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INTERACTION OF TIME-VARYING ELF MAGNETIC FIELDS WITH LIVING MATTER

T.S. Tenforde

May 1984

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1. INTRODUCTION

The principal topic of this chapter is the interaction with living systems of time-varying magnetic fields in the extremely-low-frequency (ELF) range below 300 Hz. Magnetic fields in the ELF range are present throughout the environment and originate from both natural and man-made sources.[1] The naturally occurring, time-varying fields in the atmosphere have several origins, including diurnally varying fields on the order of 30 nT associated with solar and lunar influences on ionospheric currents. The largest time-varying atmospheric magnetic fields arise intermittently from intense solar activity and thunderstorms, and reach intensities on the order of 0.5 μT during a large magnetic storm. Superimposed on the magnetic fields associated with irregular atmospheric events is a weak ELF field resulting from the Schumann resonance phenomenon. These fields are generated by lightning discharges and propagate in the resonant atmospheric cavity formed by the earth's surface and the lower boundary of the ionosphere. The five lowest resonant frequencies are below 40 Hz, and the magnetic flux densities per unit bandwidth associated with the Schumann resonance phonomenon vary from 0.25 - 3.6 $pT/Hz^{1/2}$.

The time-varying ELF magnetic fields originating from man-made sources generally have much higher intensities than the naturally occurring atmospheric fields, and in some occupational settings reach levels that approach 0.1 T. Two sources of ELF fields that have been topics of considerable public interest are high-voltage transmission lines and land-based naval communication systems. The fields at ground level beneath a 765-kV, 60-Hz power line carrying 1 kA per phase is 15 μT.[2] The surface field associated with the ELF antennas that are proposed for use in submarine communications is 20 μT.[3] Household appliances

operated from a 60-Hz line voltage produce local fields in their immediate vicinity with intensities as high as 2.5 mT.[1] However, the magnetic field strength decreases rapidly as a function of distance from the surfaces of household devices. The video display terminals present in most modern offices generate local ELF magnetic fields with intensities up to 2 μT.[4] A number of industrial processes that involve induction heating produce ELF magnetic fields of high intensity within the occupational environment. For example, based on a survey of electrosteel and welding industries in Sweden, it was reported that the local fields near 50-Hz ladle furnaces reached intensities of 8 mT, and intensities as high as 0.07 T were measured near induction heating devices operating in the 50 Hz to 10 kHz range.[5]

In this chapter a summary and critical evaluation will be given of the published literature describing effects of time-varying ELF magnetic fields on living systems. Selected aspects of this subject have also been summarized in several review articles and monographs published in recent years.[6-9] In an effort to provide a framework for the description of ELF magnetic field bioeffects, the published literature has been divided into four major categories. These categories include ELF magnetic field interactions with the visual system, the nervous system, various cellular and tissue systems, and carcinogenic effects. Brief summaries are also given of ELF magnetic field interaction mechanisms and various medical applications of these fields.

2. THEORETICAL PRINCIPLES

The interaction of time-varying ELF magnetic fields with living tissues occurs principally through the induction of electric currents in accord with Faraday's law. To illustrate the relevant physical principles, consider a purely sinusoidal time-varying magnetic field $\vec{B}$, with frequency f and amplitude $\vec{B}_o$:

$$\vec{B} = \vec{B}_o \sin(2\pi ft) \tag{1}$$

Because of the weakly diamagnetic nature of animal tissues, their magnetic permeability is nearly identical to that of air (within approximately one part in 10^6), and an applied ELF magnetic field is transmitted into and through the body tissues with negligible attenuation. In the ELF frequency range there is also no attenuation of the magnetic field at the air/tissue interface due to wave reflection or skin depth, as discussed by C. Polk in the Introduction to this monograph.

If the sinusoidal field B is incident upon a circular loop of radius r and area $S = \pi r^2$, with a parallel orientation of the field vector and the normal to the surface, then by Faraday's law the magnitude of the peak induced potential, V_{peak}, around the loop is given by:

$$V_{peak} = \left| \frac{d(\vec{B}\cdot\vec{S})}{dt} \right|_{peak} = 2\pi^2 r^2 f |\vec{B}_o| \tag{2}$$

The magnitude of the peak induced electric field, $\vec{E}_{peak}$, is equal to the peak potential divided by the loop circumference:

$$|\vec{E}|_{peak} = \frac{V_{peak}}{2\pi r} = \pi r f |\vec{B}_o| \tag{3}$$

A third quantity of interest in the analysis of ELF field interactions is the magnitude of the peak induced current density, $\vec{J}_{peak}$, which can be calculated from Ohm's law:

$$|\vec{J}|_{peak} = \sigma|\vec{E}|_{peak} = \pi r f \sigma |\vec{B}_0| \tag{4}$$

where σ = electrical conductivity.

It is of interest to use the above equations to calculate the magnitude of a time-varying ELF magnetic field that would be expected to perturb the function of critical biological tissues such as the heart and the central nervous system. Using data from several sources, Bernhardt[10] has estimated that the endogenous current densities associated with electrical activity of the brain and heart have lower limits of 1 and 10 mA/m^2, respectively, and perturbations of normal biological functions might be expected to occur in the presence of ELF magnetic fields that induce tissue currents above these levels. Consider for illustration a 60-Hz sinusoidal magnetic field that is normally incident upon a circular loop of tissue with a radius r = 0.06 m, comparable to the human heart, and a conductivity σ = 0.2 S/m.[11] From eqn. (4), the amplitude of the magnetic flux density that would induce a peak current density of 10 mA/m^2 is 4.4 mT. A similar calculation for brain tissue with an average conductivity [10] of 0.1 S/m and a loop radius r = 0.1 m, comparable to the human cranium, leads to the prediction that a peak current density of 1 mA/m^2 is induced by a 60-Hz magnetic field with an amplitude $|\vec{B}_0|$ = 0.53 mT. Because ELF magnetic fields with intensities higher than 5 mT are present in the vicinity of certain types of instruments and industrial processes, the induction of tissue fields at levels that could potentially perturb biological functions is therefore possible.

As discussed in the Introduction to this monograph and in chapter II-4, ELF magnetic fields can also interact with biological tissues through magneto-

orientation effects. This phenomenon arises from the interaction of a magnetic field with paramagnetic substances possessing permanent magnetic moments (e.g., the magnetite inclusions in magnetotactic bacteria), or with macromolecular assemblies in which the summed diamagnetic anisotropy is large (e.g., the photopigment molecules of retinal photoreceptors). The interactions of such systems with static magnetic fields have been well studied, and many of the interesting biomagnetic phenomena that have been characterized in such biological systems are summarized in chapter II-4 by R. P. Frankel. In considering the possible role of magneto-orientation phenomena in the biological interactions of time-varying magnetic fields, it is important to recognize that the frictional resistance to motion in biological tissues is high, and thus serves to damp out even low-frequency oscillations associated with time-varying magnetic orientational forces. This is well illustrated by the fact that the orientation of diamagnetically anisotropic retinal photoreceptor outer segments in a 1 T static field occurs with a characteristic time of 4 s in water.[12] A time-varying field with a frequency exceeding approximately 1 Hz would therefore be unable to induce a "flickering" orientational phenomenon in this system because the frictional drag force would not allow the motion of the retinal rods to keep pace with the oscillating field. A similar conclusion can be drawn for the interaction of paramagnetic entities such as magnetotactic bacteria with an ELF time-varying magnetic field. With the possible exception of quasi-static fields with frequencies in the range 0 to 1 Hz, it is therefore probable that magneto-orientation phenomena play little if any role in the interaction of ELF magnetic fields with living systems.

Returning to the electrical phenomena associated with time-varying magnetic field interactions, a factor that is often overlooked in biological

investigations is the importance of the waveform in determining the response of living tissues to the field. Numerous types of magnetic field waveforms have been used in biological studies, including both sinusoidal and square-wave fields, and pulsed fields with burst repetition rates that lie in the ELF frequency range. For both square-wave and pulsed fields, two parameters of key importance are the rise and decay times of the signal, which determine the maximum time rates of change of the field and hence the maximum instantaneous current densities that are induced in living tissue. For example, a sharply rising square-wave magnetic field pulse will induce a peak current density in tissue that exceeds the value achieved with a sinusoidal field having the same r.m.s. intensity and fundamental frequency. Another factor that must be considered for waveforms with a rapid rise time is the skin depth. As discussed in the Introduction to this monograph, magnetic fields with a rise time less than 10 ns will be attenuated at the air/tissue interface due to the finite skin depth and reflection losses. Pulses with such short rise times, however, are seldom used in biological studies.

Another factor that is of key importance in determining the response of living systems to ELF magnetic fields with any type of waveform is the fundamental field frequency. The phenomenon of magnetophosphenes, which will be discussed in the next section of this chapter, is limited to time-varying magnetic fields with frequencies less than 100 Hz. The mechanism underlying the loss of sensitivity at higher frequencies has not been elucidated, but it is conceivable that the visual system cannot process and respond to induced electrical currents with frequencies above 100 Hz. This hypothesis is supported by the fact that flicker fusion occurs in response to repetitive photic stimuli with frequencies above approximately 30 Hz. Although the frequency dependence of the biological response to time-varying magnetic fields

has not been well characterized for systems other than the visual apparatus, it is conceivable that a similar dependence may exist in tissues such as the CNS and heart in which the endogenous electrical activity has dominant frequencies that are less than 50 Hz.

