a rat and a man placed within a 2 T field should be 0.5 and 13.4 mV, respectively. An increase in the magnitude of magnetically-induced blood flow potentials as a function of animal size has also been demonstrated directly by experimental data obtained for rats, baboons, monkeys and dogs (6, 23 - 27).

The electrodynamic interaction between a static magnetic field and a flowing conductor such as blood also produces a net volume force within the fluid that is equal to $\vec{J} \times \vec{B}$, where $\vec{J}$ is the ionic conduction current. The hydrodynamic consequence of this electrical force is a reduction in the axial blood flow velocity. From magnetohydrodynamic theory the fractional reduction in blood flow

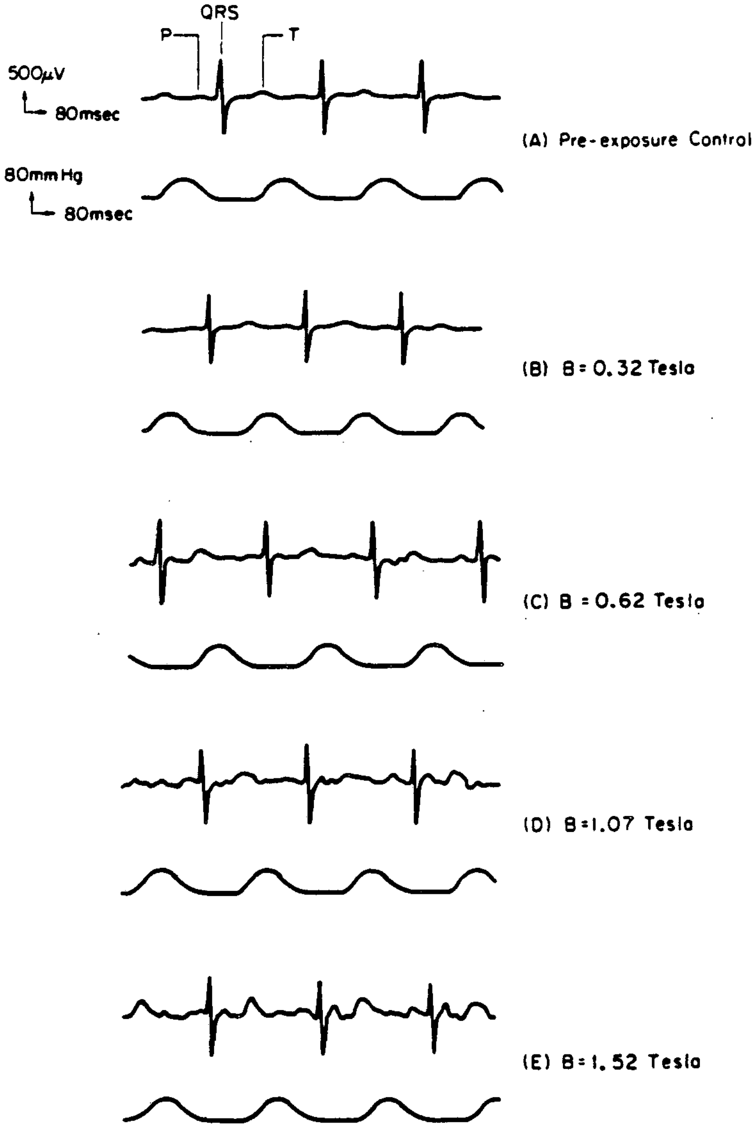


Figure 3-2. Monkey Electrocardiogram and Blood Pressure During Magnetic Field Exposure

Electrocardiogram and intraarterial blood pressure records are shown for a Macaca monkey exposed to uniform static magnetic fields up to 1.5 T. The ECG clearly demonstrates the increase in signal amplitude at the locus of the T-wave during magnetic field exposure. No measurable change occurred in the intraarterial blood pressure at field levels up to 1.5 T. (Adapted from Figure 1 of ref. 26.)

rate can be predicted to a good approximation by the equation (27):

$$\frac{v(B=0) - v(B)}{v(B=0)} = \frac{R^2 B^2 \sigma}{4\eta} \qquad (3\text{-}2)$$

where R is the vessel radius and σ and η are, respectively, the electrical conductivity and kinematic viscosity of blood. From Eq. 3-2 the estimated reduction in aortic blood flow rate for a man in static fields of 1 T and 5 T is about 1% and 7%, respectively. In accord with theoretical predictions, less than a 1% reduction in aortic blood flow rate was observed in direct laboratory measurements on 9 adult rats exposed to a 1.5 T field (27). Also, as demonstrated by the intraarterial blood pressure measurements shown in Figure 3-2, no hemodynamic alterations were observed during the exposure of three Macaca monkeys to a 1.5 T field (26). Contrary to earlier speculations (28 - 30), the extent to which magnetohydrodynamic interactions alter blood flow dynamics is therefore expected to be minimal even in relatively large magnetic fields.

Another important physiological process that is potentially sensitive to electrodynamic interactions with static magnetic fields is the conduction of nerve impulses. Simple theoretical calculations, however, demonstrate that the interaction of a magnetic field with the ionic currents in an axonal membrane is extremely weak (31, 32). For example, it has been estimated that a magnetic field in excess of 24 T would be required to produce a Lorentz force on nerve ionic currents equal to one tenth the force they experience from the electric field of the nerve membrane (31). The absence of a measurable interaction of a 2 T static field with the ionic currents of an isolated sciatic nerve is demonstrated by the action potential recordings shown in Figure 3-3. In other studies with isolated nerves, fields of 1.2-2.0 T applied in either a parallel or perpendicular configuration relative to the nerve axis have been found to have no influence on the amplitude or conduction velocity of evoked action potentials (33 - 35). Static magnetic fields were also found to have no effect on other bioelectric properties of sciatic nerves, including the threshold for nerve excitation and the duration of the absolute and the relative refractory periods that follow the passage of an action potential (35).

Magnetomechanical Effects

Macromolecules with a high degree of magnetic anisotropy will rotate in a static magnetic field and reach an equilibrium orientation that represents a minimum energy state. In general, these macromolecules have a rodlike shape and magneto-orientation occurs as a result of anisotropy of the magnetic susceptibility tensor

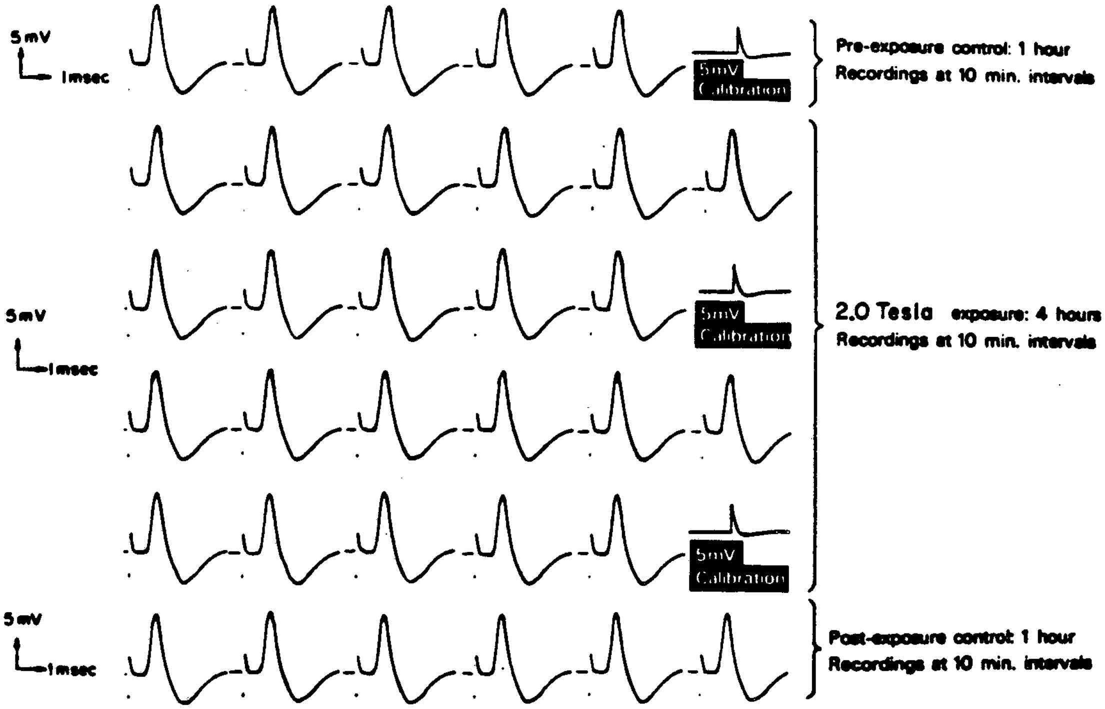


Figure 3-3. Sciatic Nerve Bioelectric Activity in Strong Magnetic Fields

Evoked action potentials in a frog sciatic nerve are shown before, during and after a 4-hr exposure to a uniform static 2.0-T field. The nerve axis was oriented parallel to the magnetic field lines, and there was no significant variation in the 20-mV amplitude of the maximal action potential during exposure to the field. An identical result was obtained when the nerve axis was oriented perpendicular to a 2.0-T field. [Reproduced from Figure 1 of ref. 35.]

along the different axes of symmetry. The total interaction energy with the field, U, is obtained by integrating the tensorial product of the magnetic flux density, $\vec{B}$, and the magnetic moment per unit volume, $\vec{M}$, over the molecular volume, V. The resulting expression for U is (5):

$$U = - VB^2[\chi_z + (\chi_z - \chi_r)\cos^2\theta]/2\mu_0 \qquad (3\text{-}3)$$

where χ_z and χ_r are the axial and radial components of the magnetic susceptibility, θ is the angle between the direction of the field and the z axis, μ_0 is the magnetic permeability of free space ($\mu_0 = 1$ in CGS units and $4\pi \times 10^{-7}$ N/A^2 in MKS units). Because the rodlike molecules will rotate in the field to achieve a minimum energy, then the equilibrium orientation will be at $\theta = 0$ or π if $\chi_z > \chi_r > 0$ (paramagnetic molecules) or $\chi_r < \chi_z < 0$ (diamagnetic molecules). The equilibrium orientation will be at $\theta = \pi/2$ if $\chi_r > \chi_z > 0$ (paramagnetic) or $\chi_z < \chi_r < 0$ (diamagnetic).

For individual macromolecules of biological importance, the magnetic interaction energy given by Eq. 3-3 is small compared to the thermal energy, kT, where k is Boltzmann's constant and T is the absolute temperature. As a result, the extent of orientation of individual molecules in strong magnetic fields is very small. For example, optical birefringence measurements on calf thymus DNA in solution have demonstrated that a field of 13 T is required to produce orientation of 1% of the molecules (36) [Figure 3-4]. In contrast, there are several examples of macromolecular assemblies that can be oriented in fields of 1 T or less. These assemblies behave as structurally coupled units in which the summed magnetic anisotropy is large, thus giving rise to a large magnetic interaction energy. Examples of molecular aggregates that orient in fields of 1 T or less include retinal rod outer segments (37 - 43), muscle fibers (44), photosynthetic systems (chloroplast grana, photosynthetic bacteria and Chlorella cells) (45-49), and purple membranes of Halobacteria (50). Although the magneto-orientation of biologically important structures such as retinal rods can be demonstrated by optical techniques when these units are suspended in an aqueous medium (49) [Figure 3-5], the implications of this effect for visual functions in vivo is unclear. As discussed in a later section of this chapter, there is no experimental evidence that the visual apparatus of mammals is influenced by static fields up to 1.5 T. It is likely that a magnetic orientational torque has little influence on the strong structural matrix in which retinal rods are imbedded within the intact retina.

There are also biological examples of cellular structures with permanent magnetic moments in which significant magnetic orientational effects occur. One example is the magnetotactic bacterium (51), in which approximately 2% of the dry mass is iron contained in magnetite (Fe_3O_4) crystals (52). These bacteria require a low oxygen tension for survival, and their net magnetic moments interact with the geomagnetic field to produce a downward directed motion that carries them into the bottom sediments of their aquatic environment. This fascinating survival mechanism requires that there be opposite polarities of the magnetic moments of these bacteria in the northern and southern hemispheres, and this feature of magnetotactic bacteria has been confirmed experimentally (51, 53, 54).