3. MAGNETOPHOSPHENES

Among the various interactions of time-varying ELF fields with living tissues, perhaps the most widely known and well documented effect is the production of visual sensations known as phosphenes. In the broadest sense, the term phosphene, which is derived from the Greek words "phos" (light) and "phainein" (to show), means the production of luminous sensations in the eye by agents other than light. These physical agents include mechanical pressure applied directly to the eye, and electrical stimulation at ELF frequencies applied to the body surface in the region of the head through contact electrodes. In 1896 d'Arsonval first reported that phosphenes could also be produced by placing the head in an external magnetic field oscillating in the ELF frequency range.[13]

d'Arsonval's initial qualitative observations, which were made with a 42 Hz magnetic field, have been followed by numerous studies in which efforts have been made to define the visual characteristics of magnetophosphenes, their dependence on the frequency and intensity of the applied field, and the exact locus of the field effect within the complex visual pathway. In 1910 Thompson,[14] who was apparently unaware of d'Arsonval's earlier work, reported that a 50-Hz, 0.1-T (peak) field produced a colorless, flickering illumination over the entire visual field which was most intense in the peripheral region. Dunlap[15] confirmed Thompson's observations during the following year, and he further demonstrated that more intense magnetophosphenes were generated by a 25-Hz field relative to a 60-Hz field of comparable intensity. Shortly after Dunlap's experiments were published, Magnusson and Stevens[16] reported the results of phosphene studies in which they used pulsed DC fields and time-varying fields with frequencies ranging from 7 - 68 Hz. With pulsed fields

they were able to elicit a flash of light that moved rapidly in a narrow band across the visual field. Using AC magnetic fields of various frequencies and approximately equal intensities, Magnusson and Steven found that the strongest magnetophosphenes were produced in the 20 - 30 Hz frequency range. They also found that field frequencies less than 15 Hz led to a pulsating succession of flashes covering the entire visual field. In the 10 - 35 Hz frequency range, the magnetophosphenes were reported to form a continuous network of standing waves that flickered at a rate synchronized with the frequency of the applied magnetic field. Frequencies above 40 Hz generated magnetophosphenes with a more uniform luminosity, but which continued to exhibit flickering.

The first systematic study of the dependence of magnetophosphene properties on the intensity of the applied magnetic field was made by Barlow et al.[17] These investigators demonstrated that the duration of an induced phosphene was dependent upon the magnetic field intensity above a threshold level of 20 mT (r.m.s.). These workers also characterized a "fatigue" phenomenon in which the application of an ELF magnetic field stimulus for periods up to 1 min led to a subsequent refractory period during which a second magnetophosphene could not be elicited. With a 60-Hz, 79-mT (r.m.s.) field applied for 1 min, the subsequent refractory period lasted as long as 40 s. Barlow et al.[17] also demonstrated that magnetophosphenes are produced by ELF magnetic fields applied in the region of the eye and not by fields directed towards the visual cortex in the occipital region of the brain. Together with the observation that pressure on the eyeball abolished visual sensitivity to ELF magnetic fields, this fact led Barlow and his coworkers to suggest that the retina is the locus of excitation leading to the phosphene phenomenon. Another interesting finding by Barlow et al.[17,18] was that magneto- and electrophosphenes shared many properties in common, except that the threshold intensity

for inducing phosphenes by ELF magnetic fields was relatively insensitive to background lighting conditions, whereas the threshold intensity for electrophosphene induction changed rapidly as a function of light or dark adaptation. In a later study, Seidel et al.[19] also reported that the types of light patterns induced in the visual field by ELF magnetic and electric fields were similar, but that the probability of occurrence of various classes of patterns was different for the two types of stimuli. A comprehensive description of the various types of phosphene patterns has been given by Oster.[20]

During the past several years, an extensive series of investigations of magnetophosphenes has been carried out by the Swedish scientists P. Lövsund, P. Å. Öberg and S. E. G. Nilsson.[21-15] In this research, the relationship between the frequency of the applied field and the threshold intensity required to elicit phosphenes has been defined with precision for both ELF electric and magnetic field stimuli. A determination of the threshold magnetic field intensity required to elicit phosphenes was measured over the frequency range of 10 - 45 Hz.[21,23,24] The threshold versus frequency curve was found to be a clear function of the state of dark adaptation, the intensity of superimposed background lighting, and the wavelength (and hence color) of the transmitted background illumination within the visual field. Following a 30-min dark adaptation period, the maximum sensitivity for magnetically-induced phosphenes occurred at a frequency of 30 Hz. The minimum field intensity required for the generation of phosphenes was 10 mT at this frequency. In broad-spectrum light with intensities ranging from 0.1 - 130 cd/m^2, the sensitivity maximum occurred at 20 Hz. For low levels of background illumination (0.1 - 1.2 cd/m^2), the magnetic field threshold intensity was 10 mT. However, with background illumination at the 130 cd/m^2 level, the threshold field intensity increased to 14 mT. Immediately following removal of the 130 cd/m^2 light, the average

threshold field intensity measured at frequencies of 20, 30 and 35 Hz dropped to 10 mT and then slowly rose to a plateau level of 16 mT during the ensuing 30-min dark adaptation period. During the same dark adaptation interval, the threshold value for light detection dropped by a factor of 10^4. Lövsund et al.[24] concluded from this observation that the visual elements responsible for slow dark adaptation processes lie before the "magnetoreceptors" in the optic pathway.

A very interesting series of experiments that related normal color vision to magnetophosphene sensitivity was also performed by Lövsund et al.[24] For subjects with normal color vision and for deutans who possess defects in green-sensitive photopigments, measurements were made of the magnetic field threshold intensity as a function of frequency when the background illumination was filtered to produce narrow wavelength bands centered at 443, 531 and 572 nm, which correspond to light absorption maxima of different cone photopigments. For all three wavelengths, normal subjects exhibited a local maximum in magnetic field sensitivity at 20 Hz, a local minimum at 30 Hz, and an increase in sensitivity at higher frequencies that reached a greater level at 40 - 45 Hz than the sensitivity measured at 20 Hz (Figure 1). For broad-spectrum light, the local maximum and minimum at 20 and 30 Hz, respectively, were also observed, but the increase in sensitivity at higher frequencies was less pronounced and did not reach the same level as the sensitivity maximum at 20 Hz. For deutans the maximum sensitivity was observed at 20 Hz with the three wavelengths of background light, but the local minimum in sensitivity at 30 Hz was found only for 443 nm background illumination. With all three background colors, the sensitivity of deutans was less at 40 - 45 Hz than at 20 Hz, in distinct contrast to the observations made with subjects having normal color vision. From these observations, Lövsund et al.[24] concluded that visual

processes mediated by green- and red-sensitive cones, which are responsive to flickering light frequencies as high as 60 Hz, may provide the pathways for enhanced reception by normal subjects of magnetophosphenes induced by fields with frequencies in the 40 - 45 Hz range. The cone pigment defects present in deutans would inhibit sensitivity to magnetophosphenes induced by fields in this range of frequencies.

Two other studies with visually defective subjects that implicate the retina as a site of generation of phosphenes by ELF magnetic fields were performed by Lövsund et al.[24] In a patient with Retinitis pigmentosa, in whom the photoreceptors and pigment epithelium were defective but the bipolar and ganglion cell layers of the retina were conserved, magnetophosphenes could be generated that had prolonged after-images. In a second patient in which both eyes had been removed as the result of severe glaucoma, phosphenes could not be induced by ELF magnetic fields, thereby precluding the possibility that magnetophosphenes can be initiated directly in the visual pathways of the brain.

The Swedish investigators have also extended the comparative studies of magneto- and electrophosphene phenomena that were initiated by Barlow et al.[17] The threshold field intensities required to elicit phosphenes were measured both for electric and magnetic fields over the frequency range 10 - 45 Hz.[23] Because the eddy currents induced by magnetic fields vary as the product of field frequency and peak intensity, the threshold electric field current required to generate phosphenes was divided by the frequency in order to permit a direct comparison with the threshold magnetic field intensity. When this "normalization" procedure was used, the curves of threshold stimuli versus frequency for the generation of phosphenes by ELF electric and magnetic fields were qualitatively similar (Figure 2). With both types of fields, the maximum

sensitivity occurred at a frequency of 20 Hz. However, the threshold intensity versus frequency curve for electrophosphenes did not exhibit the local minimum in sensitivity at 30 Hz observed for magnetophosphenes. This observation suggests that some differences may exist in the retinal current paths involved in the generation of phosphenes by ELF electric and magnetic fields. The differences in sensitivity to magneto- and electrophosphenes that are associated with the state of dark adaptation[17] and the wavelength of light used for background illumination[23] also support this tentative conclusion.

In a recent series of studies on in vitro frog retinal preparations, Lövsund et al.[25] have made intracellular electrical recordings from the ganglion cell layer of the retina immediately following termination of exposure to a 20-Hz, 60-mT field in the presence or absence of broad-spectrum background light. It was found that the average latency time for response of the ganglion cells to a photic stimulus was increased from 87 to 92 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 an ELF magnetic field elicits responses in similar post-synaptic neural pathways.