Another example of an intact cell that can be oriented magnetically is the deoxygenated sickled erythrocyte. It has been shown that these cells, in which the deoxygenated hemoglobin is paramagnetic, will align in a 0.35 T field with the long axis of the sickled cell oriented perpendicular to the magnetic flux lines(55). This equilibrium orientation results from the stacking of the planar haem moieties

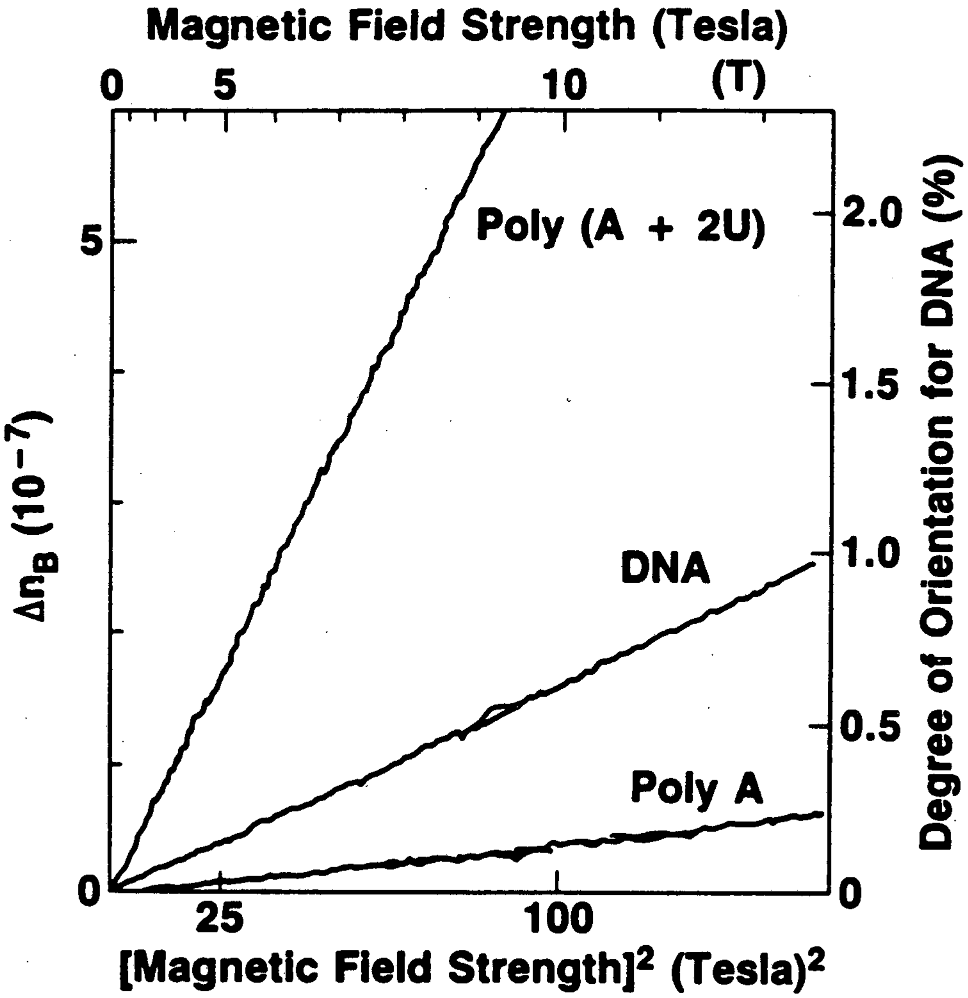


Figure 3-4. DNA Orientation in Strong Magnetic Fields

The optical birefringence (Δn_B) is plotted as a function of the magnetic flux density applied to solutions of calf thymus DNA, polyadenylic acid (Poly A) and polyadenylic-2-polyuridylic acid [Poly (A + 2U)]. The degree of orientation of the DNA is proportional to the ratio of the magnetic field interaction energy (Eq. 3-3 in the text) to the thermal energy, kT. [Reproduced from Figure 1 of ref. 36.]

parallel to the long axis of the sickled erythrocyte, with the net magnetic moment oriented perpendicular to the long axis.

Another type of magnetomechanical interaction is the translation of paramagnetic and ferromagnetic substances in static magnetic field spatial gradients. Denoting the magnetic susceptibility as χ and the volume as V, the force, F(z), experienced in a linear magnetic field gradient, dB/dz, is equal to the product of the net

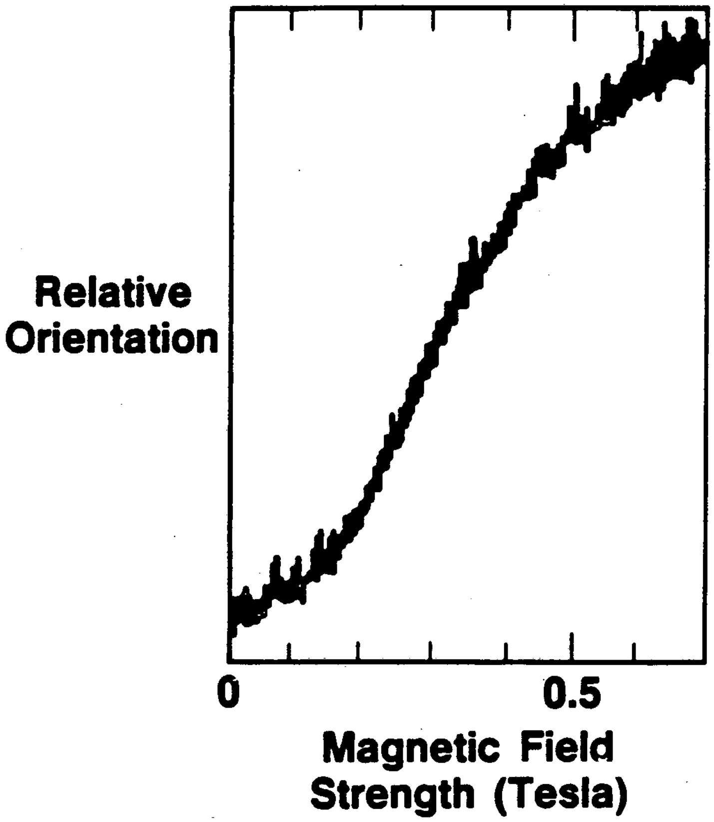


Figure 3-5. Orientation of Retinal Rod Outer Segments in Strong Magnetic Fields

The orientation of bovine retinal rod outer segments in aqueous solution is shown as a function of magnetic field strength up to 0.7 T. Orientation was monitored by measuring the light scattered at an angle of 90° relative to the incident light. [Adapted from Figure 1 of ref. 41.]

magnetic moment and the gradient:

$$F(z) = \frac{\chi VB}{\mu_0} (dB/dz) \qquad (3\text{-}4)$$

From simple energetic calculations it can be shown that extremely large magnetic fields and gradients must be used to produce a significant translation of individual paramagnetic molecules. A similar conclusion can be drawn for large collections of paramagnetic molecules such as the deoxyhemoglobin contained within a deoxygenated erythrocyte. This theoretical expectation is supported by experimental observations on the magnetic separation of erythrocytes from whole blood following conversion of the diamagnetic hemoglobin to paramagnetic deoxyhemoglobin (Figure 3-6). In order to achieve an efficient separation of the cells, they must be attracted to a wire mesh that is highly magnetized in a 2 T field to produce a gradient at the surface which approaches 10^4 T/m (56, 57). Fields and spatial gradients of this magnitude are seldom encountered by man, even in the vicinity of high-field superconducting magnets.

Magnetic Field Effects on Electronic Spin States

There are several classes of organic chemical reactions that can be influenced by static magnetic fields in the range of 10-100 mT as a result of effects on the electronic spin states of the reaction intermediates (7, 58, 59). One well-studied example of such reactions that involves an important biological process is the photo-induced charge transfer reaction in bacterial photosynthesis (60 - 65). This reaction involves a radical pair intermediate state through which electron transfer occurs to the ultimate acceptor molecule, a ubiquinone-iron complex. Under natural conditions the electron transfer occurs within 200 picosec following flash excitation of the bacteriochlorophyll. However, chemical reduction of the acceptor molecules extends the lifetime of the intermediate state to about 10 ns. With an extended lifetime, the singlet state of the radical pair intermediate evolves into a triplet state via the hyperfine mechanism. However, in the presence of an external magnetic field greater than approximately 10 mT, the triplet channels are blocked and the resulting yield of triplet product is expected to decrease by two thirds. This predicted blocking of triplet channels by a weak magnetic field has been confirmed experimentally using laser pulse excitation and optical absorption measurements (63) [Figure 3-7]. Although these observations may have implications for naturally occurring biological processes, it should be emphasized that the magnetic field effects studied to date occur only when the photosynthetic system is placed in an abnormal state by chemical reduction of the electron acceptor molecules.

TIME-VARYING MAGNETIC FIELDS

The primary physical interaction of time-varying magnetic fields with living systems is the induction of electric fields and currents in tissue. In accord with Faraday's law of induction, the relationship between the induced electric field intensity, $\vec{E}$, and the time rate of change of the magnetic flux density is given by the equation:

$$\oint \vec{E}\cdot d\vec{\ell} = - d/dt \iint \vec{B}\cdot d\vec{S} \qquad (3\text{-}5)$$

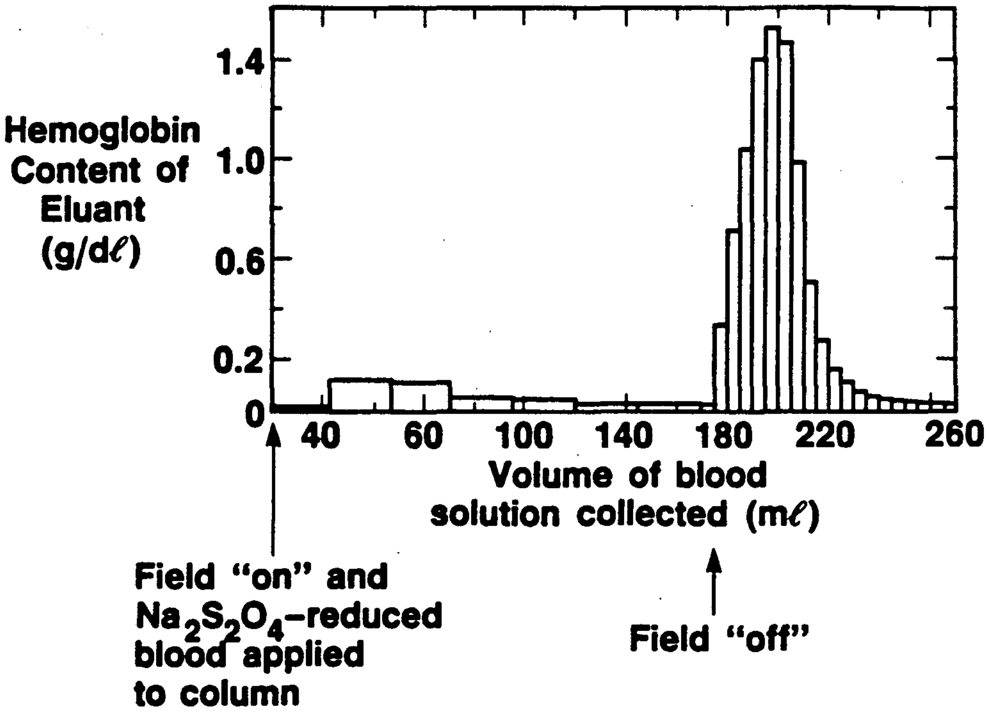


Figure 3-6. Magnetic Separation of Erythrocytes

The retention of deoxygenated, paramagnetic erythrocytes on a stainless steel wire mesh packed in a polyethylene cylinder is shown during the application of a 1.75-T static magnetic field. The magnetic field gradient near the surface of the wire was estimated to be 8000 T/m. When the field is turned off, the erythrocytes can be eluted from the column as a cohort free of white blood cells or platelets. [Adapted from Figure 1 of ref. 56.]

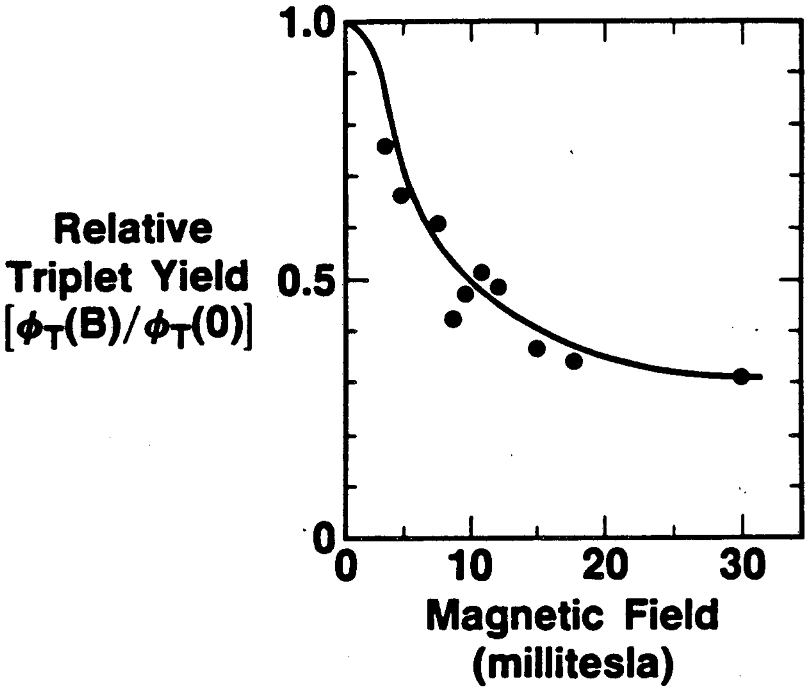


Figure 3-7. Magnetic Field Effect on Charge Transfer Reaction

The yield of triplet product in the primary charge transfer reaction in photosynthetic bacteria (Rhodopseudomonas sphaeroides) is plotted as a function of the applied magnetic field strength. The ubiquinone electron acceptor molecules were chemically reduced with sodium dithionite to extend the lifetime of the radical pair intermediate state through which the charge transfer reaction proceeds. Laser pulse excitation and optical absorption measurements were used to quantitate the yield of triplet intermediate state product. [Adapted from Figure 3 of ref. 63.]

In Eq. 3-5 the line integral is around a closed curve and $d\vec{\ell}$ is a differential element of length along the curve; $\vec{B}$ is the magnetic flux density and $d\vec{S}$ is a differential surface area element directed normal to the surface enclosed by the curve over which the line integral is taken. For the specific case of a circular loop with radius R intersected by a spatially uniform, time-varying magnetic field orthogonal to the loop, Eq. 3-5 gives for the magnitude of the average electric field tangent to the loop surface:

$$E = (R/2)\,\frac{dB}{dt} \qquad (3\text{-}6)$$

If the magnetic field is sinusoidal with an amplitude B_0 and a frequency υ, then $B = B_0 \sin(2\pi\upsilon t)$ and from Eq. 3-6:

$$E = \pi\upsilon R B_0 \sin(2\pi\upsilon t) \tag{3-7}$$

From Ohm's law, the current density, $\vec{J}$, induced in tissue with an average conductivity σ is given by

$$\vec{J} = \sigma \vec{E} \tag{3-8}$$

The rate of energy dissipation in tissue per unit time, P, is equal to:

$$P = \vec{J} \cdot \vec{E} = \sigma E^2 \tag{3-9}$$

The MKS units of B, E, J and P are Tesla, V/m, A/m^2 and W/m^3, respectively. The magnetically-induced electric field, E, and current density, J, will be used later in Section 4 as the fundamental parameters to which biological effects produced by time-varying magnetic fields are related.

Electrical potentials can also be induced magnetically by fields that are static, i.e., not varying in time. One example is the induction of potentials in a moving electrolytic conductor such as blood, which was discussed earlier in Section 3. A magnetically-induced potential can also result from the application of a static field when the area linked by the lines of magnetic flux changes as a function of time. From Eq. 3-5 the resulting potential ϕ can be estimated as (25):

$$\phi = B f \Delta S \tag{3-10}$$

where ΔS is the area change and f is the frequency of motion leading to the change in area and magnetic flux linkage. This type of induced potential results from changes in the area of the chest during breathing, and can be detected in the ECG of animals placed in extremely high fields. The magnitude of ϕ is small, typically being less than 25% of the magnitude of the induced aortic blood flow potential (25).

Various physical characteristics of time-varying magnetic fields are of importance in assessing their biological effects, including the fundamental field frequency, the maximum and average flux density, the presence of harmonic frequencies, and the waveform and polarity of the signal. Several types of waveforms have been used in biological research with extremely low frequency (ELF) magnetic fields,* including sinusoidal, square-wave, and pulsed waveforms (Figure 3-8). Two characteristics that are of key importance in analyzing the effects of square-wave and pulsed fields are the rise and decay times of the magnetic field waveform. These parameters determine the maximum time rate of change of the magnetic field and hence the maximum instantaneous electric field and resulting conduction current density induced in tissue.

Apart from the well established mechanism of magnetic induction, several other theoretical concepts have been proposed for the interaction of ELF fields with biological tissue. As recently reviewed by Tenforde (4), these mechanisms include nonlinear interactions (e.g., solitons) producing long-range cooperative phenomena at the surfaces of living cells, magnetic resonance interactions with biologically important ions, electromechanical effects on ions and larger macromolecular structures, and distortion of counterion motion at cellular surfaces. At the present time, there is no convincing experimental evidence to indicate that any of these proposed mechanisms of ELF field interaction are responsible for the observed physiological effects of magnetic fields described later in Section 4. The issue of possible synergistic effects of static magnetic fields and time-varying electric and/or magnetic fields which may be present simultaneously in the environment of an SMES facility will be discussed below in Section 9.

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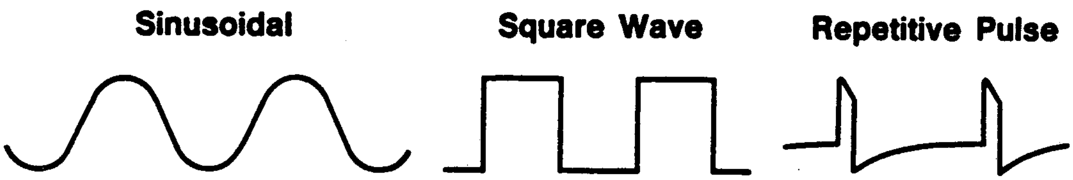
* ELF is defined as the frequency range below 300 Hz.



- **Peak to peak amplitudes similar**
- **Peak dB/dt not similar**
- **Harmonic frequency content not similar**

Figure 3-8. Time-Varying Magnetic Field Waveforms

Waveforms and physical properties are shown for several types of ELF magnetic fields. The repetitive pulse waveform is similar to that used in several clinical trials on the facilitation of bone fracture reunion by pulsed magnetic fields. High-frequency bursts of magnetic pulses with repetition frequencies in the ELF range have also been used clinically. Although the three types of waveforms shown in this figure have similar peak-to-peak amplitudes, they differ significantly in the peak value of dB/dt and the harmonic frequency content.

Section 4

LABORATORY STUDIES OF MAGNETIC FIELD EFFECTS ON LIVING SYSTEMS

STATIC MAGNETIC FIELDS

Several species of marine animals and various lower life forms possess an inherent sensitivity to static magnetic fields with intensities as low as that of the geomagnetic field, i.e., approximately 50 μT. It has been established experimentally that weak magnetic fields influence direction finding by elasmobranch fish (13 - 16) and the orientation and swimming direction of magnetotactic bacteria (51 - 54). As discussed in Section 3, the biophysical mechanisms underlying the magnetic field sensitivity of these organisms are well understood. In addition, evidence has been presented that the kinetic movements of mollusks (66), the waggle dance of bees (67), and migratory patterns of birds (68 - 71) are all influenced by weak static fields. The precise mechanism underlying the magnetic field sensitivity of these species has not been determined, although magnetomechanical effects leading to the stimulation of sensory receptors may be involved since small deposits of magnetite have been found in the tooth denticles of mollusks (72 - 73), the abdominal region of bees (74), and the cranium of pigeons (75, 76). The orientational information from the geomagnetic field appears to provide only a secondary directional cue in migratory avian species, since they exhibit a response to an artificially applied magnetic field only under totally overcast skies (68).

Studies of static magnetic field interactions with higher organisms have produced numerous contradictory findings, and the only effect that is well established at the present time is the induction of electrical potentials in the central circulatory system. Detailed reviews of the literature on static magnetic field bioeffects have revealed a number of examples of recent experimental results that contradicted earlier claims of significant magnetic field effects at the cellular and animal levels (3, 6). Several examples of the disparity between early and recent findings include: (1) the report (77) of cell transformation resulting from exposure to a 0.5 T field at 4 K was shown to be an artifact resulting from unconventional culture techniques (78); (2) numerous reports of alterations induced by static magnetic fields in the metabolism, respiration, and growth properties of normal and tumor cells (79 - 89) have not been successfully replicated (90 - 98); (3) genetic and developmental changes in several animal species and lower organisms exposed to magnetic fields (80, 99 - 112) have not been observed in more recent studies (113 - 122); (4) adverse effects of static magnetic fields on sensitive target tissues such as the hematologic, immunologic and endocrine systems (81, 82, 123 - 145) have not been found in several recent studies (146 - 149); (5) several reports of magnetic field effects on physiological regulation and circadian timing (150 - 157) have not been confirmed in carefully controlled studies with rodents (6, 158 - 160). One recent example of an effect that could not be replicated in another laboratory is the report that thermoregulation in rodents is influenced by strong magnetic field gradients (161, 162).

During the past decade a significant number of studies have been reported in which the bioeffects of static magnetic fields were examined under well-controlled laboratory conditions, including the use of precise dosimetry, large numbers of experimental subjects, quantitative biochemical and physiological end points, and careful attention to environmental conditions other than the magnetic field that could influence the experimental outcome. Based on experiments conducted with field levels of 1 T or greater, the following important biological processes appear not to be influenced by static magnetic fields at high intensities: (1) cell growth and morphology (78, 92, 96, 98), (2) DNA structure and gene expression (116 - 119, 122), (3) reproduction and development (pre- and post-natal) (114, 115, 120), (4) bioelectric properties of isolated neurons (33 - 35), (5) animal behavior (163), (6) visual response to photic stimulation (164), (7) cardiovascular dynamics (acute exposures) (25, 26), (8) hematological indices (148, 158), (9) immune responsiveness (149), and (10) physiological regulation and circadian rhythms (6, 158 - 160).

It should also be noted that in several of the reports cited in the preceding two paragraphs (78, 90 - 93, 95, 119, 121, 146, 147), no bioeffects were observed as a result of exposing cellular, tissue and animal systems to static fields with flux densities less than 1 T. In general, there is no convincing evidence to support the existence of narrow ranges of static magnetic field intensities ("windows") below 1 T in which biological responses might occur that would not be detected at higher field strengths.

Although there is an increasing database which suggests that mammals experience no adverse effects from exposure to fields with flux densities up to the highest levels to which man is generally exposed, i.e., 1 to 2T, additional research is needed in several key areas. These include: (1) studies of cardiovascular performance in mammals exposed chronically to magnetic field levels that induce electrical potentials on the order of 1 mV or larger within the central circulatory system; (2) electroencephalographic measurements of evoked and non-evoked electrical activity in the central nervous system, which has previously been reported to exhibit both excitatory and inhibitory responses to static magnetic fields (165 - 168) (Figure 4-1); (3) additional studies are needed to clarify whether adrenergic and cholinergic hormonal responses occur in exposed animals (142 - 144); (4) cellular, tissue and animal studies are needed to assess the effects of static magnetic fields at intensities greater than 2 T; information of this nature would advance our understanding of magnetic field interaction mechanisms, and would also provide baseline data for assessing the potential bioeffects resulting from the exposure of living systems to ultrahigh fields.

TIME-VARYING MAGNETIC FIELDS

Four levels of biological effects from time-varying magnetic fields can be defined on the basis of the electrical currents induced in living tissues: (1) fields that induce current densities above 1 A/m^2 in tissue can be expected to produce rapid, irreversible effects such as cardiac fibrillation; (2) fields inducing current densities above 10 mA/m^2 lead to reversible visual effects (magnetophosphenes and changes in visually evoked potentials) during acute exposures; (3) the chronic application of fields that induce current densities in the range of 10-100 mA/m^2 can produce irreversible alterations in the biochemistry and physiology of cells and organized tissues, an example being the effects of bidirectional pulsed fields used to facilitate bone fracture reunion; (4) fields that induce current densities less than approximately 1-10 mA/m^2, which is the range of endogeneous current densities present in organs such as the brain and heart (169, 170) lead to few (if any) biological effects irrespective of the exposure duration. The following discussion of bioeffects associated with exposure to time-varying magnetic fields is subdivided into three sections: (a) neuromuscular stimulation, (b) magnetophosphenes and other visual phenomena, and (c) effects on cellular, tissue and animal systems.