An important electrophysiological finding by Lövsund et al.[25] was the observation that the electrical response of frog retinal ganglion cells to both photic and ELF magnetic field stimuli was blocked when either sodium aspartate or cobalt chloride was added to the Ringer's solution in the eyecup preparation. These compounds inhibit the transfer of information from the photoreceptors to the neuronal elements of the retina. The electrophysiological observations on chemically-blocked retinal preparations

appear to implicate the photoreceptors per se as the locus of ELF magnetic field stimulation. The origin of magnetic field responses within the receptors is consistent with the hypothesis of Knighton[26] that a transretinal electric current may act to polarize the photoreceptor synaptic membrane, and thereby alter the post-synaptic transmission of electrical information. One experimental observation made by Lövsund et al.[24] which appears to be inconsistent with this hypothesis is the ability of an applied ELF magnetic field to induce phosphenes in a patient with Retinitis pigmentosa, as described previously. The disparity in these observations, however, may be attributable to a small number of functional photoreceptors within the otherwise degenerated retina of the Retinitis patient. In this context, it is of interest to note that Kato et al.[27] found that electrophosphenes could be generated in patients with pigmentary retinal dystrophy, but a substantially larger stimulus intensity was required over the entire frequency range of 7 - 80 Hz than with subjects that had normal vision. Lövsund et al.[25] have also speculated that sensitivity to ELF magnetic fields may exist within both the photoreceptor and the neuronal elements of the retina, but that the former are stimulated with greater ease. In order to identify more clearly the retinal elements stimulated by ELF magnetic fields, it would be advantageous to conduct further studies on the induction of magnetophosphenes in subjects with well-defined pathological alterations of the retina.

4. NERVOUS TISSUE INTERACTIONS AND ANIMAL BEHAVIOR

Several studies have been made of the electrical response of neurons to stimulation with time-varying magnetic fields. As discussed by Bernhardt,[10] the current densities induced by the field must exceed 1 - 10 mA/m^2 in order to have an appreciable effect on nerve bioelectric activity, and a threshold extracellular current density of about 20 mA/m^2 has been found experimentally with Aplysia pacemaker neurons stimulated by an ELF electric field.[28] In a subsequent study with Aplysia,[29] an induced current density of approximately 5 mA/m^2 produced by a 10 mT, 60-Hz sinusoidal field was ineffective in altering the spontaneous neuronal electrical activity. Ueno et al.[30] were also unable to alter the amplitude, conduction velocity or refractory period of evoked action potentials in lobster giant axons by applying ELF magnetic fields with intensities of 1.2 T at 5 - 20 Hz, 0.8 T at 50 Hz, and 0.5 T at 100 Hz. However, using magnetic flux densities in the range of 0.2 - 0.8 T, Kolin et al.[31] were able to stimulate frog nerve-muscle preparations at field frequencies of 60 and 1000 Hz. Öberg[32] and Ueno et al.[33] were also able to stimulate contractions in frog nerve-muscle preparations by using pulsed magnetic fields with pulse durations less than 1 ms. In addition, the excitation of frog sartorius and cardiac muscles[34] and the sciatic nerves of dogs and rabbits[35] has been reported to occur in response to pulsed magnetic fields. From these studies, it appears that sinusoidal ELF magnetic fields with intensities in the range generally used in the laboratory or encountered by humans in occupational settings are insufficient to alter the bioelectric properties of isolated neurons. However, direct magnetic stimulation of nerve and muscle tissues can be achieved by using pulsed fields with a large time rate of change of the magnetic flux density. It should also be borne in mind

that the effects of ELF sinusoidal fields on complex, integrated neuronal networks such as those within the central nervous system may be considerably greater than the effects that occur in single neurons or nerve bundles. This amplification of a field effect could occur through a summation of the small responses evoked in individual neuronal elements.[36] An additive response mechanism may also underlie the production of magnetophosphenes through the stimulation of multiple neuronal elements of the retina by ELF magnetic fields.[37]

Turning next to the subject of potential effects of magnetic fields on behavior, reports from a number of laboratories suggest that the activity patterns and reaction rates of several species of animals are altered by low-intensity fields in the ELF frequency range.[38-49] These reports are summarized in Table 1, which does not include studies in which the behavior of birds and honeybees was found to be altered in the presence of combined ELF electric and magnetic fields.[50-53] Based on the simple theoretical principles discussed earlier in this chapter, the ELF magnetic field intensities used in many of the experiments described in Table 1 would not be expected to induce sufficiently large internal currents to directly influence the nervous system of the various animal species in which positive effects were found. However, in the case of bees and avian species, the observed sensitivity to ELF time-varying fields may originate through a field interaction mechanism similar to that which is believed to underlie the response of these animals to low-intensity static magnetic fields. As discussed in chapter II-4 by R. B. Frankel, deposits of magnetite crystals have been identified in bees and avians,[54,55] and the magnetic force interaction with these ferrimagnetic inclusions may produce autonomic responses. From a theoretical perspective, it is unlikely that a time-varying ELF field could orient or produce significant motion of the

magnetite inclusions, as discussed earlier in this chapter. The time-varying force produced by the field may, however, trigger somatosensory responses. At present there is no convincing evidence to suggest that a similar interaction mechanism exists in mammalian species.

In addition to the relatively large number of positive findings of ELF magnetic field effects on the behavior of mammals including man, several extensive reports[56-64] have appeared during recent years in which no evidence could be found for a behavioral response of mice, monkeys and humans to ELF magnetic fields with intensities in the range 1 - 2 mT. These behavioral studies are also summarized in Table 1. With the exception of the study by Beischer et al.[56] on human reaction time, the field intensities used in these experiments produced intracranial current densities that approached, or were slightly above, the value 1 mA/m^2 which has been predicted on theoretical grounds to be the lower threshold limit for producing a direct effect on the central nervous system.[10] It is interesting to note that among the various positive findings of ELF magnetic field effects on mammalian behavior, only one study with mice[46] used a field frequency and intensity that would be expected to induce internal body currents comparable to those present in the experiments where no field effects were observed. In examining the possible reasons underlying the disparity among experimental results obtained in different laboratories, it is important to assess the potential role of extraneous factors such as mechanical vibration and audible noise that may accompany the activation of magnet coils. The importance of these factors has been elegantly demonstrated by Tucker and Schmitt,[63] who found that perceptive individuals could sense the presence of a 60-Hz magnetic field through auxiliary clues. When these investigators developed an exposure chamber that provided extreme isolation from vibration and audible noise, none of the more than 200

individuals tested could detect 60-Hz fields with intensities of 1.1 mT over the whole body or 2.1 mT over the head region. The sensitivity of behavioral indices to adventitious factors such as changes in barometric pressure has also been discussed by deLorge,[59] who emphasized that the correlation of such variables to positive findings of apparent ELF field effects must be examined.

Another aspect of ELF magnetic field effects that should be considered in the context of behavioral alterations is the recent report of a correlation between the incidence of suicides and the intensity of residential 50-Hz magnetic fields from power-line sources.[65] Based on coroner and police records from various urban and rural regions within a 5000 km^2 area in the Midlands of England, a statistically significant increase in suicide rate was found among individuals that lived in residences where the 50-Hz field intensity exceeded 0.15 μT at the front entrance. A subsequent statistical analysis of the same data indicated that the cumulative probability ratio for the incidence of suicide increased above the null effect level of unity for residential 50-Hz magnetic field intensities exceeding 15 nT.[66] However, oscillations occurred in the cumulative probability ratio as a function of increasing magnetic field intensity, and at 0.2 μT the ratio for the "urban" study group was consistent with the absence of any 50-Hz magnetic field effect. From an epidemiological perspective, the lack of a clear-cut dependence of the suicide incidence on magnetic field intensity suggests that the apparent correlation between these variables may be purely fortuitous. An extension of the studies initiated by Perry et al.[65] using a significantly larger population of individuals will be required before any firm judgment can be made regarding the proposed correlation between suicide incidence and ELF magnetic field exposure.

5. ELF MAGNETIC FIELDS AND CANCER

Nine reports have appeared in the literature during the past 5 years which suggest from epidemiological evidence that a link may exist between residential and occupational exposure to ELF magnetic fields and the incidence of cancer. The first of these reports was by Wertheimer and Leeper,[67] who found that cancer deaths (primarily leukemia) in children less than 19 years of age in the Denver, Colorado area was correlated with the presence of high-current primary and secondary wiring configurations in the vicinity of their residences. This retrospective epidemiological study was based on 344 fatal childhood cancer cases during the period 1950-1973, and an equal number of age-matched controls chosen from birth records. The electrical power lines near the birth and death residences of the cancer cases and the residences of the controls were inspected and classified as being either high-current configurations (HCC) or low-current configurations (LCC), which were assumed to reflect the local intensity of the 60-Hz magnetic field within the homes of the subjects. The percentage of the cancer cases whose birth and death residences were near HCC was found to be significantly greater than for the residences of the control subjects, from which Wertheimer and Leeper concluded that an association may exist between the strength of magnetic fields from the residential power distribution lines and the frequency of childhood cancer. In a subsequent publication, these authors reported that a similar association exists for the incidence of adult cancer.[68] This later study was based on 1179 cancer cases (78% fatal cancers) in Denver, Boulder and Longmont, Colorado during the period 1967-1977.

Following the initial report of Wertheimer and Leeper on childhood cancer, two other epidemiological studies have been made to determine whether a

relationship exists between residential magnetic fields from power-line sources and the incidence of leukemia in children. In the first of these studies, Fulton et al.[69] used methodology that was matched as closely as possible to that of Wertheimer and Leeper's study, including the designation of HCC and LCC power lines. This study involved 119 leukemia patients with ages of onset from 0 - 20 years, whose address histories were obtained from medical records at Rhode Island Hospital, and 240 control subjects chosen from Rhode Island birth certificates. In their study, Fulton et al.[69] concluded that no statistically significant correlation existed between the incidence of leukemia and the residential power-lines configurations. Wertheimer and Leeper[70] were critical of the study by Fulton et al.[69] on the basis that the control and case groups had not been matched for interstate migration, for years of occupancy of residences, or for the ages of the children at the time their residential addresses were determined from birth records and hospital medical records. In a subsequent analysis of the data obtained by Fulton et al.[69] Wertheimer and Leeper[70] excluded cases and controls aged eight and above in order to define a complete residential history for the remaining subjects (53 cases and 71 controls). In this subset of the total population studied by Fulton and his associates, Wertheimer and Leeper found a weakly significant correlation ($p \sim 0.05$) between the incidence of leukemia and residential HCC wiring configurations.