Neuromuscular Stimulation

In the first class of phenomena described above, direct neuromuscular effects result from large tissue currents induced by a time-varying magnetic field. Several investigators (171 - 178) have achieved direct neural stimulation using pulsed or sinusoidal magnetic fields that induced tissue current densities in the

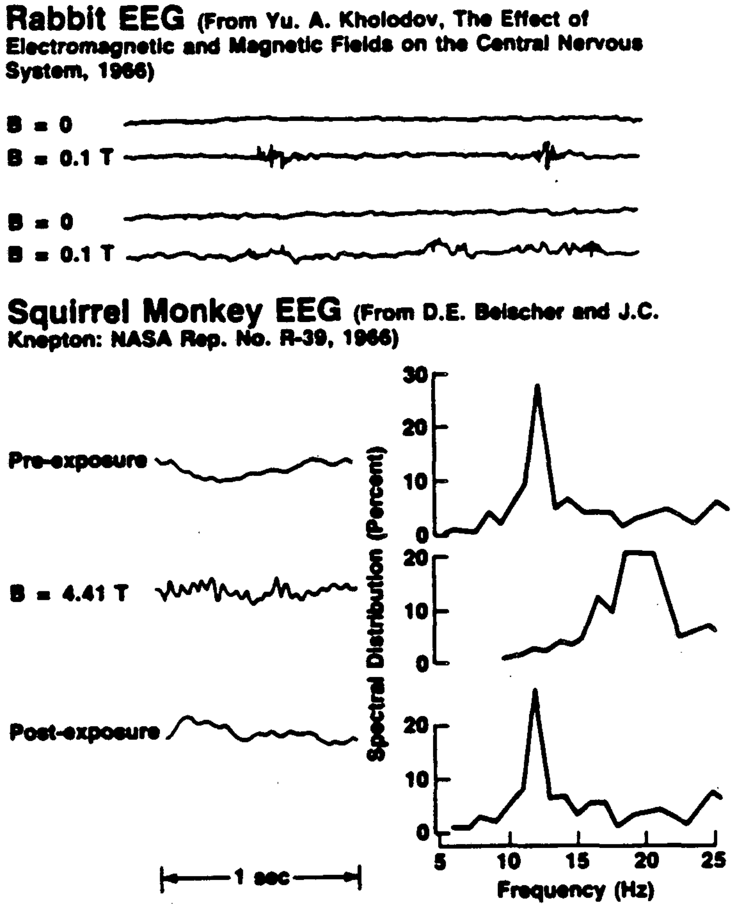


Figure 4-1. Electroencephalograms of Mammals Exposed to Strong Magnetic Fields

Electroencephalographic (EEG) recordings from a rabbit and a squirrel monkey are shown before and during exposure to a static magnetic field. In a 0.1-T field the rabbit EEG was found to exhibit high-amplitude spindles and slow waves with frequencies less than 4 Hz, which are characteristic of a general inhibitory state in the central nervous system. In contrast, the monkey EEG recorded in fields ranging from 1.47 to 9.13 T was found to be characteristic of an excitatory state. During application of a static magnetic field, the amplitude of the monkey EEG signals increased from the control level of 25-50 μV to 50-400 μV. The predominant EEG frequencies shifted from their pre-exposure range of 8-12 Hz to 14-50 Hz during application of the field. The basis for these apparently dichotomous findings of inhibitory and excitatory responses to an applied magnetic field is not presently understood. [The rabbit EEG traces were reproduced from Figure 36 of ref. 167, and the monkey EEG data are from Figure 5 of ref. 165.]

range of 1-10 A/m^2. In one study involving electromyographic recordings from the human arm (177), it was found that a pulsed field with dB/dt greater than 10^4 T/sec was required to stimulate the median nerve trunk. The duration of the magnetic stimulus has also been found to be an important parameter in the excitation of nerve and nerve-muscle preparations. Using a 20 kHz sinusoidal field applied in bursts of 0.5 to 50 msec duration, Öberg (174) found that a progressive increase in the magnetic flux density was required to stimulate the frog gastrocnemius neuromuscular preparation when the burst duration was reduced to less than 2-5 ms. A similar rise in threshold stimulus strength has been observed for frog neuromuscular stimulation using pulsed magnetic fields with pulse durations less than approximately 1 ms (175, 178).

The threshold current density required to produce ventricular fibrillation has been studied in several species of laboratory animals in which large currents were induced by sinusoidal voltages applied through contact electrodes (179 - 184). From these data it can be estimated that the threshold current density required to produce ventricular fibrillation in the human heart is in the range of 2-10 A/m^2. For sinusoidal voltages, the minimum threshold current densities were observed in the frequency range of 20-200 Hz (179). In experiments with dog hearts subjected to 60 Hz voltage stimuli it was found that the threshold current required to elicit fibrillation increased by a factor of approximately 140 as the stimulus duration was decreased from 1.6 s to 16 ms (182). Dalziel (185) has estimated that the stimulus strength producing cardiac fibrillation varies as the reciprocal square root of the shock duration over the range of exposure times from 8 ms to 5 s.

The thresholds for several other forms of neuromuscular effects in laboratory animals and man, including the stimulation of seizures, extrasystoles and respiratory tetanus, have been estimated. From electroshock studies in humans it has been estimated that a current density of 30 A/m^2 must be induced for 300 ms to produce convulsive seizures (186). The threshold current density for stimulation of extrasystoles was found in studies with guinea pig hearts to be 3-5 times lower than the threshold for eliciting ventricular fibrillation (183). However, a prolonged stimulation of extrasystoles was found to ultimately lead to ventricular fibrillation. Based on limited studies with humans, it can be estimated that the threshold stimulus required to produce respiratory tetanus is approximately 10-15 times less than that which produces ventricular fibrillation (187 - 189). This estimate suggests that induced current densities in the range of 0.15 - 1.0 A/m^2 could produce tetanic contractions of the muscles involved in breathing.

It is important to note that extremely large values of the magnetic flux density are required to elicit stimulatory effects on the neuromuscular system of animals when sinusoidal waveforms are used. As an example, consider a 60-Hz field that is axially incident on a circular loop of tissue with $R = 0.06$ m and $\sigma = 0.2$ S/m, comparable to the human heart. From Eqs. 3-7 and 3-8 it can be calculated that the magnetic flux density must be 0.88 T to induce a current density of 2 A/m^2, which is the estimated lower threshold for inducing ventricular fibrillation. The corresponding time rate of change of the magnetic field and the induced electric field intensity are 330 T/s and 9.95 V/m, respectively. ELF magnetic fields with this magnitude and time variation are seldom, if ever, encountered by man. However, some caution must be taken in assessing the effects of time-varying magnetic fields on potentially sensitive neuromuscular substrates, such as pacemaker cells. In a study with pacemaker neurons from the Aplysia abdominal ganglion, Wachtel (190) demonstrated that an ELF field with a frequency synchronized to the endogenous neuronal firing rate could alter the membrane electrical activity when the induced current density in the extracellular medium exceeded 20 mA/m^2.

Magnetophosphenes and Other Visual Phenomena

One of the most extensively studied effects of time-varying magnetic fields is the induction of a flickering illumination within the visual field known as magnetophosphenes (191 - 203). This phenomenon occurs as an immediate response to stimulation by either pulsed or sinusoidal magnetic fields with frequencies less than 100 Hz, and the effect is completely reversible with no apparent influence on visual acuity. The maximum visual sensitivity to sinusoidal magnetic fields has been found at a frequency of 20 Hz in human subjects with normal vision (200). At this frequency the threshold magnetic field intensity required to elicit phosphenes is approximately 10 mT, as shown in Figure 4-2. The corresponding time rate of change of the field is 1.26 T/s. In studies with pulsed fields having a rise time of 2 ms and a repetition rate of 15 Hz, the threshold values of dB/dt for eliciting phosphenes ranged from 1.3 to 1.9 T/s in five adult subjects (203). There was a trend in the data which suggested that the threshold was lower among younger subjects. In related studies it was also observed that the stimulus duration is an important parameter, since pulses of 0.9 ms duration with dB/dt = 12 T/s did not evoke phosphenes.

Several types of experimental evidence indicate that the magnetic field interaction leading to magnetophosphenes occurs in the retina: (1) magnetophosphenes are produced by time-varying magnetic fields applied in the region of the eye, and not

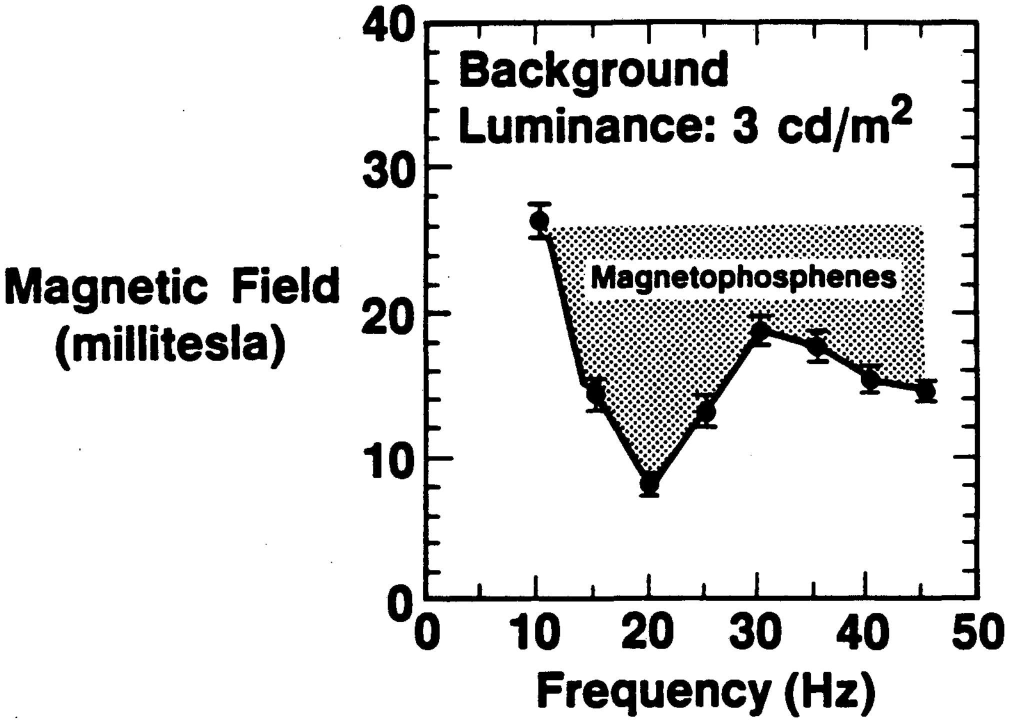


Figure 4-2. Magnetophosphene Thresholds

Threshold values of the magnetic flux density required to elicit magnetophosphenes are plotted as a function of the field frequency. Each data point represents the mean value ± 1 S.E. for 10 volunteers, all of whom were studied with a background white light level of 3 cd/m^2. [Adapted from Figure 3 of ref. 197.]

by fields directed toward the visual cortex in the occipital region of the brain (195); (2) pressure on the eyeball abolishes sensitivity to magnetophosphenes (195); (3) the threshold magnetic field intensity required to elicit magnetophosphenes in human subjects with defects in color vision was found to have a different dependence on the field frequency than that observed for subjects with normal color vision (200); (4) in a patient in whom both eyes had been removed as the result of severe glaucoma, phosphenes could not be induced by time-varying magnetic fields, thereby precluding the possibility that magnetophosphenes can be initiated directly in the visual pathways of the brain (200).

Although experimental evidence has clearly implicated the retina as the site of magnetic field action leading to phosphenes, it is not as yet resolved whether the photoreceptors or the neuronal elements of the retina are the sensitive substrates that respond to the field. In a series of experiments on in vitro frog retinal preparations, extracellular electrical recordings were made from the ganglion cell layer of the retina immediately following termination of exposure to a 20-Hz, 60-mT field (201). It was found that the average latency time for response of the ganglion cells to a photic stimulus increased by 5 ms ($p < 0.05$) in the presence of the magnetic field. In addition, the ganglion cells that exhibited electrical activity during photic stimulation ("on" cells) ceased their activity during magnetic field stimulation (i.e., they became "off" cells). The converse behavior of ganglion cells was also observed. These observations indicate that stimulation of the retina by light and by a time-varying magnetic field elicits responses in similar post-synaptic neural pathways.

Several other phenomena related to the sensitivity of the visuosensory system to time-varying magnetic fields have also been studied by Silny (204). In experiments with human subjects it was found that distinct flickering could be elicited in the visual field by sinusoidal magnetic fields in the frequency range 5-60 Hz. The threshold field intensity varied with the field frequency and background light level, but was as low as 5 mT under optimal conditions. Alterations in visually evoked potentials (VEP) were also been reported to occur in sinusoidal ELF magnetic fields at intensity levels that are 5-10 times greater than those which produce magnetophosphenes (204). The change in VEP is characterized by a reversal of polarity and a decreased amplitude of the three major evoked potentials. These effects were observed within 3 min following onset of the magnetic field exposure, and the VEP returned to normal only after a recovery period of approximately 30-70 min following termination of the exposure. The relationship of these changes in the VEP to the mechanism of magnetophosphene induction is not clear from the evidence that is presently available.

Effects on Cellular, Tissue and Animal Systems

A large number of reports have appeared in the literature on the biochemical, physiological and behavioral effects of time-varying magnetic fields in the ELF frequency range (163, 205 - 274). The information gained in these studies is in many cases difficult to interpret for several reasons: (1) A wide range of field intensities, frequencies, waveforms, and exposure durations have been used. Many of the earlier studies utilized sinusoidal ELF magnetic fields, but recent research has focused increasingly on the effects of pulsed fields with complex waveforms. (2) Few of the findings of positive bioeffects have been verified by independent replication in different laboratories. (3) A number of apparent inconsistencies can be found among the reported behavioral and physiological effects of time-varying magnetic fields. For example, behavioral alterations were observed in a majority of studies with animals exposed to ELF sinusoidal fields that induced maximum current densities of less than 1 mA/m^2 in the cranium (259 - 267). In contrast, no effects were noted in several behavioral studies conducted with magnetic fields that induced maximum intracranial current densities of 1 mA/m^2 or larger (163, 212, 268 - 273). There is evidence that these apparent inconsistencies may have arisen from the failure of some investigators to eliminate extraneous variables that can significantly influence animal behavior, for example, the vibration and audible noise that accompany the activation of magnet coils (273). Another example of contradictory data are the reports that exposure to a low-intensity ELF magnetic field produced an elevation in serum triglyceride levels in human subjects (211), but comparable effects were not observed in monkeys (212).

Although many uncertainties exist in the interpretation of the existing laboratory data on the cellular, tissue and animal effects of time-varying magnetic fields, there is increasing evidence that several biochemical and physiological properties of cells and organized tissues are altered. Briefly summarized, these biological effects include: (1) altered cell growth rate (219, 223, 231, 235, 236, 256), (2) decreased rate of cellular respiration (231 - 233), (3) altered metabolism of carbohydrates, proteins and nucleic acids (218, 221, 227, 233, 238, 246, 253, 254, 258), (4) effects on gene expression and genetic regulation of cell functions (230, 241, 249), (5) teratological and developmental effects (209, 210, 240, 251, 252), (6) morphological and other nonspecific tissue changes in adult animals, frequently reversible with time following exposure (206, 213, 237, 239, 242, 245), (7) endocrine alterations (207, 214, 220, 222, 226, 239), (8) altered hormonal responses of cells and tissues, including effects on cell surface receptors (244, 247, 250, 255), and (9) altered immune response to antigens and lectins (205, 215, 248).

The results of these studies have been summarized schematically in Figure 4-3, in which the observations of bioeffects from exposure to time-varying magnetic fields have been grouped according to estimates of the maximum value of dB/dt and the maximum induced current density in the target tissues that were examined. The magnetophosphene and behavioral studies described above have been excluded in this evaluation. Also, studies involving a combination of electric and magnetic fields have been excluded because of the obvious difficulty of delineating the relative influence of the two types of fields when they are applied simultaneously. It is evident from Figure 4-3 that alterations were observed at the cellular and tissue levels in the majority of studies in which the induced current densities exceeded 1 mA/m^2, which is a level typical of the endogenous current densities within living

Time-Varying Magnetic Fields –
Cell, Tissue and Animal Studies

- **Magnetophosphene and behavioral studies excluded**
- **Combined electric and magnetic field experiments excluded**
- **Complete description of field and exposure conditions required**
- **Quantitative physiological and/or biochemical end points required**

dB/dt (T/s)	Findings (+)	Findings (–)
<1	6	8
1→3	3	1
3→20	25	1
>20	9	1

J_{max} (mA/m^2)	Findings (+)	Findings (–)
<1	5	6
1→10	8	2
10→20	10	3
>20	20	0

Positive Effects Reported:

- **Altered cell growth rate**
- **Decreased cellular respiration**
- **Effects on gene expression**
- **Developmental effects**
- **Altered immune response**
- **Endocrine alterations**
- **Altered metabolism of carbohydrates, nucleic acids and proteins**

Mammalian systems:	**42/54**
Non-mammalian systems:	**12/54**
In vivo studies:	**32/54**
In vitro studies:	**22/54**
Sinusoidal fields:	**39/54**
Square-wave fields:	**3/54**
Pulsed fields:	**12/54**

Figure 4-3. Bioeffects of Time-Varying Magnetic Fields

Experimental observations on the bioeffects of time-varying magnetic fields in the ELF frequency range are summarized on the basis of the estimated maximum values of dB/dt and induced current density in the exposed samples. The literature database used in preparing this summary is from refs. 205-258. Criteria employed in the selection of literature are stated at the top, and several of the observed bioeffects are listed on the right side of the figure. A summary is given at the bottom of the general characteristics of the biological systems studied and the magnetic field waveforms that were tested.

tissues. It should be noted in particular that the investigations in which either square waveforms or pulsed fields that induced tissue current densities greater than 10 mA/m^2 led to findings of positive bioeffects (230, 235, 240, 241, 244, 246 - 253, 255, 258). The suggestion has been made that these fields may exert electrochemical effects at the cell surface (244, 250). Such effects, in turn, could influence hormone-receptor interactions, adenylate cyclase activity, and the membrane transport and intracellular concentration of calcium ions. These membrane functions have been shown to exert a major influence on cellular metabolism and growth dynamics.

Several investigations using bidirectional pulsed magnetic fields have shown an enhanced synthesis of collagen, decreased intracellular cAMP (cyclic adenosine monophosphate), and altered synthesis of cell surface glycoproteins in cultures of fibroblasts and bone-forming cells (246, 253, 255, 258, 274). These findings suggest biochemical and biophysical mechanisms through which the stimulation of bone growth may occur in response to pulsed magnetic fields. Beginning in the early 1970's, several clinical reports have indicated that the use of pulsed magnetic fields with repetition frequencies in the ELF range may provide an effective, noninvasive procedure for the treatment of bone nonunions and pseudoarthroses via electrical stimulation (275 - 281). Current densities of approximately 20 mA/m^2 can be induced in bone by the pulsed field applicators that are presently used for fracture therapy (8, 282). Although the initial clinical trials yielded success rates up to 85% in achieving bone fracture reunion via magnetic stimulation, a recent report has suggested that prolonged immobilization of a patient wearing the magnetic field applicator may also be an important factor contributing to the success of this procedure (283).

Section 5

HUMAN HEALTH STUDIES

STATIC MAGNETIC FIELDS

A clinical study of Soviet workers in the magnet production and machine-building industries was reported by Vyalov (284). The exposure group consisted of 645 workers whose hands were routinely exposed to static fields of 2 to 5 mT, and whose chest and head were in fields of 0.3 to 0.5 mT under normal working conditions. It was estimated that the magnetic field exposure levels were 10 to 50 times larger than the typical values during 10 to 15 percent of the workday. The control group in this study consisted of 138 supervisors in a machine-building plant who were not in contact with magnets. A number of subjective symptoms were reported among the exposed group, including headache, fatigue, dizziness, unclear vision, noise in the ears, and itching and sweating on the palms of the hands. Edema and desquamation on the palms of the hands were also reported. In addition, minor physiological effects including decreased blood pressure and changes in hematological parameters were noted in the exposed group. These studies were qualitative in nature and no statistical analysis was performed on the clinical data. There was also no effort made to assess the possible effects of stressful environmental factors such as high ambient temperature, airborne metallic particles, or the chemical agents used for degreasing and other procedures.

In contrast to the Soviet study, two recent epidemiological surveys in the United States failed to reveal any significant health effects associated with chronic exposure to static magnetic fields. Marsh et al. (285) conducted a cross-sectional study on the health data of 320 workers in plants using large electrolytic cells for chemical separation processes. The average static field level in the work environment was 7.6 mT and the maximum field was 14.6 mT. The study included a control group of 186 unexposed workers. Among the exposed group, slight decreases were found in the blood leukocyte count and the percent of monocytes, while a small increase occurred in the lymphocyte percentage. However, the mean value of the white cell count for the exposed group remained within the normal range. There was also a slight tendency for elevated systolic and diastolic blood pressures among the black workers in the study. None of the observed changes in blood pressure or hematologic parameters was considered indicative of a significant adverse effect associated with magnetic field exposure.

A recently completed study characterized the prevalence of disease among 792 workers at U.S. National Laboratories who were exposed occupationally to static magnetic fields (286). The control group consisted of 792 unexposed workers matched for age, race and socioeconomic status. The range of magnetic field exposures was from 0.5 mT for long durations to 2 T for periods of several hours. No significant increase or decrease in the prevalence of 19 categories of disease was observed in the exposed group relative to the controls. Of the 792 exposed subjects, 198 had experienced exposures of 0.3 T or higher for periods of 1 h or longer. No difference in the prevalence of disease was found between this subgroup and the remainder of the exposed population or the matched controls. No trends were observed in the health data suggestive of a dose-response relationship.

Milham (287) recently reported that workers exposed to large static magnetic fields in the aluminum industry have an elevated leukemia mortality rate. The proportionate mortality ratios (PMR) for all forms of leukemia and for acute leukemia among these workers were compared with general population values determined from 438,000 death records of adult males in the state of Washington during the period 1950-1979. The PMR values for all types of leukemia and for acute leukemia were reported to be 189 and 258, respectively, both of which differed significantly from the no-effect level of 100. Because of the large magnetic fields associated with the aluminum reduction process, which have been measured using a magnetic field personal dosimeter and found to be as high as 57 mT during anode changes on prebake cells (288), Milham suggested that a correlation may exist between exposure to these fields and leukemogenesis (287). The excess of leukemias observed in Milham's study was confirmed in a subsequent study involving 21,829 workers in 14 aluminum reduction plants (289). In this second study, an excess incidence of pancreatic, genitourinary and benign tumors was also found among the aluminum workers.

Although these two epidemiological studies have demonstrated an increased cancer risk for persons directly involved in aluminum production, there is at present no clear evidence to indicate the responsible carcinogenic factors within the work environment. The process used for aluminum reduction creates coal tar pitch volatiles, fluoride fumes, sulfur oxides and carbon dioxide. The presence of hydrocarbon particulates, and perhaps other environmental contaminants, must be taken into account in any attempt to relate magnetic field exposure and increased cancer risk among persons working in the aluminum industry.

TIME-VARYING MAGNETIC FIELDS

Several laboratory studies have been conducted with human subjects exposed to sinusoidally time-varying magnetic fields with frequencies in the ELF range (211, 217, 243). None of these investigations have revealed adverse clinical or psychological changes in the exposed subjects. Beischer et al. (211) observed an elevation in serum triglycerides at 24 and 48 h post-exposure, but the subjects were not fasted prior to blood sampling and the change in triglyceride concentration could have resulted from differences in diet or physical activity. In a subsequent study with rhesus monkeys exposed to similar fields, no change in serum triglyceride concentration was observed (212). The strongest field used in the various laboratory studies with humans was a 5-mT, 50-Hz field to which subjects were exposed for 4 h by Sander et al. (243). In this investigation no field-associated changes were observed in serum chemistry, blood cell counts, blood gases and lactate concentration, electrocardiogram, pulse rate, skin temperature, circulating hormones (cortisol, insulin, gastrin, thyroxin), and various neuronal measurements including visually evoked potentials recorded in the electroencephalogram.

Recent concern over the possible health effects of time-varying magnetic fields has been raised by several reports of an apparent correlation between cancer incidence and exposure to power-frequency fields. The first publication on this subject appeared in 1979, and reported a correlation between the incidence of leukemia among children living in the Denver, CO, area and exposure to 60-Hz magnetic fields from high-current primary and secondary wiring configurations in the vicinity of their residences (290). This finding was followed by 12 additional epidemiological studies during the period 1980-1985. Three of these studies involved the analysis of cancer incidence in relation to residential exposure to power-frequency fields (291 - 293). In the other nine studies, cancer incidence was analyzed for groups of individuals in various electrical, electronic and telecommunication occupations (287, 294 - 301). As summarized in Table 5-1, 11 of the 13 epidemiological surveys conducted to date have shown an apparent correlation between the incidence of various forms of cancer and residential and/or occupational exposure to power-frequency fields. In nearly all cases where a positive finding was obtained, the increased risk of cancer among the exposed group of individuals was small, generally less than a factor of two relative to a control group or the general population.

Table 5-1

EPIDEMIOLOGICAL STUDIES ON THE POTENTIAL RELATIONSHIP OF RESIDENTIAL AND OCCUPATIONAL EXPOSURE TO ELF ELECTRIC AND MAGNETIC FIELDS AND CANCER

Reference	Subjects	Correlation Between Increased Cancer Incidence and Residential or Occupational Exposures
Wertheimer and Leeper, 1979 (Ref. No. 290)	Children (< 19 yr); residential fields [344 cases; 344 controls]	(+)
Fulton et al., 1980 (Ref. No. 291)	Children (< 20 yr); residential fields [119 cases; 240 controls]	(-)
Tomenius et al., 1982 (Ref. No. 292)	Children (< 18 yr); residential fields [716 cases; 716 controls]	(+)
Wertheimer and Leeper, 1982 (Ref. No. 293)	Adults; residential fields [1179 cases; 1179 controls]	(+)
Wiklund et al., 1981 (Ref. No. 294)	Adults; telecommunication workers [Swedish Cancer Registry with 385,000 cases, 1961-1973]	(-)
Milham, 1982 (Ref. No. 287)	Adults; male workers in 11 occupations involving electric and/or magnetic fields [Survey of 438,000 deaths in Washington State men from 1950-1979]	(+)
Wright et al., 1982 (Ref. No. 295)	Adults; male workers in 10 electrical/electronic occupations [Cancer Surveillance Program in Los Angeles County, 1972-1979]	(+)
McDowall, 1983 (Ref. No. 296)	Males aged 15-74; workers in 10 electrical/electronic occupations [Survey of occupational mortality in England and Wales, 1970-1972]	(+)

Table 5-1 (continued)

EPIDEMIOLOGICAL STUDIES ON THE POTENTIAL RELATIONSHIP OF RESIDENTIAL AND OCCUPATIONAL EXPOSURE TO ELF ELECTRIC AND MAGNETIC FIELDS AND CANCER

Reference	Subjects	Correlation Between Increased Cancer Incidence and Residential or Occupational Exposures
Coleman et al., 1983 (Ref. No. 297)	Males aged 15-74; workers in 10 electrical/electronic occupations [South Thames Cancer Registry from 1961-1979]	(+)
Vågarö and Olin, 1983 (Ref. No. 298)	Males and females aged 15-64; workers in electrical/electronic occupations [Swedish Cancer Registry with 385,000 cases from 1961-1973]	(+)
Pearce et al., 1985 (Ref. No. 299)	Adults; male workers in 8 electrical/electronic occupations [546 cases; 2184 controls]	(+)
Milham, 1985 (Ref. No. 300)	Adults; male members of American Radio Relay League in states of Washington and California [1691 male cancer deaths in these two states compared with U.S. age-specific white male death frequencies in 1976]	(+)
Lin et al., 1985 (Ref. No. 301)	Adults; white male workers in 3 electrical/electronic occupations [Brain tumor decedents in state of Maryland from 1969 through 1982]	(+)

Despite the large number of positive findings that have been reported, it is not possible to conclude at the present time that a definite association exists between the exposure of individuals to ELF electromagnetic fields and their relative risk of contracting leukemia or other forms of cancer. This uncertainty arises from numerous methodological deficiencies in the epidemiological surveys conducted to date. Several specific problems are the following. (1) In all of the studies thus far reported, the electric and magnetic field dosimetry was at best qualitative. In studies of residential ELF fields, the neglect of local fields from appliances may have led to incorrect conclusions concerning the peak and average exposure of individuals to power-frequency fields and the harmonic frequencies that emanate from electrical devices used within the home. (2) The sample populations in many of the epidemiological studies were small, and the reported increases in cancer incidence by a factor of 2 or less might be expected to occur on the basis of chance alone. In these studies, it would have been informative if the authors had presented data on several nonexposed occupational groups in which the sample size was comparable to that of the exposed groups. (3) Control groups were frequently chosen in a nonblind manner involving subjective criteria, and the control population was often not matched with the exposed group on the basis of age, sex, race, socioeconomic class, or urban/rural residential status. (4) Several of the studies used weak statistical methods such as the calculation of proportionate mortality ratios, which can lead to extremely misleading conclusions for population subgroups in which the overall incidence of disease is low with the exception of one disease class such as cancer (or some specific form of cancer such as leukemia). (5) The existence of confounding factors such as smoking habits and exposure to industrial pollutants of known carcinogenic potential (e.g., aryl hydrocarbons) has been ignored in all of the epidemiological studies that have attempted to relate ELF fields and cancer incidence.