Another study of childhood leukemia incidence was conducted in the County of Stockholm by Tomenius et al.,[71] who analyzed the residential 50-Hz magnetic fields for 716 cases that had a stable address from the time of birth to the time of leukemia diagnosis, and for 716 controls that were matched for age, sex and birth location. These investigators evaluated the electrical wiring configurations near the residences of the study population, and also made

measurements at the entrance door to each residence of the magnetic field intensity in the frequency range above 30 Hz. Among the residences where a magnetic field intensity exceeding 0.3 μT was recorded, the incidence of leukemia was greater by a statistically significant amount than the expected level. From the data presented by Tomenius et al.,[71] it is interesting to note that a statistically significant increase in the incidence of leukemia was not evident for the study population living in residences where the magnetic field intensity exceeded 0.4 μT. In addition, the arithmetic mean of the magnetic field intensity for the residences of all the leukemia cases did not exceed the mean value for the residences of the control group.

During 1982 and 1983, a total of four brief epidemiological reports were published in the format of letters to journal editors, all of which showed an apparent association between the incidence of adult leukemia and occupational exposure to ELF electric and magnetic fields. The following is a brief summary of these four reports. (1) Milham[72] analyzed 438,000 deaths among adult males in Washington State during the period 1950-1979, and encoded the data into 158 cause-of-death groups in each of 218 occupational classes. In 10 out of 11 occupations in which the exposure to electric and magnetic fields was assumed to be greater than average, the proportionate mortality ratio for leukemia was found to be elevated. The increase in leukemia mortality was significant at the level $p < 0.01$ for electricians, power-station operators and aluminum workers. It is interesting to note that the highest magnetic field intensities to which the aluminum workers are exposed originate from DC electric current sources,[73] rather than from power-frequency sources. (2) Wright et al.[74] used the Cancer Surveillance Program registry for Los Angeles County during the years 1972-1979 to study the proportional incidence ratios for all leukemias, acute leukemias and acute myelogenous leukemia among white males in 10

occupations that involved exposure to ELF electric and magnetic fields. At the significance level $p < 0.05$, a higher than average incidence of acute leukemia was found among power linemen, and of acute myelogenous leukemia among power linemen and telephone linemen. In the pooled data for all 10 job classifications, the overall proportional incidence ratios for acute leukemia and acute myelogenous leukemia were significant at the level $p < 0.05$. (3) McDowall[75] analyzed the incidence of leukemia using occupational mortality data for males with ages of 15 and above that were collected in England and Wales during the period 1970-1973. For 10 electrical occupations the overall incidence of leukemia was not greater than expected at a statistically significant level. However, a trend towards increased risk was noted in the data, and the relative risk of contracting acute myelogenous leukemia for the various electrical occupations that were studied was 1.6 - 4.0 in comparison with a randomly-selected control population. (4) Coleman et al.[76] analyzed the incidence of leukemia in South-East England among men aged 15 - 74 working in the same 10 electrical occupations that were studied by McDowall.[75] In the study by Coleman et al.[76] the South Thames Cancer Registry, which encompasses a total population of 6.5 million, was used to determine the proportional registration ratio for leukemia during the period 1961-1979. For all 10 electrical occupations taken together, there was a 17% excess of all types of leukemias above the expected level, which was significant at the $p < 0.05$ level. Two occupations for which the incidence of all leukemias was significantly above the expected level were electrical/electronic fitters and telegraph/radio operators, for which the excess incidence was 84% and 146%, respectively.

Two other studies have recently been published on the incidence of leukemia among electrical and telecommunications workers, in both of which the Swedish Cancer-Environment Registry for the period 1961-1977 was used as an

epidemiological data base. In the first study by Wiklund et al.,[77] no increased risk was observed for telecommunications workers compared with the Swedish population as a whole. The second study by Vågerö and Olin[78] reported a slightly higher total incidence of cancer among male and female workers in electrical manufacturing industries as compared to the general population.

Overall, 9 or the 11 recent epidemiological studies that have sought to find an association between cancer incidence and residential or occupational exposure to ELF fields from electric power sources have obtained positive results. As pointed out by Liburdy,[79] a number of other studies on humans and laboratory animals have not found an association between exposure to electromagnetic fields and carcinogenesis. In assessing the literature in which positive correlations have been found, the following methodological deficiencies should be noted: (1) The sample populations in many of the epidemiological studies were small, and an increase in cancer incidence by a factor of 2 or less might be expected on the basis of chance alone. In these studies, it would have been informative if the authors had presented data on several non-exposed occupational groups in which the sample size was comparable to that of the exposed groups. (2) 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, socioeconomic class, or urban/rural residential status. (3) In all of the studies thus far reported, the magnetic field dosimetry was at best qualitative. In studies of residential ELF magnetic fields, the neglect of local fields from appliances may have lead to incorrect conclusions concerning the peak and average exposure of individuals to power-frequency fields and the higher harmonics that emanate from electrical devices used within the home.[80] (4) Concomitant environmental factors of known carcinogenic potential (e.g., aryl

hydrocarbons) were ignored in all of the epidemiological studies that have attempted to relate ELF fields and cancer incidence.

In view of the numerous deficiencies in the epidemiological studies conducted to date, it is not possible at this point in time to conclude that a definite association exists between the exposure of individuals to ELF magnetic (or electric) fields and their relative risk of contracting leukemia or other forms of cancer. In addition, the field levels to which humans are generally exposed are sufficiently low that it is difficult to conceive plausible mechanisms that might underlie a causal relationship between cancer incidence and ELF magnetic field exposure. To put this issue into clearer perspective, it is instructive to consider the internal potentials and currents induced in humans as the result of motion through the earth's magnetic field. A straightforward calculation based on Faraday's law indicates that the motion of a human bending forward at the waist within the geomagnetic field will induce instantaneous internal currents comparable to those produced by exposure to an external 60-Hz sinusoidal field with an intensity of approximately 0.1 - 0.2 μT. This magnetic field intensity is comparable to the ambient power-frequency fields in many residences and occupational settings. Such considerations indicate the clear need for careful dosimetry in any attempt to detect a relationship between power-frequency magnetic fields and cancer. The conduct of prospective epidemiological studies with carefully matched control groups would also be of great value in assessing the validity of conclusions drawn from many of the retrospective studies that have been carried out during the past few years.

6. SUMMARY OF CELLULAR AND TISSUE INTERACTIONS

During the past two decades, a large number of reports have appeared in the literature that describe the effects of time-varying ELF magnetic fields on a variety of cellular and tissue systems. Many of these reports are summarized in Table 2, in which the literature citations have been ordered chronologically. Publications in which the magnetic field parameters and/or the exposure conditions were not described have been excluded from the table. In addition, reports of research that involved combined exposures to ELF electric and magnetic fields have not been included (e.g., refs. 3, 112, 113) because of the obvious difficulty in delineating the relative effects of the two types of fields.

Despite the large number of test specimens that have been examined for sensitivity to ELF magnetic fields, it is difficult at present to draw firm conclusions concerning the bioeffects of these fields at the cellular and tissue levels as a result of several factors: (1) A wide range of intensities, frequencies, waveforms, and exposure durations have been used. Many of the earlier studies utilized sinusoidal fields oscillating at 15-75 Hz, but research during the last few years has focused increasingly on the bioeffects of square-wave or pulsed fields with complex waveforms. Among the studies conducted with purely sinusoidal fields, the field intensities have ranged from approximately 1 μT to 0.1 T, and the exposure durations have varied from 10 min to 1-4 weeks of either continuous or intermittent exposures. (2) Although the vast majority of the published literature describes positive bioeffects of time-varying ELF magnetic fields, none of the findings listed in Table 2 have been verified by means of independent replication in other laboratories. (3) A number of apparent inconsistencies can be found in the comparison of data

acquired on similar (but not identical) test specimens. For example, exposure to a low-intensity ELF magnetic field was reported to produce an elevation in the serum triglyceride levels of human subjects,[56] but comparable effects were not observed in monkeys.[59]

Irrespective of the inadequacies in the existing database, a survey of the extant literature indicates that several aspects of the biochemistry and physiology of cells and organized tissues may be perturbed by exposure to time-varying ELF magnetic fields. Briefly summarized, the reported bioeffects for which there is a growing body of evidence include: (1) decreased rate of cellular respiration;[91,93,94] (2) altered metabolism of carbohydrates, proteins and nucleic acids;[88,94,106,110,111] (3) endocrine changes and altered hormonal responses of cells and tissues;[82,83,85,98,104,107] (4) decreased cellular growth rate;[89,91-93,96,97] (5) teratology and developmental effects;[100,101,108,109] (6) morphological tissue changes in adult animals, frequently reversible with time after exposure;[84,99,102] and (7) altered immune response to various antigens and lectins.[81,86,105] It is also interesting to note that no consistent field-associated alterations have been observed in the hematological system,[56,59,95,103] which is known to be sensitive to ionizing radiation and high-intensity microwave fields.

With regard to the interaction mechanisms that may underlie the reported cellular and tissue effects of time-varying ELF magnetic fields, an interpretive difficulty is once again posed by the large variety of waveforms, intensities and frequencies that have been used by different investigators. In studies on the effects of pulsed magnetic fields with time rates of change from 5-100 T/s,[104,106,107] the peak induced electric field and current density in the medium were greater than 100 mV/m and 10 mA/m^2, respectively. The induced currents exceed the endogenous electrical currents that are normally present in

extracellular fluids in vivo. It has been suggested that the currents induced by pulsed magnetic fields may exert an electrochemical effect at the cell surface which, in turn, influences the membrane transport and intracellular concentration of calcium ions.[104,107] Because of the important role played by calcium ions in metabolism and growth regulation, this proposal deserves careful consideration in the context of ELF magnetic field effects at the cellular and tissue levels.

In several studies that used repetitive square waveforms with frequencies in the ELF range,[100,101,105,108-110] a high time rate of change of the magnetic flux density may have been present during the rising portion of the square wave. Unfortunately, the time constants associated with the square wave pulses were usually not stated by the authors of these reports, and it is therefore difficult to estimate the peak fields and currents that were induced in their experimental specimens. One exception is the report by Ubeda et al.[109] on embryological changes in chick eggs exposed to 0.5-ms bidirectional pulses repeated with a 100 Hz frequency. Four different waveforms with pulse rise times of 2, 42 and 100 μs and pulse amplitudes ranging from 0.4 - 104 μT were used in this study. Although not all combinations of pulse rise times and amplitudes were used, the teratogenic effects observed in chick embryos appeared to be relatively insensitive to the peak value of dB/dt that occurred during the rising portion of the pulse. Unfortunately, the authors used only the lowest pulse amplitude in combination with the shortest pulse rise time, and the maximum value of dB/dt that was achieved with any combination of amplitude and rise time was 1 T/s. This value is small in comparison with the maximum value of 52 T/s that could have been achieved by using a 2 μs rise time in combination with a 104 μT pulse amplitude.

Several investigations with ELF sinusoidal fields have involved the

exposure of rodents to 50 and 60 Hz fields with intensities in the range 0.02 - 0.16 T.[81,84-86,88,90,95,98,99] The maximum current densities induced in the experimental subjects ranged from approximately 1 - 20 mA/m^2 in these studies, which may be sufficient to perturb certain biological functions as discussed above. However, many of the other studies on ELF sinusoidal fields that are summarized in Table 2 were conducted with low field intensities that induced current densities substantially less than 1 mA/m^2 in the test specimens. In these studies, it is possible that the observed biological effects may have resulted from interaction mechanisms other than the induction of electrical currents in accord with Faraday's law. This possibility was recently suggested by Liboff et al.[111] on the basis of measurements of DNA synthesis in human fibroblasts exposed to sinusoidal magnetic fields with low intensities in the range 2.3 - 560 μT. An enhanced DNA synthesis rate was observed for field frequencies ranging from 15 Hz to 4 kHz, and this effect was independent of the current density induced in the cell cultures. The lack of dependence on the time rate of change of the field (and hence the induced current density) was tested for values of dB/dt (= $2\pi f|B_0|$) that ranged from approximately 1.8 x 10^{-4} T/s to 1.8 T/s. As a possible explanation of the observations made by Liboff et al.,[111] Polk[114] has recently suggested an interaction mechanism in which the Lorentz force exerted on moving counterions produces motion and a resulting electric current that is independent of the field frequency. This interaction, which relies upon the preexistence of coherent motion within a surface-bound counterion atmosphere, could produce local currents that are several orders of magnitude larger than the Faraday currents induced on the cell surface by the time-varying magnetic fields used in the experiments of Liboff et al.[111]

7. MEDICAL AND DIAGNOSTIC APPLICATIONS OF ELF MAGNETIC FIELDS

Magnetic fields have been used medically in several types of diagnostic and therapeutic procedures, and some relatively new techniques such as magnetoencephalography have considerable potential for future medical applications. In this section, a brief description is given of electromagnetic blood flow measurements, the use of pulsed magnetic fields for the facilitation of bone fracture reunion, and the measurement of endogenous magnetic fields as indicators of various biological functions. A large number of publications has appeared on each of these topics, and an effort will not be made here to provide an extensive review. Each of the techniques will be briefly described, citing only a limited number of relevant publications.

Electromagnetic Blood Flow Measurements

As a result of magnetic induction, a conductive fluid such as blood will develop a transverse electrical potential when flowing in the presence of a magnetic field. It can be shown from simple physical principles that the magnitude of the induced potential, V_i, for axisymmetric blood flow in a cylindrical vessel is given by:[115,116]

$$V_i = |\vec{u}||\vec{B}|\, d \sin\theta \qquad (5)$$

where $\vec{u}$ = mean axial flow velocity, d = vessel diameter, $\vec{B}$ = magnetic flux density (static or time-varying), and θ = angle between $\vec{u}$ and $\vec{B}$. The magnetically-induced potential described by eqn. (5) was first used by Kolin as the basis of a method for measuring blood flow rate without opening a vessel or introducing foreign substances such as dyes into the circulation.[115,117] The original electromagnetic flowmeter developed by Kolin employed a static

magnetic field, which was later replaced by a 60-Hz field in order to avoid artifacts associated with polarization of the electrodes used to measure the induced potential. Present models of the blood flowmeter are constructed with small cuffs that fit closely around the blood vessel perimeter, and contain both the magnet coil and the pick-up electrodes. The use of flowmeters with either perivascular or intravascular transducers has become over the years a widely accepted clinical method for monitoring blood flow during surgical procedures.[118] This technique can be used for measuring the rate of blood flow in major vessels such as the portal vein[119] and the coronary artery[120] with a precision of 1 - 2% over a period of several hours. Other useful applications of the flowmeter principle include the measurement of microscopic variations in vascular diameter[121] and the determination of blood flow through large segments of an organ such as the pancreas.[122]

Several studies with experimental animals have also demonstrated the feasibility of exposing the whole body, or a large segment of the body such as the chest, to an external uniform magnetic field in order to measure blood flow rates in major vessels of the circulatory system.[123] This procedure is noninvasive insofar as the conventional surface leads used to measure the electrocardiogram can also detect the major blood flow potentials that are induced by an external magnetic field. The applied field can be either static or time-varying, although the former is technically simpler to use in this application. The measurement with surface electrodes of magnetically-induced potentials associated with pulsatile blood flow into the aorta has been demonstrated for several species of animals, including monkeys,[124-126] baboons,[127] rabbits[128] and rats.[129] A possible future medical application of this technique is the noninvasive measurement of blood flows within the atrial and ventricular chambers of the heart following the opening and closing of the

mitral and tricuspid valves.

Facilitation of Bone Fracture Reunion by ELF Pulsed Magnetic Fields

The use of direct current electrical stimulation to treat bone nonunions and pseudoarthroses dates back to the early part of the nineteenth century. As described by Bassett,[130] several investigators during the nineteenth century and the first half of the twentieth century reported success in the treatment of bone fractures by electrotherapy. Heightened interest in this area arose during the 1950's and 1960's as the result of several demonstrations of the piezoelectric properties of bone.[131,132]

Although some measure of success was achieved in treating bone nonunions by electrical stimulation, the use of direct currents led to several undesirable side effects, including (1) surgical trauma and a risk of infection through the implantation of electrodes in bone; (2) the development of electrode polarization with time, which led to increased impedance and decreased current for a given applied voltage; (3) osteogenesis was found to be increased near the negative (cathodic) pole, but decreased near the positive (anodic) pole. These disadvantages of direct current electrical stimulation were overcome by the recent introduction of pulsed magnetic field generators as a means of inducing ELF electrical currents into bone tissue.[133] By using magnetic coils placed about a limb containing a fractured bone, electric fields with a typical strength of 0.2 - 2.0 V/m can be induced within the bone tissue. In the usual configuration, two coils are placed about the limb and positioned such that the bone fracture lies along a line joining the centers of the coils, and hence along the magnetic field lines. Assuming the conductivity of bone to be 0.01 S/m at ELF frequencies,[134] the local current densities induced in bone by the pulsed magnetic field can be estimated to lie in the range of

approximately 2 - 20 mA/m^2. Initial studies on bone fracture reunion in dogs demonstrated that a pulse repetition frequency of 65 Hz was more effective than 1 Hz,[133] and several subsequent studies have found that frequencies of 60 - 75 Hz are the most advantageous in facilitating fracture union and preventing pseudoarthroses.[130]

Following the initial demonstration of the efficacy of pulsed magnetic fields in achieving bone fracture reunion in experimental animals, several clinical trials have reported success in treating bone fractures and arthroses in humans by this method. In a 4-year clinical trial involving more than 100 patients, Bassett et al.[135] reported an 85% success rate in the treatment of long-established pseudoarthroses. The successful use of pulsed magnetic fields in the facilitation of bone healing in human subjects has subsequently been reported by several clinical groups.[136-139] The importance of continuing these clinical trials, including the use of dummy stimulators in control subjects, has been emphasized by Barker and Lunt.[140] In this context, the recent development of a light-weight portable magnetic field stimulator by Watson and Downes[141] may prove very beneficial in facilitating the long-term treatment of patients with bone fractures.