Section 6

PHYSICAL HAZARDS ASSOCIATED WITH MAGNETIC FIELDS

Two classes of physical hazards are associated with an environment in which static or time-varying magnetic fields are present: (1) forces and torques are exerted on ferromagnetic and paramagnetic materials by static magnetic fields, and (2) time-varying magnetic fields can produce electromagnetic interference in the operation of medical electronic devices such as pacemakers. New et al. (302) measured the magnetic forces and torques exerted on 21 hemostatic clips and various other materials such as dental amalgam. Of the 21 clips, 19 of which were aneurysm clips, 16 showed a deflection near the portals of two magnets operating at 0.147 T and 1.44 T, respectively. Five of the 16 magnetic clips exhibited slight deflections of less than 5° arc, and 5 others showed marked deflections greater than 45° arc. Of the remaining materials tested, only a shunt connector demonstrated significant ferromagnetic properties. The nonmagnetic materials were primarily composed of austenitic stainless steel, which has a high (10 to 20 percent) nickel content that stabilizes the iron in a nonmagnetic form. Clips composed of tantalum or titanium are also non-ferromagnetic (303). Surgical clips composed of martensitic stainless steels are ferromagnetic and experience significant forces and torques in magnetic fields (304). Barrafato and Henkelman (305) conducted a systematic study of 54 different types of surgical clips and characterized their magnetic properties based on the rotational torque experienced in a 0.15 T static field, and the force experienced when a 1.5 mT/m field gradient was imposed. These studies confirmed the nonmagnetic character of clips composed of tantalum and various austenitic stainless steel alloys and silver alloys.

An issue of particular concern is the malfunction of implanted cardiac pacemakers in response to static and time-varying magnetic fields. Because modern pacemakers contain a reed relay switch that can be closed by applying an external magnetic field in order to remotely test the battery strength, it is expected that implanted pacemakers will be influenced by relatively weak static magnetic fields. Based on in vitro tests with demand pacemakers from six major manufacturers, Pavlicek et al. (307) found that fields of 1.7 to 4.7 mT produced closure of the reed switch, thereby resulting in a change from a synchronous to an asynchronous pacing mode. All six of the pacemakers studied were found to experience forces and torques when placed in NMR devices operating at fields up to 0.5 T. Two of the pacemakers experienced a torque that was judged on subjective criteria to be sufficient to cause significant movement within tissue.

A second aspect of pacemaker vulnerability is the electromagnetic interference (EMI) that can result from signals introduced by time-varying magnetic fields in the ELF frequency range. The "unipolar" design of demand pacemakers, in which the cathode lead is implanted in the heart and the pacemaker case serves as the anode, is particularly susceptible to low-frequency EMI. This sensitivity results from the considerable physical separation of the anode and cathode, which thus provides a large antenna for the detection of EMI signals. The "bipolar" pacemaker design is much less sensitive to EMI because both leads are implanted within the heart at a small distance of separation. It has been estimated that among the 350,000 to 500,000 individuals in the United States with implanted pacemakers, approximately 50 percent have models with the unipolar electrode design (308). It should also be noted that some manufacturers of pacemakers with the unipolar electrode configuration have overcome the problem of low-frequency EMI by incorporating a design feature that automatically decreases the sensitivity of the amplifier circuit when an interference signal is sensed. These specific pacemaker models thereby avoid reversion to an asynchronous mode in response to EMI (309).

Pavlicek et al. (307) have found that a rapidly-switched gradient field with a time variation of 3 T/s can induce potentials up to 20 mV in the loop formed by the electrode lead and the case of a unipolar pacemaker. This signal amplitude is sufficiently large to avoid rejection by the pacemaker's EMI discrimination circuitry, and it could therefore be mistakenly recognized as a valid cardiac electrical signal. A total of 26 pacemaker models were examined by Jenkins and Woody (310) for sensitivity to 60-Hz magnetic fields. Twenty of these units were found to revert to an asynchronous mode or to exhibit abnormal pacing characteristics in 60-Hz fields with amplitudes ranging from 0.1 to 0.4 mT. The average threshold field strength for inducing pacemaker malfunction was 0.2 mT, which corresponds to a dB/dt of 75 mT/s.

Section 7

MAGNETIC FIELD EXPOSURE GUIDELINES

There are currently no formal standards for occupational or public exposure to static or time-varying magnetic fields in the ELF frequency range. Three sets of informal guidelines limiting occupational exposure to static magnetic fields have been proposed in the U.S.S.R. and the United States. Based on clinical observations of workers in occupations involving magnets and magnetic materials, (311), Vyalov proposed the set of exposure limits shown in Table 7-1. As discussed in Section 5, many of the clinical symptoms reported by Vyalov for workers exposed to magnetic fields were subjective in nature (284, 311), and no clear rationale was given for the recommended limits of exposure to static magnetic fields or magnetic field gradients. A second set of static magnetic field exposure guidelines (312) was established in 1970 by the Director of the Stanford Linear Accelerator Laboratory (SLAC) based on a review of a book edited by M.F. Barnothy (313). As discussed in Section 4, many of the biological effects of static magnetic fields reported in this book have been refuted on the basis of later research. Nevertheless, the SLAC guidelines for static magnetic field exposure (Table 7-2) have been widely used in U.S. accelerator laboratories during the last 15 yr. A third set of exposure criteria was developed by a seven-member committee established by the U.S. Department of Energy in the late 1970's. Table 7-3 summarizes the set of guidelines for static magnetic field exposure recommended by this committee in 1979 (314). The committee noted the lack of adequate data upon which appropriate exposure criteria could be based, and recommended that their guidelines should be re-examined in approximately 3-5 yr. At present this re-evaluation has not been initiated.

During the 1980's the rapid development of nuclear magnetic resonance (NMR) as a technique for medical imaging and in vivo spectroscopy has necessitated the establishment of clinical exposure guidelines. The static magnetic fields used in the present generation of NMR devices extend up to 2 T, and higher levels are proposed for future machines (315). In addition, magnetic field gradients are used for spatial localization of magnetic nuclei (e.g., protons) within the imaging volume. Although these gradients are less than 5 mT/m in present NMR devices, they are rapidly switched between locations within the imaging volume. The associated

Table 7-1

U.S.S.R. MAGNETIC FIELD EXPOSURE GUIDELINES[a]

	Field	Gradient
Whole body limits:	0.03 Tesla	0.2 Tesla/meter
Limits for hands:	0.07 Tesla	0.2 Tesla/meter

[a] Values given in the table are the maximum allowed levels during a continuous 8-h work day.

Table 7-2

STANFORD LINEAR ACCELERATOR MAGNETIC FIELD EXPOSURE GUIDELINES

Whole body or head limits:	
Extended periods (h):	0.02 Tesla
Short periods (min):	0.2 Tesla
Limits for arms and hands:	
Extended periods (h):	0.2 Tesla
Short periods (min):	2.0 Tesla

Table 7-3

DEPARTMENT OF ENERGY INTERIM GUIDELINES FOR OCCUPATIONAL EXPOSURE TO MAGNETIC FIELDS

	8-h work day	Exposures of < 1 h	Exposures of < 10 min
Whole body or head exposure limits:	0.01 Tesla	0.1 Tesla	0.5 Tesla
Exposure limits for extremities:	0.1 Telsa	1.0 Tesla	2.0 Tesla

time variation in the magnetic flux density (dB/dt) approaches 3 T/s in some NMR machines currently in use (315).

Three sets of exposure guidelines were proposed in the period 1982-1984 for patients undergoing clinical NMR examinations. These guidelines recommended exposure limits on the static magnetic field, the time-varying field associated with rapidly-switched gradients, and the radiofrequency fild used in NMR devices. Table 7-4 summarizes the recommended limits for exposure to static and time-varying magnetic fields in the clinical NMR guidelines issued in the United States (316), the United Kingdom (317), and the Federal Republic of Germany (318). It is immediately apparent that these limits are much less restrictive than those in the occupational exposure guidelines summarized in Tables 7-1, 7-2 and 7-3. This difference results primarily from three factors: (1) clinical NMR examinations involve patient exposure for relatively short periods (typically 30 min per imaging session), as contrasted with long-term occupational exposures; (2) the NMR clinical guidelines are based on a review of the recent literature, in which many of the earlier claims of magnetic field bioeffects were refuted; and (3) in any medical technique the ultimate exposure criterion is the estimated benefit-to-risk ratio for the patient, and this criterion generally leads to an acceptable level of exposure that is significantly higher than would be permitted for chronic exposure in an occupational environment.

Table 7-4

MAGNETIC FIELD EXPOSURE GUIDELINES IN CLINICAL NMR

		Maximum Levels
Source	B (Tesla)	dB/dt (Tesla/s) or J (mA/m^2)[c]
National Center for Devices and Radiological Health, DHHS[a]	2.0 T	3 T/s
National Radiation Protection Board, U.K.[b]	2.5 T	20 T/s (r.m.s.) for pulses > 10 ms; $2/\sqrt{t}$ T/s (r.m.s.) for pulses < 10 ms (t in s)
Federal Health Office, F.R.G.	2.0 T	30 mA/m^2 for pulses > 10 ms 0.3/t mA/m^2 for pulses < 10 ms (t in s)

[a] The NCDRH guidelines are intended as a demarcation of B and dB/dt levels above which potential health risks to patients should be evaluated for any specific NMR unit.

[b] NRPB also recommended that operation staff should limit exposure to field levels recommended in the Stanford Linear Accelerator guidelines.

[c] J is the maximum induced current density in tissue.

Section 8

SUMMARY AND CONCLUSIONS

Based on the review presented in earlier sections of this report on magnetic field interaction mechanisms and biological effects, the following summary statements and conclusions can be made regarding the potential environmental and human health effects of SMES fields.

STATIC MAGNETIC FIELDS

Several lower life forms are responsive to extremely weak static magnetic fields. The orientational cues provided by the geomagnetic field to elasmobranch fish and magnetotactic bacteria are essential for their navigation, and artifically imposed magnetic fields could represent a serious risk to these organisms. However, the fringe magnetic fields from land-based SMES facilities obviously do not constitute an environmental issue relative to these aquatic species.

A different situation exists for bees and migratory avian species, which have been claimed to derive directional cues from the geomagnetic field in the absence of direct sunlight. Controversy currently exists in regard to the question of whether an altered magnetic field environment can affect the orientation of the waggle dance used by bees to communicate the direction of food. The sun provides a primary directional reference in both the navigation of bees and their dance language, and it has been proposed that geomagnetic orientational cues serve as a secondary source of directional information under overcast skies. However, recent careful studies indicate that geomagnetic information is not important since bees apparently possess a memory from previous days of the sun's position at each time of day relative to their flight direction or other landmarks (319).

The evidence that migratory avian species (e.g., pigeons, gulls and robins) respond to directional information from magnetic fields in the absence of sunlight is now reasonably well established. Unfortunately, nearly all of the available information on this subject has been obtained either from field tests in which small magnets were attached to the heads of migrating birds, or from laboratory studies in which birds were placed in cages surrounded by Helmholtz coils to produce an altered magnetic field environment. The avians in these studies were thus subjected continuously to magnetic fields that differed from the natural geomagnetic field. It is difficult to assess from these investigations whether the long-range navigational route of a migratory avian species would be significantly influenced if a transient alteration in the ambient magnetic field were to be encountered during nocturnal navigation or during daytime migration under overcast skies. This type of transient magnetic field disturbance would be presented to avians flying over or near an SMES facility, and it poses an environmental problem that will be difficult to resolve even by implementing the various shielding options discussed in Section 2.