The mechanism by which the weak ELF electric currents induced in bone tissue by pulsed magnetic fields exert an influence on fracture repair is under investigation in a number of laboratories. Evidence from in vitro studies on osteoblasts and chondrocytes indicate that the pulsed fields depress the intracellular concentrations of calcium ions and cyclic AMP.[104,130] These effects, in turn, can significantly influence cellular metabolism and stimulate growth. Studies by Hinsenkamp and Rooze[142] with in vitro cultures of limbs from mouse fetuses have demonstrated that electromagnetic stimulation leads to chondrocyte proliferation and an improved alignment of trabeculae and

cartilage. Archer and Ratcliffe[110] recently demonstrated that cultured tibiae from chicken embryos exhibit a reduced collagen content following exposure to a pulsed magnetic field for 7 days. The interesting observation was also made in this study that the total synthesis of sulfated glycosoaminoglycans, which are major components of the extracellular matrix, was not affected by exposure to the pulsed magnetic field. The further elucidation of the macromolecular and developmental changes that accompany the stimulation of bone tissue by pulsed ELF magnetic fields remains a challenging area of research, which will ultimately lend useful insight into the mechanisms by which weak ELF fields interact with living cells.

Another aspect of pulsed magnetic field interactions that should be noted is their apparent stimulatory effect on certain nonosseous tissues. It has been reported, for example, that electromagnetic stimulation facilitates ligament healing in rabbits,[143] and promotes the regeneration of peripheral nerves and the spinal cord following injury.[144-146] One final aspect of the clinical use of pulsed ELF magnetic fields that deserves mention is the concern that has been expressed regarding the potential tumorigenic risk arising from the growth stimulatory effects of these fields.[134,147] This issue has not been fully resolved, but it has been reported that increased tumor incidence did not result from the continuous exposure of rats during 94 weeks of adult life to a 5 Hz pulsed field with a 5 ns rise time produced by a 447 kV/m electric field generator.[148] This field exposure was also found not to produce untoward effects on the hematological system, fertility, or reproductive capacity.

Magnetic Fields of Biological Origin and Their Potential Use in Medical Diagnosis

Circulating electric currents from excitable tissues produce small

magnetic fields in the ELF frequency range that can be measured externally. Two studies in the early 1960's using multiturn loops of copper wire as pick-up coils first demonstrated that the magnetic field produced by a nerve impulse could be detected.[149,150] In 1963 Baule and McFee[151] extended this work to show that the peak magnetic fields associated with cardiac bioelectric activity could be detected by coils at the body surface. Cohen[152] subsequently made similar measurements in a magnetically shielded room that substantially reduced the background fields and allowed a clear recording of the magnetocardiogram (MCG). By using signal averaging techniques, Cohen[153] was also able to detect the alpha rhythm in the magnetoencephalogram (MEG) with a coil detector in the magnetically shielded room. However, the peak magnetic field of the brain measured at the body surface[154] (~ 3 pT) is substantially lower than the peak field of the heart[154] (~ 100 pT), and a direct measurement of the MEG was not possible with a coil detector. In the early 1970's, this limitation was overcome by the development of the superconducting quantum interference device (SQUID), which is capable of measuring extraordinarily small magnetic fields.[155] By using this device in a magnetically shielded room, Cohen[156] was able to make the first direct measurement of the MEG without signal averaging. During the past decade, the SQUID technique has been further developed and used in combination with first-order and second-order gradiometer configurations of the detection coils. The use of a gradiometer coil configuration provides a substantial reduction in the level of interference from ambient magnetic noise. These external fields have a nearly uniform intensity over dimensions comparable to the human body, while the fields originating within the body are highly nonuniform over the same spatial dimensions. The SQUID gradiometer technique now provides a field detection sensitivity of approximately 5 - 10 $fT/Hz^{1/2}$ for static and ELF time-varying fields.[157]

The development of SQUID instrumentation for the measurement of biomagnetic fields has led to a rapid expansion of research in this area, as reviewed by Williamson and Kaufman.[158] A comprehensive monograph that discusses all of the major aspects of biomagnetism was published in 1982.[159] Four organs that have been a focus of biomagnetic research efforts are the heart, brain, lung and liver. Various abnormal cardiac conditions such as arteriovenous block, myocardial infarction, and coronary artery disease have been analyzed from the MCG,[160-162] although it is not clear as yet that this technique provides unique information relative to the electrocardiogram. Studies of the MEG have received increased interest during the past decade, primarily because the MEG appears to give a more precise localization of current sources within the brain than is provided by the electroencephalogram (EEG).[163,164] The MEG and EEG also provide complementary information because of the orthogonal configuration of the electric and magnetic field vectors arising from the same current source.[165-167] Both the spatial and temporal features of visually and somatically evoked responses in the brain have been shown in several studies to be well characterized by the MEG.[168-172]

An application of biomagnetic measurements that appears to be particularly promising from a clinical viewpoint is the detection of ferromagnetic materials within the lung and other organs. Cohen[173] has demonstrated that the accumulation of small quantities of asbestos within the lung can be detected magnetically as a result of the adsorbed magnetite carried by asbestos particles. A SQUID magnetometer has also been used to detect an abnormally large quantity of iron within the liver in patients with Thalassemia major.[174] Although the total number of clinical applications up to the present time has been relatively small, the initial results have indicated the potential of biomagnetic measurements as a noninvasive tool for studying both normal and

pathological conditions of various organs.

8. GENERAL SUMMARY AND CONCLUSIONS

It is evident from the literature survey presented in this chapter that a wide variety of effects of time-varying ELF magnetic fields have been observed in cellular, tissue and animal systems. Several of these effects have been well established through careful research in different laboratories. Notable examples are the experimental studies on magnetophosphenes, the induction of blood flow potentials and the facilitation of bone fracture reunion. However, in many instances the reports of ELF magnetic field bioeffects must be viewed with caution, either because of a lack of independent verification of the experimental findings, or because the reported field effects may have resulted from the presence of confounding variables. Examples of ELF magnetic field effects where such considerations are clearly relevant are the findings of behavioral alterations in laboratory animals and the association between human cancer incidence and exposure to power-frequency fields. These reported effects, as well as many findings of ELF magnetic field effects in cellular and tissue systems, also present a difficult interpretive problem because the field intensities involved are so low that no plausible mechanism can be proposed at the present time to explain the observed effects. From this perspective there is a clear need for substantially more research of both a theoretical and an experimental nature to define in an unambiguous manner the interactions that occur between ELF magnetic fields and living organisms.

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REFERENCES

1. Grandolfo, M. and Vecchia, P., Natural and man-made environmental exposures to static and ELF electromagnetic fields, in Biological Effects and Dosimetry of Non-ionizing Radiation: Static and ELF Electromagnetic Fields, Grandolfo, M., Michaelson, S. M., and Rindi, A., Eds., Plenum, New York, 1984, in press.

2. Scott-Walton, B., Clark, K. M., Holt, B. R., Jones, D. C., Kaplan, S. D., Krebs, J. S., Polson, P., Shepherd, R. A., and Young, J. R., Potential Environmental Effects of 765-kV Transmission Lines: Views Before the New York State Public Service Commission, Cases 26529 and 26559, 1976-1978, NTIS Rep. No. DOE/EV-0056, Springfield, Virginia, 1979, II-7.

3. Grissett, J. D., Biological effects of electric and magnetic fields associated with ELF communications systems, Proc. IEEE, 68, 98, 1980.

4. Stuchly, M. A., Lecuyer, D. W., and Mann, R. D., Extremely low frequency electromagnetic emissions from video display terminals and other devices, Health Physics, 45, 713, 1983.

5. Lövsund, P., Öberg, P. Å., and Nilsson, S. E. G., ELF magnetic fields in electrosteel and welding industries, Radio Science 17 (5S), 35S, 1982.

6. Sheppard, A. R. and Eisenbud, M., Biologic Effects of Electric and Magnetic Fields of Extremely Low Frequency, New York University Press, New York, 1977.

7. Tenforde, T. S., Ed., Magnetic Field Effects on Biological Systems, Plenum, New York, 1979.

8. Adey, W. R., Some fundamental aspects of biological effects of extremely low frequency (ELF), in Biological Effects and Dosimetry of Nonionizing Radiation, Grandolfo, M., Michaelson, S. M., and Rindi, A., Eds., Plenum, New York, 1983, 561.

9. Budinger, T. F., Nuclear magnetic resonance (NMR) in vivo studies: known thresholds for health effects, J. Comp. Assist. Tomogr., 5, 800, 1981.

10. Bernhardt, J., The direct influence of electromagnetic fields on nerve and muscle cells of man within the frequency range of 1 Hz to 30 MHz, Radiat. Environ. Biophys., 16, 309, 1979.

11. Schwan, H. P. and Kay, C. F., Specific resistance of body tissues, Circ. Res., 4, 644, 1956.

12. Hong, F. T., Mauzerall, D., and Mauro, A., Magnetic anisotropy and the orientation of retinal rods in a homogeneous magnetic field, Proc. Natl. Acad. Sci (USA), 68, 1283, 1971.

13. d'Arsonval, M. A., Dispositifs pour la mesure des courants alternatifs à toutes frequences, C. R. Soc. Biol. (Paris), 3 (100 Ser.), 451, 1896.

14. Thompson, S. P., A physiological effect of an alternating magnetic field, Proc. Roy. Soc. Lond. (Ser. B), 82, 396, 1909-1910.

15. Dunlap, K., Visual sensations from the alternating magnetic field, Science, 33, 68, 1911.

16. Magnusson, C. E. and Stevens, H. C., Visual sensations caused by changes in the strength of a magnetic field, Am. J. Physiol., 29, 124, 1911-1912.

17. Barlow, H. B., Kohn, H. I., and Walsh, E. G., Visual sensations aroused by magnetic fields, Am. J. Physiol., 148, 372, 1947.

18. Barlow, H. B., Kohn, H. I., and Walsh, E. G., The effect of dark adaptation and of light upon the electric threshold of the human eye, Am. J. Physiol., 148, 376, 1947.