A study by Larkin and Sutherland (320) used radar tracking of nocturnal migratory birds to detect navigational irregularities as the avians flew over an ELF antenna operating at 72 to 80 Hz. A total of 469 long-range flight tracks were analyzed, and a majority showed either no disturbance or a minimal disturbance in the bird's general flight path. However, there was a statistically significant number of changes in either the birds' migratory course or their rate-of-climb during flight when the antenna was in the energized relative to the non-energized state. In addition, the largest number of flight tracks were observed during changes in the antenna current from 0 to 75 A or from 75 to 0 A, corresponding to changes in the magnetic flux density at the location of the migrating birds of approximately 0.1 to 0.5 μT. The magnitude of these alterations in the ambient magnetic field were thus < 1% of the local geomagnetic field intensity. The authors concluded that their data support the existence of avian sensitivity to weak electromagnetic fields, but they could draw no conclusion on the long-term environmental impact of these fields.

In regard to mammalian species, there is now substantial evidence that static magnetic fields do not produce adverse behavioral or physiological changes at levels up to approximately 2 T. Electrical potentials induced within the central circulatory system of laboratory animals placed in fields up to 2 T do not significantly affect cardiac performance during brief exposures. Additional studies are needed to assess the effects of prolonged exposure to fields of this magnitude on the cardiovascular and central nervous systems.

TIME-VARYING MAGNETIC FIELDS

The induction of tissue current densities less than 1 mA/m^2 by time-varying magnetic fields has not been demonstrated to produce harmful effects, although some laboratory findings of behavioral and physiological alterations have been reported.

A time variation of 0.1 to 0.2 T/s would induce maximum current densities of this magnitude in critical organs such as the heart and brain. Acute visual phenomena that occur in sinusoidal and pulsed magnetic fields with a time rate of change exceeding 1.3 T/s are completely reversible and produce no harmful long-term effects. The time rate of change of the slowly varying SMES magnetic fields is below the level that would be anticipated on the basis of laboratory studies to represent a risk to operations personnel or to natural biota (with the possible exception of migratory avian species).

HUMAN HEALTH STUDIES

Epidemiological studies on human populations exposed to large static magnetic fields have provided no consistent evidence for adverse health effects. Similarly, laboratory studies on humans exposed for short periods (hours) to time-varying magnetic fields in the ELF frequency range have not shown alterations in numerous physiological and behavioral indices. Controversy currently surrounds the recent reports of elevated cancer risk among individuals exposed residentially and/or occupationally to ELF electric and magnetic fields above the normal ambient levels. A direct correlation between cancer risk and exposure to ELF fields has not been established, and numerous criticisms have been raised of the epidemiological procedures used in the studies reported to date. Among the various methodological deficiences noted in these studies, the failure to account for confounding variables has been the most widely criticized (321, 322).

PHYSICAL HAZARDS ASSOCIATED WITH MAGNETIC FIELDS

A serious health risk is associated with the forces and torques exerted by large static magnetic fields and magnetic field gradients on metallic implants such as vascular clips and prosthetic devices. Static magnetic fields greater than 1.5 mT and time-varying fields with dB/dt greater than approximately 75 mT/s can alter the performance of implanted cardiac pacemakers. Although the slow time variation of the magnetic fields in the vicinity of a SMES facility does not pose a clear physical hazard, the static magnetic field intensities are sufficiently large to constitute a direct health risk to operations personnel with implanted pacemakers, vascular clips, or prostheses.

EXPOSURE GUIDELINES

The three extant guidelines for occupational exposure to static magnetic fields are now outdated, and they provide exposure limits that appear to be too conservative in the context of available information from recent laboratory and epidemiological studies. Reports that are currently in preparation by the World Health Organization Non-Ionizing Radiation Committee and the U.S. National Council on Radiation Protection and Measurements (Committee 67) may lead to new recommendations for occupational exposure standards by the end of this decade.

Clinical NMR exposure guidelines have recently been proposed for static and time-varying magnetic fields, and these provide useful criteria for short-term exposures of less than one hour duration. All three of the extant NMR guidelines recommend a 2.0 to 2.5 T limit on static magnetic field exposures. The 3 T/s exposure limit recommended in the U.S. guideline for time-varying fields appears reasonable on the basis of available information from laboratory studies, including several clinical investigations on human subjects. The West German guideline limiting the induced current density in tissue to 30 mA/m^2 is consistent with the U.S. guideline, since a 3 T/s field variation would induce a maximum current density of this magnitude at the outer perimeter of the torso of an adult human subject. From the available laboratory information on cellular, tissue and animal systems, the 20 T/s (r.m.s.) exposure limit recommended in the United Kingdom NMR guideline appears to be excessive.

At the present time, the NMR imaging procedure is sufficiently new that information on possible adverse human health effects is confined to short follow-up periods. Two literature reports indicate that no untoward health effects were observed during a six-month follow-up period in patients that had undergone NMR imaging (323,324). Ultimately, clinical studies of this nature will provide much useful data on the health profile of humans subjected to the relatively large static and time-varying magnetic fields associated with medical NMR devices.

Section 9

RECOMMENDATIONS

As additional SMES prototype test facilities are constructed and operated, it will become increasingly important to understand the potential environmental and human health impacts of the large fringe magnetic fields associated with this technology. It is projected that SMES will become a commercially viable energy storage technology in the next century, by which time it can be anticipated that the biological effects of static and time-varying magnetic fields will be sufficiently well understood that rational standards will exist to regulate occupational exposures. However, during the coming decade it is likely that formal criteria defining human exposure limits will not exist, and judgments based on contemporary knowledge of magnetic field effects on living systems will be required to assess safe limits of exposure.

STATIC MAGNETIC FIELDS

Based on the literature summary and critique provided in this report, several recommendations can be made on acceptable levels of static magnetic field exposure to occupational personnel, the general public, and natural biota.

Public Exposures

The well documented sensitivity of cardiac pacemakers to static magnetic fields exceeding 1.7 mT suggests that a prudent guideline for the field intensity at the outer perimeter of an SMES facility would be 1.0 mT or less. At this level the SMES fringe magnetic fields should not pose a health risk to any segment of the general population, nor would they be expected to constitute a "public nuisance" in terms of erasure of magnetically-encoded data on commercial cards (e.g., bank cards).

Environmental Effects

Concern over potential impacts of static magnetic fields on natural biota extends to several species of animals that possess unique sensitivity to weak fields, and to photosynthetic reaction systems that involve a charge transfer intermediate state which can be influenced under certain specific conditions by modest fields on the order of 5 to 10 mT. As discussed in Section 3, the sensitivity of photosynthetic systems to static magnetic fields occurs only when the electron acceptor molecules are chemically reduced. Because this condition has not been observed in nature, it is highly improbable that the fringe magnetic fields from SMES facilities would influence natural photosynthetic reaction systems. As discussed in Section 8, the primary concern over animal sensitivity to magnetic fields relates to the effects of these fields on the navigation of migratory birds. On the basis of available information, the possibility exists that avians navigating under nocturnal conditions or under totally overcast skies will be disoriented by SMES fringe magnetic fields. The extent to which stray magnetic fields can influence long-range avian navigational routes is uncertain. Previous observations on the flight paths of birds near an ELF antenna system (320) indicated that little or no disturbance was experienced by animals flying on a linear route at a constant altitude. However, disturbances were noted in the flight paths of birds executing turns or changing altitude in the vicinity of the ELF antenna. It is probable that similar effects would result from transient encounters of migratory birds with the fringe magnetic fields from SMES facilities. Because of the apparent sensitivity of these animals to fields as weak as the geomagnetic field, it will be difficult (and perhaps impossible) to mitigate effects on migratory birds even with extensive shielding of the SMES fringe fields. In the context of this environmental issue, there is a clear need to gain more information on the sensitivity of migratory avians to magnetic fields under realistic experimental test conditions.

Occupational Exposures

As discussed in Section 8, the extant guidelines limiting occupational exposure to static magnetic fields are now outdated in terms of the database upon which they were established. In addition, there are no extant guidelines for time-varying magnetic fields. The recent guidelines for clinical NMR exposures provide useful criteria for brief exposures of less than one hour duration, but are not suitable as criteria for chronic occupational exposures.

In view of the lack of formal guidance on magnetic field exposure limits, two options can be followed in new technologies such as SMES that involve occupational exposures to relatively large fields: (1) One of the extant guidelines can be adopted as an operational guideline. Many accelerator laboratories and other technologies currently use the Stanford Linear Accelerator guidelines, even though these criteria are now 15 years old. (2) An ad hoc committee of experts could be established to review the current state of knowledge on magnetic field bioeffects.

Based on its findings, the committee would recommend a set of interim occupational exposure guidelines to be used at SMES prototype facilities. These interim guidelines would be discontinued in the event that formal magnetic field exposure standards were promulgated at the Federal level.

Another aspect of occupational magnetic field exposure guidelines is the regulation of access to high-field regions by personnel with metallic implants. In accord with the preceding discussion of this issue, it would be prudent to exclude operations personnel and visitors who wear cardiac pacemakers from areas where the field level exceeds 1.0 mT. A more difficult problem is posed by the choice of appropriate exposure guidelines for personnel with aneurysm clips, prosthetic devices, or other types of implants constructed from ferromagnetic materials. In many cases an implanted device may be fabricated from tantalum, austenitic stainless steel, or other types of nonmagnetic material. When the nonmagnetic composition of an implanted object in a specific employee can be verified from medical records, there is no obvious reason to impose magnetic field exposure limitations on this individual that differ from the limits for the general work force. In the case of personnel with ferromagnetic implants, the advisability of excluding these individuals from areas with static fields exceeding approximately 0.1 T is clearly indicated by the results of previous research (discussed in Section 6 of this report). However, the threshold magnetic field intensity and spatial gradient above which significant (and potentially harmful) movements of an implant might occur are a function of both the composition and the physical size of the object. One possible approach is to estimate the threshold field that could produce implant movement under a worst-case scenario (i.e., the largest conceivable implant with the highest anticipated value of magnetic susceptibility), and use this estimate as an exposure limit for all of the individuals at risk. Another approach that may be more expedient, but possibly too restrictive, would be to limit the access of these personnel to areas where the static field level is at or below 1.0 mT. The recommendations of an ad hoc committee of experts could prove useful in resolving this issue.

Another issue of potential concern arises from the report (55) that a significant orientational torque is exerted on deoxygenated sickled erythrocytes by a uniform 0.35-T static field (discussed in Section 3). Under normal conditions it would be anticipated that erythrocytes are well oxygenated within the circulation of persons with the sickle cell trait. However, the possibility of occluded blood flow leading to regional hypoxia and a resultant conversion of hemoglobin in significant numbers of erythrocytes to a deoxygenated, paramagnetic state exists during a sickle cell crisis. Unfortunately, the available information is not sufficient to judge whether the orientational torque exerted by a magnetic field on deoxygenated sickled erythrocytes would necessarily be harmful. In general, the possibility appears remote that persons with the sickle cell trait would experience a significant health risk as the result of exposure to static magnetic fields. However, this issue is another area in which the recommendations of an ad hoc committee of experts could prove valuable.

TIME-VARYING MAGNETIC FIELDS

With regard to the slowly time-varying fields from SMES facilities, in the EPRI design of a 5500-MWh plant the average value of dB/dt during a magnet shutdown would be 14 mT/s, as discussed in Section 3. The diurnal variation in the magnetic field intensity is nearly two orders of magnitude smaller than this value. Using Eqs. (6) and (8) in Section 3, it can be calculated that a time-varying field with dB/dt = 14 mT/s would induce a maximum electric field and current density at the outer perimeter of the torso of an adult human ($R = 0.17$ m and $\sigma = 0.2$ S/m) of 1.2 mV/m and 0.24 mA/m^2, respectively. These values of the electric field and current density are below the endogenous levels present in living tissue. Based on the discussion of laboratory studies presented in Section 4, little or no disturbance of normal physiological functions would be expected to occur in response to the tissue currents induced by the slowly time-varying fields associated with SMES facilities. The lack of formal criteria for occupational exposure to time-varying magnetic fields in the ELF frequency range should therefore pose no operational limitations for SMES facilities.

COMBINED STATIC AND TIME-VARYING FIELDS

The environment of an SMES plant will contain both static magnetic fields and power-frequency fields associated with the high-voltage transmission lines that are interfaced with the SMES power conversion system. As a result, static fringe fields from the SMES facility with intensities up to approximately 1 mT, 60-Hz magnetic fields up to 33 μT and 60-Hz electric fields up to 12.9 kV/m may be present simultaneously if 765-KV lines are used for electric power transmission (189,325). If lower power-line voltages are used, the resulting 60-Hz environmental fields would, of course, be lower than those stated above for a 765-kV line.

Three recent studies have indicated that small, but measurable, biological effects may result when magnetic resonance conditions are established in the test specimen by simultaneously applying weak static fields (below 1 mT) and time-varying fields in an orthogonal configuration (326 - 328). Briefly summarized, it has been reported that magnetic resonance conditions influence the dielectric properties and growth rate of yeast cells (326), the rate of lysozyme reaction with a cell membrane substrate (326), the behavior of rats in a timing discrimination task (327), and the rate of calcium ion release from brain tissue exposed in vitro to low-intensity electromagnetic fields (328). 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 ^{1}H, ^{23}Na, ^{31}P, ^{35}Cl and ^{39}K. In the third study (327), reversible changes in rodent timing behavior were observed when rats were simultaneously exposed to a horizontal 60-Hz magnetic field and a vertical 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 lithium ions, which are thought to exert neuropharmacological effects. In the fourth study (328), a generalized heuristic relationship was derived between the biologically 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. This heuristic relationship is consistent with an ion cyclotron resonance motion of calcium ions under the influence of combined static and oscillating magnetic fields.

Although these findings suggest that the combined static magnetic fields and time-varying electromagnetic fields in the vicinity of an SMES plant could influence living systems, a precisely defined set of conditions related to field strength, frequency, and orientation are required. In contrast to the well-defined exposure conditions that exist in laboratory studies, the movements of humans and wildlife species result in their exposure to ambient fields of varying magnitude and orientation. The probability is therefore low that a prolonged exposure of man and other animals to a biologically effective set of static and time-varying field parameters could occur in the vicinity of an SMES plant. There is an obvious need for replication and extension of the biological studies cited above on combined static magnetic fields and time-varying electromagnetic fields, but at present there is no compelling reason to view the possible effects of these combined fields as being harmful to living systems.

FUTURE RESEARCH NEEDS

The development of formal magnetic field exposure standards will require additional information in several areas related to the biological effects and the human health effects of these fields. Based on the literature summary and critique given in this report, the following aspects of static and time-varying magnetic field interactions with living systems require further exploration.

Static Magnetic Fields

For static fields there is a clear need for additional experimentation in the following six areas, in each of which the available information is either inadequate or contradictory:

- effects of transient magnetic field exposure on the navigational routes of migratory avian species;
- response of implants (e.g., aneurysm clips and prostheses) containing paramagnetic or ferromagnetic materials to uniform fields and spatial gradients;
- effects of chronic exposure on the cardiovascular system;
- acute and chronic exposure effects on the electrical properties of the central nervous system;
- response of the endocrine system to chronic exposure;
- cellular, tissue and animal responses to ultrahigh static fields at intensities above 2 T.

Time-varying Magnetic Fields

For time-varying magnetic fields with frequencies in the ELF range and for combined static and time-varying fields, six key areas of future research can be recommended on the basis of information that is presently available:

- carcinogenesis studies involving research on experimental cellular and animal systems, and carefully designed and executed epidemiological studies on human populations;
- studies on the response of cellular systems, with a particular focus on membrane components that have been identified as targets of ELF magnetic field interactions; potentially important avenues of research include studies of cell growth and metabolism, and membrane studies in the areas of biochemistry, electrochemistry, enzymology, surface hormone receptors, and transport properties;
- studies of ELF magnetic field effects on gene expression and organism development;

- studies on the response of the endocrine system to ELF magnetic fields;
- studies on ELF magnetic field effects on immune system function;
- studies on the combined effects of static magnetic fields and ELF electromagnetic fields in cell, tissue and animal systems.

Section 10

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APPENDIX A

GLOSSARY

action potential	- a change in electrical potential between the inside and outside of a nerve cell membrane during the passage of an impulse
ampulla of Lorenzini	- a saccular dilation at the terminus of a jelly-filled canal extending from the surface into the head of an elasmobranch fish
aneurysm	- circumscribed dilation of an artery, or a blood-containing tumor connected directly to the lumen of an artery
anode	- the positive electrode terminal
antigen	- a protein or glycoprotein substance that stimulates antibody production when injected into the body
aorta	- the large trunk artery that carries blood from the heart to be distributed by branch arteries throughout the body
Aplysia	- a marine nudibranch, also known as the sea hare
aryl hydrocarbon	- a derivative of an aromatic hydrocarbon obtained by the removal of a hydrogen atom
austenitic stainless steel	- an alloy composed of iron, carbon and other elements
birefringence	- the refraction of light in two different directions to form two rays
cathode	- the negative electrode terminal
circadian	- occurring in approximately 24-h cycles
circulatory system	- the system composed of blood, blood vessels, lymphatics and the heart that produce the circulation of blood and lymph
collagen	- a fibrous protein that is the major constituent of connective tissue fibrils
convulsive seizure	- an abnormally violent and involuntary series of muscle contractions

Glossary (cont'd)

cortisol	- an adrenal hormone that is a dihydro derivative of cortisone; used in the treatment of rheumatoid arthritis
counterion	- an ion present in solution with an opposite electrical charge to that of a neighboring ion present either in the same solution or bound to a surface in contact with the solution
cyclic adenosine monophosphate (cAMP)	- a cyclic mononucleotide of adenosine that has been implicated in various biological control systems that regulate cell metabolism and function
desquamation	- The shedding of the epidermis in scales
diamagnetic anisotropy	- the difference in magnetic susceptibilities along different principal axes of symmetry of a molecule or organized molecular aggregate
diamagnetism	- a substance with a magnetic permeability less than unity; materials with this property are repelled by a magnet
diastolic blood pressure	- the reduced blood pressure associated with the rhythmic dilation of the heart cavities during which they fill with blood
diurnal	- having a daily cycle
edema	- an accumulation of excessive watery fluid in tissues
elasmobranch	- a class of fish with lamellate gills that include the sharks, skates and rays
electrocardiogram (ECG)	- a recording of the electrical activity that occurs in cardiac tissue during each heart beat
electrochemical	- the interconverson of electrical and chemical energy
electrodynamic	- physical phenomena associated with the interaction of electric currents with magnetic fields, with other currents, or with themselves
electroencephalogram (EEG)	- a recording of the electrical signals emanating from the brain
electromyogram	- a record of the electrical signals associated with activity of skeletal muscles
electronic spin state	- the physical state of electrons of a system as specified by their spin orientations
endocrine	- denoting a gland that secretes a hormone

epidemiology	- a branch of medical science concerned with the incidence, distribution and control of disease in a population
extrasystole	- a premature beat of one of the chambers of the heart that leads to momentary arrhythmia
extremely low frequency	- the range of electromagnetic field frequencies below 300 Hertz
ferromagnetism	- a property exhibited by certain metals, alloys and compounds of the transition rare-earth and actinide elements in which the internal magnetic moments spontaneously organize in a common direction
fibrillation	- a muscular twitching involving individual muscle fibers acting without coordination
fibroblast	- a flat, elongated cell present in connective tissue
flux density (magnetic)	- a vector quantity that is used as a quantitative measure of the magnetic field strength; the flux density is defined by the Lorentz equation, which states that the magnetic force on a charged particle moving in a field is equal to the particle's charge times the vector cross-product of the particle's velocity with the magnetic flux density (in the MKS system of units); also known as the "magnetic induction"
ganglion	- a mass of nerve tissue containing nerve cells external to the brain or spinal cord
gastrin	- a compound present in gastric mucosa that stimulates the secretion of gastric acid
gastrocnemius muscle	- the largest and most superficial muscle in the calf of the leg
glaucoma	- a disease of the eye that characteristically produces increased pressure within the eyeball, damage to the optic disk and a gradual loss of vision
glycoprotein	- a class of conjugated protein-carbohydrate molecules
harmonic frequency	- a component frequency of an electromagnetic wave that is a multiple of the fundamental frequency
hematology	- a branch of biology concerned with blood and blood-forming organs
hemodynamic	- relating to the dynamic mechanisms involved in blood circulation

Glossary (cont'd)

hemoglobin	- an iron-containing protein present in the red blood cells of vertebrates; transports oxygen from the lungs to tissues, where oxygen is released; carbon dioxide is bound in the tissues and transported to the lungs where it is released into the air
hertz (Hz)	- a unit of frequency equal to one reciprocal second
hyperfine interaction	- the interaction of the total angular momentum of orbital electrons with the nuclear spin magnetic moment
hypoxia	- a state of oxygen deficiency
immunology	- a science that deals with the phenomena and causes of immunity
insulin	- a polypeptide hormone involved in the regulation of carbohydrate metabolism
ionic conduction current	- a current due to the flow of electrically charged ions
lectin	- any of various proteins that agglutinate red blood cells and other types of cells such as tumor cells, and have other properties including mitogenic activity and toxicity in animals; lectins are derived from plants, bacteria, fish and various invertebrate animals
leukemia	- an acute or chronic disease in man and other warm-blooded animals characterized by an abnormal increase in the number of leukocytes in the tissues and often in blood
leukocyte	- any one of the white blood cells, which include lymphocytes and myelocytes
Lorentz force	- the net force on a charged particle moving in electric and magnetic fields, equal to the particle's charge times the sum of the electric field and the vector cross-product of the particle's velocity and the magnetic flux density
lysozyme	- a hydrolyzing enzyme acting on mucopolysaccharide compounds and destructive to certain bacteria because of its effect on the cell wall
magnetite	- a black oxide of iron with the chemical structure Fe_3O_4
magnetohydrodynamics	- the study of the dynamics of motion of an electrically conducting fluid in the presence of a magnetic field

Glossary (cont'd)

magnetomechanical	- mechanical forces and torques exerted on substances in a magnetic field
magnetophosphene	- a flickering colorless illumination of the visual field in response to a pulsed or ELF time-varying magnetic field
magnetotactic bacterium	- a class of iron-rich mud bacteria that are attracted by weak magnetic fields such as that of the earth
monocyte	- a relatively large mononuclear leukocyte present in the blood
nuclear magnetic resonance (NMR)	- precession of a nuclear magnetic moment about the direction of a static magnetic field; the precession frequency (Larmor frequency) is proportional to the magnetic moment and the field strength
neuromuscular stimulation	- stimulation of nerves directly associated with muscular elements of the body
occipital region	- a region of the brain at the back of the head
pacemaker	- a rhythmic center controlling the heart's activity (normally, the sinus node); also, an artificial electronic device that substitutes for the normal cardiac pacemaker's function
paramagnetism	- a property exhibited by substances that are magnetized in a direction parallel to an applied magnetic field, and to an extent proportional to the field; the magnetic permeability of such substances is greater than unity
permeability (magnetic)	- a factor, characteristic of a material, that is equal to the magnetic flux density produced in the material divided by the applied magnetic field intensity; the permeability is a tensor when the quantities are not parallel
photoreceptors	- any one of the classes of cells in the retina (rods and cones) that absorb light and produce nerve impulses that lead to visual perception
photosynthesis	- a process by which carbohydrates are formed in the chlorophyll-containing tissues of plants exposed to light
prothesis	- an artificial limb or joint
pseudoarthrosis	- motion in the shaft of a long bone which results from an ununited fracture
radical ion pair	- a pair of ions that possess at least one unpaired electron

Glossary (cont'd)

radiofrequency (RF)	- the range of electromagnetic field frequencies between 300 kHz and 3000 GHz
reed switch	- a switch that has contacts mounted on ferromagnetic reeds sealed in a glass tube, designed for actuation by an external magnetic field
retinal rod outer segments	- a portion of rod photoreceptor cells in the retina that contains the photopigment rhodopsin
sciatic nerve	- one of a pair of large nerves that pass from the pelvic region down the back of the thigh
sensory epithelium	- a membranous cellular tissue that covers the surface of a sensory receptor
sensory receptor	- an element of the sensory system that detects and conveys sensations via the nervous system
sickle cell	- a red blood cell shaped in the form of a crescent or sickle; associated with a hereditary genetic trait in sickle-cell anemia
soliton	- a traveling wave in which a single disturbance is neither preceded or followed by other such disturbances; mathematically, a nonlinear wave that propagates with a characteristic constant shape
superconducting magnetic energy storage (SMES)	- a system in which electrical energy is stored in a superconducting magnet
superconductivity	- a property of many metals, alloys and chemical compounds at temperatures near absolute zero by virtue of which their electrical resistivity vanishes and they become strongly diamagnetic
susceptibility (magnetic)	- the ratio of the magnetization of a material to the applied magnetic field intensity; the susceptibility is a tensor when these two quantities are not parallel
systolic blood pressure	- the elevated blood pressure associated with the rhythmic contraction of the heart cavities during which blood is driven into the pulmonary and aortic vessels
teratology	- the study of malformations in developing organisms
tesla (T)	- the International System unit of magnetic flux density, equal to one weber per square meter (1 T = 10,000 gauss)
tetanus	- sustained muscular contraction caused by rapidly repeated nerve stimuli

Glossary (cont'd)

thermoregulation	- the process by which the body controls its internal pressure
thyroxin	- the biologically active iodine compound existing normally in the thyroid gland
triglyceride	- a form of glycerol containing esterified fatty acids
T wave	- the electrical signal recorded in the electrocardiogram during repolarization of ventricular muscle tissue at the end of each heart beat
ventricle	- a chamber of the heart that receives blood from the corresponding atrium and from which blood is forced into the arteries
visual cortex	- the brain region where visual stimuli are registered
visually evoked potentials (VEP)	- electrical potentials in the visual cortex evoked by photic stimulation of the eye
visuosensory system	- the portions of the central nervous system involved in the perception of visual stimuli

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