19. Seidel, D., Knoll, M., and Eichmeier, J., Anregung von subjektiven Lichterscheinungen (Phosphenen) beim Menschen durch magnetische Sinusfelder, Pflüg. Arch., 299, 11, 1968.

20. Oster, G., Phosphenes, Sci. Am., Feb., 1970, 83.

21. Lövsund, P., Öberg, P. Å., and Nilsson, S. E. G., Influence on vision of extremely low frequency electromagnetic fields, Acta Ophth., 57, 812, 1979.

22. Lövsund, P., Öberg, P. Å., and Nilsson, S. E. G., A method for the study of retinal ganglion cell activity induced by ELF magnetic fields, Radio Science, 14(6S), 125, 1979.

23. Lövsund, P., Öberg, P. Å., and Nilsson, S. E. G., Magneto- and electrophosphenes: a comparative study, Med. Biol. Engin. Comput., 18, 758, 1980.

24. Lövsund, P., Öberg, P. Å., Nilsson, S. E. G., and Reuter, T., Magnetophosphenes: a quantitative analysis of thresholds, Med. Biol. Engin. Comput., 18, 326, 1980.

25. Lövsund, P., Nilsson, S. E. G., and Öberg, P. Å., Influence on frog retina of alternating magnetic fields with special reference to ganglion cell activity, Med. Biol. Engin. Comput., 19, 679, 1981.

26. Knighton, R. W., An electrically evoked slow potential of the frog's retina: I. Properties of response, J. Neurophysiol., 38, 185, 1975.

27. Kato, S., Saito, M., and Tanino, T., Response of the visual system evoked by an alternating current, Med. Biol. Engin. Comput., 21, 47, 1983.

28. Wachtel, H., Firing pattern changes and transmembrane current produced by extremely low frequency fields in pacemaker neurons, in Biological Effects of Extremely Low Frequency Electromagnetic Fields, Phillips, R. D., Gillis, M. F., Kaune, W. T., and Mahlum, D. D., Eds., NTIS Rep. No. CONF-781016, Springfield, Virginia, 1979, 132.

29. Sheppard, A. R., Results of exposure of Aplysia pacemaker neurons to ELF/60 Hz and DC magnetic fields, presented at 5th Ann. Meeting Bioelectromagnetics Society, Boulder, June 12-16, 1983, 25.

30. Ueno, S., Lövsund, P., and Öberg, P. Å., On the effect of alternating magnetic fields on action potential in lobster giant axon, Proc. 5th Nordic Meeting on Med. Biol. Engin., Linkoping, Sweden, 1981, 262.

31. Kolin, A., Brill, N. Q., and Bromberg, P. J., Stimulation of irritable tissues by means of an alternating magnetic field, Proc. Soc. Exp. Biol. Med. (N.Y.), 102, 251, 1959.

32. Öberg, P. Å., Magnetic stimulation of nerve tissue, Med. Biol. Engin., 11, 55, 1973.

33. Ueno, S., Matsumoto, S., Harada, K., and Oomura, Y., Capacitive stimulatory effect in magnetic stimulation of nerve tissue, IEEE Trans. Mag., MAG-14, 958, 1978.

34. Irwin, D. D., Rush, S., Evering, R., Lepeschkin, E., Montgomery, D. B., and Weggel, R. J., Stimulation of cardiac muscle by a time-varying magnetic field, IEEE Trans. Mag., MAG-6, 321, 1970.

35. Maass, J. A. and Asa, M. M., Contactless nerve stimulation and signal detection by inductive transducer, IEEE Trans. Mag., MAG-6, 322, 1970.

36. Valentinuzzi, M., Notes of magnetic actions upon the nervous system, Bull. Math. Biophys., 27, 203, 1965.

37. Valentinuzzi, M., Theory of magnetophosphenes, Am. J. Med. Electr., 1, 112, 1962.

38. Friedman, H., Becker, R. O., and Bachman, C. H., Effect of magnetic fields on reaction time performance, Nature, 213, 949, 1967.

39. Caldwell, W. E. and Russo, F., An exploratory study of the effects of an A.C. magnetic field upon the behavior of the Italian honeybee (Apis mellifica), J. Genet. Psych., 113, 233, 1968.

40. Persinger, M. A., Open-field behavior in rats exposed prenatally to a low intensity-low frequency, rotating magnetic field, Develop. Psychobiol., 2, 168, 1969.

41. Persinger, M. A. and Foster, W. S. IV, ELF rotating magnetic fields: prenatal exposure and adult behavior, Arch. Met. Geoph. Biokl. (Ser. B), 18, 363, 1970.

42. Persinger, M. A. and Pear, J. J., Prenatal exposure to an ELF-rotating magnetic field and subsequent increase in conditioned suppression, Develop. Psychobiol., 5, 269, 1972.

43. Persinger, M. A., Ossenkopp, K.-P., and Glavin, G. B., Behavioral changes in adult rats exposed to ELF magnetic fields, Int. J. Biometeor., 16, 155, 1972.

44. Ossenkopp, K.-P. and Shapiro, J., Effects of prenatal exposure to a 0.5-Hz low-intensity rotating magnetic field on White Peking ducklings, Am. Zool., 12, 650, 1972.

45. Medvedev, M. A., Urazaev, A. M., and Kulakov, I. U. A., Effect of a constant and low frequency magnetic field on the behavioral and autonomic responses of the human operator, Zh. Vyssh. Nerv. Deiat., 26, 1131, 1976.

46. Smith, R. F. and Justesen, D. R., Effects of a 60-Hz magnetic field on activity levels of mice, Radio Science, 12(6S), 279, 1977.

47. Brown, F. A. Jr. and Scow, K. M., Magnetic induction of a circadian cycle in hamsters, J. Interdiscipl. Cycle Res., 9, 137, 1978.

48. Clarke, R. L. and Justesen, D. R., Behavioral sensitivity of a domestic bird to 60-Hz ac and to dc magnetic fields, Radio Science, 14(6S), 209, 1979.

49. Delgado, J. M. R., Monteagudo, J. L., and Ramiriz, E., Non-invasive magnetic stimulation of the monkey cerebellum, presented at 5th Ann. Meeting Bioelectromagnetics Society, Boulder, June 12-16, 1983, 103.

50. Southern, W. E., Orientation of gull chicks exposed to Project Sanguine's electromagnetic field, Science, 189, 143, 1975.

51. Larkin, R. P. and Sutherland, P. J., Migrating birds respond to Project Seafarer's electromagnetic field, Science, 195, 777, 1977.

52. Greenberg, B., Effects of 60-Hz electromagnetic fields on bees and soil arthropods, in Magnetic Field Effects on Biological Systems, Tenforde, T. S., Ed., Plenum, New York, 1979, 21.

53. Greenberg, B., Bindokas, V. P., Frazier, M. J., and Gauger, J. R., Response of honey bees, Apis mellifera L., to high-voltage transmission lines, Environ. Entomol., 10, 600, 1981.

54. Gould, J. L., Kirschvink, J. L. and Deffeyes, K. S., Bees have magnetic remanence, Science, 201, 1026, 1978.

55. Walcott, C., Gould, J. L., and Kirschvink, J. L., Pigeons have magnets, Science, 205, 1027, 1979.

56. Beischer, D. E., Grissett, J. D., and Mitchell, R. R., Exposure of man to magnetic fields alternating at extremely low frequency, Rep. No. NAMRL-1180, Naval Aerosp. Med. Res. Lab., Pensacola, 1973.

57. deLorge, J., Operant behavior of rhesus monkeys in the presence of low-frequency low-intensity magnetic and electric fields: experiment 1, Rep. No. NAMRL-1155 (NTIS No. AD754058), Naval Aerosp. Med. Res. Lab., Pensacola, 1972.

58. deLorge, J., Operant behavior of rhesus monkeys in the presence of low-frequency low-intensity magnetic and electric fields: experiment 2, Rep. No. NAMRL 1179 (NTIS No. AD764532), Naval Aerosp. Med. Res. Lab., Pensacola, 1973.

59. deLorge, J., Operant behavior of rhesus monkeys in the presence of low-frequency low-intensity magnetic and electric fields: experiment 3, Rep. No. NAMRL 1196 (NTIS No. AD774106), Naval Aerosp. Med. Res. Lab., Pensacola, 1973).

60. deLorge, J., A psychobiological study of rhesus monkeys exposed to extremely low frequency-low intensity magnetic fields, Rep. No. NAMRL 1203 (NTIS No. AD/A000078), Naval Aerosp. Med. Res. Lab., Pensacola, 1974.

61. deLorge, J., Effects of magnetic fields on behavior in nonhuman primates, in Magnetic Field Effects on Biological Systems, Tenforde, T. S., Ed., Plenum, New York, 1979, 37.

62. deLorge, J., Behavioral studies of monkeys in electric and magnetic fields at ELF frequencies, in Biological Effects and Dosimetry of Non-ionizing Radiation: Static and ELF Electromagnetic Fields, Grandolfo, M., Michaelson, S. M., and Rindi, A., Eds., Plenum, New York, 1984, in press.

63. Tucker, R. D. and Schmitt, O. H., Tests for human perception of 60 Hz moderate strength magnetic fields, IEEE Trans. Biomed. Engin., BME-25, 509, 1978.

64. Davis, H. P., Mizumori, S. J. Y., Allen, H., Rosenzweig, M. R., Bennett, E. L., and Tenforde, T. S., Behavioral studies with mice exposed to DC and 60-Hz magnetic fields, Bioelectromagnetics, 5, 147, 1984.

65. Perry, F. S., Reichmanis, M., Marino, A. A., and Becker, R. O., Environmental power-frequency magnetic fields and suicide, Health Phys., 41, 267, 1981.

66. Smith, C. W., Comments on the paper "Environmental power-frequency magnetic fields and suicide," Health Phys., 43, 439, 1982.

67. Wertheimer, N. and Leeper, E., Electrical wiring configurations and childhood cancer, Am. J. Epidemiol., 109, 273, 1976.

68. Wertheimer, N. and Leeper, E., Adult cancer related to electrical wires near the home, Int. J. Epidemiol., 11, 345, 1982.

69. Fulton, J. P., Cobb, S., Preble, L., Leone, L., and Forman, E., Electrical wiring configurations and childhood leukemia in Rhode Island, Am. J. Epidemiol., 111, 292, 1980.

70. Wertheimer, N. and Leeper, E., Re: "Electrical wiring configurations and childhood leukemia in Rhode Island," Am. J. Epidemiol., 111, 461, 1980.

71. Tomenius, L., Hellström, L., and Enander, B., Electrical constructions and 50 Hz magnetic field at the dwellings of tumour cases (0 - 18 years of age) in the county of Stockholm, presented at the Inst. Symp. Occup. Health and Safety in Mining and Tunnelling, Prague, June 21-25, 1982.

72. Milham, S. Jr., Mortality from leukemia in workers exposed to electrical and magnetic fields, New Engl. J. Med., 307, 249, 1982.

73. Tenforde, T. S., Geyer, A. B., Fujita, T. Y., Bristol, K. S., Goulding, F.S., and Budinger, T. F., Magnetic field monitoring with a portable dosimeter, presented at 5th Ann. Meeting Bioelectromagnetics Society, Boulder, June 12-16, 1983, 36.

74. Wright, W. E., Peters, J. M., and Mack, T. M., Leukemia in workers exposed to electrical and magnetic fields, Lancet, 2 (8308), 1160, 1982.

75. McDowall, M. E., Leukemia mortality in electrical workers in England and Wales, Lancet, 1 (8318), 246, 1983.

76. Coleman, M., Bell, J., and Skeet, R., Leukemia incidence in electrical workers, Lancet, 1 (8332), 982, 1983.

77. Wiklund, K., Einhorn, J., and Eklund, G., An application of the Swedish cancer-environment registry. Leukaemia among telephone operators at the telecommunications administration in Sweden, Int. J. Epidemiol., 10, 373, 1981.

78. Vågerö, D. and Olin, R., Incidence of cancer in the electronics industry: using the new Swedish Cancer Environment Registry as a screening instrument, Brit. J. Ind. Med., 40, 188, 1983.

79. Liburdy, R. P., Carcinogenesis and exposure to electrical and magnetic fields, New Engl. J. Med., 307, 1402, 1982.

80. Miller, M. W., Re: "Electrical wiring configurations and childhood cancer," Am. J. Epidemiol., 112, 165, 1980.

81. Odintsov, Y. N., The effect of a magnetic field on the natural resistance of white mice to Listeria infection, Tr. Tomskogo Vaktsyn. Syvorotok 16, 234, 1965.

82. Riesen, W. H., Aranyi, C., Kyle, J. L., Valentino, A. R., and Miller, D. A., A pilot study of the interaction of extremely low frequency electromagnetic fields with brain organelles, in Compilation of Navy Sponsored ELF Biomedical and Ecological Research Reports, Vol. 1, Tech. Memo. No. 3 (IITRI Proj. E6185), Bethesda, Naval Med. Res. Develop. Command, 1971.

83. Ossenkopp, K.-P., Koltek, W. T., and Persinger, M. A., Prenatal exposure to an extremely low frequency-low intensity rotating magnetic field and increases in thyroid and testicle weight in rats, Develop. Psychobiol., 5, 275, 1972.

84. Toroptsev, I. V., Garganeyev, G. P., Gorshenina, T. I., and Teplyakova, N. L., Pathologoanatomic characteristics of changes in experimental animals under the influence of magnetic fields, in Influence of Magnetic Fields on Biological Objects, Kholodov, Yu. A., Ed., NTIS Rep. No. JPRS 63038, Springfield, Virginia, 1974, 95.

85. Udintsev, N. A. and Moroz, V. V., Response of the pituitary-adrenal system to the action of a variable magnetic field, Byull. Éksp. Biol. Med., 77, 51, 1974.

86. Mizushima, Y., Akaoka, I., and Nishida, Y., Effects of magnetic field on inflammation, Experientia, 21, 1411, 1975.

87. Beischer, D. E. and Brehl, R. J., Search for effects of 45 Hz magnetic fields on liver triglycerides in mice, Rep. No. NAMRL-1197, Naval Aerosp. Med. Res. Lab., Pensacola, 1975.

88. Udintesev, N. A., Kanskaia, N. V., Shchepetil'nifova, A. I., Ordina, O. M., and Pichurina, R. A., Dynamics of cardiac and skeletal muscle lactate dehydrogenase activity following a single exposure to an alternating magnetic field, Byull. Éksp. Biol. Med. 81, 670, 1976.

89. Batkin, S. and Tabrah, F. L., Effects of alternating magnetic field (12 Gauss) on transplanted neuroblastoma, Res. Commun. Chem. Pathol. Pharmacol., 16, 351, 1977.

90. Chandra, S. and Stefani, S., Effect of constant and alternating magnetic fields on tumor cells in vitro and in vivo, in Biological Effects of Extremely Low Frequency Electromagnetic Fields, Phillips, R. D., Gillis, M. F., Kaune, W. T., and Mahlum, D. D., Eds., NTIS Rep. No. CONF-781016, Springfield, Virginia, 1979, 436.

91. Goodman, E. M., Greenebaum, B., and Marron, M. T., Bioeffects of extremely low-frequency electromagnetic fields: variation with intensity, waveform, and individual or combined electric and magnetic fields, Radiat. Res., 78, 485, 1979.

92. Greenebaum, B., Goodman, E. M., and Marron, M. T., Extremely-low-frequency fields and the slime mold Physarum polycephalum: evidence of depressed cellular function and of internuclear interaction, Radio Science, 14(6S), 103, 1979.

93. Greenebaum, B., Goodman, E. M., and Marron, M. T., Magnetic field effects on mitotic cycle length in Physarum, Europ. J. Cell Biol., 27, 156, 1982.

94. Kolodub, F. A. and Chernysheva, O. N., Special features of carbohydrate-energy and nitrogen metabolism in the rat brain under the influence of magnetic fields of commercial frequency, Ukr. Biokhim. Zh. (Kiev), 3, 299, 1980.

95. Fam, W. Z., Biological effects of 60-Hz magnetic field on mice, IEEE Trans. Mag., MAG-17, 1510, 1981.

96. Aarholt, E., Flinn, E. A., and Smith, C. W., Effects of low-frequency magnetic fields on bacterial growth rate, Phys. Med. Biol., 26, 613, 1981.

97. Ramon, C., Ayaz, M. and Streeter, D. D. Jr., Inhibition of growth rate of Escherichia coli induced by extremely low-frequency weak magnetic fields, Bioelectromagnetics, 2, 285, 1981.

98. Sakharova, S. A., Ryzhov, A. I., and Udintsev, N. A., Mechanism of the sympathoadrenal system's response to the one time action of a variable magnetic field, Kosm. Biol. Aviakosm. Med., 15, 52, 1981.

99. Toroptsev, I. V. and Soldatova, L. P., Pathomorphological reactions of cerebrocortical neural elements to alternating magnetic field, Arkh. Patol. (Moscow), 43, 33, 1981.

100. Delgado, J. M. R., Monteagudo, J. L., Garcia, M. G., and Leal, J., Teratogenic effects of weak magnetic fields, IRCS Med. Sci., 9, 392, 1981.

101. Delgado, J. M. R., Leal, J., Monteagudo, J. L., and Garcia, M. G., Embryological changes induced by weak, extremely low frequency electromagnetic fields, J. Anat., 134, 533, 1982.

102. Soldatova, L. P., Sequence of pathomorphological reactions to the effect of alternating magnetic fields, Arkh. Anat. Gistol. Embriol., 83, 12, 1982.

103. Sander, R., Brinkmann, J., and Kuhne, B., Laboratory studies on animals and human beings exposed to 50 Hz electric and magnetic fields, Paper 36-01, Int. Cong. Large High Voltage Elect. Syst., Paris, Sept. 1-9, 1982.

104. Lubin, R. A., Cain, C. D., Chen, M. C.-Y., Rosen, D. M., and Adey, W. R., Effects of electromagnetic stimuli on bone and bone cells in vitro: inhibition of responses to parathyroid hormone by low-energy low-frequency fields, Proc. Natl. Acad. Sci. (USA), 79, 4180, 1982.

105. Conti, P., Gigante, G. E., Cifone, M. G., Alesse, E., Ianni, G., Reale, M., and Angeletti, P. U., Reduced mitogenic stimulation of human lymphocytes by extremely low frequency electromagnetic fields, FEBS Lett., 162, 156, 1983.

106. Goodman, R., Bassett, C. A. L., and Henderson, A. S., Pulsing electromagnetic fields induce cellular transcription, Science, 220, 1283, 1983.

107. Jolley, W. B., Hinshaw, D. B., Knierim, K., and Hinshaw, D. B., Magnetic field effects on calcium efflux and insulin secretion in isolated rabbit islets of Langerhans, Bioelectromagnetics, 4, 103, 1983.

108. Ramirez, E., Monteagudo, J. L., Garcia-Gracia, M., and Delgado, J. M. R., Oviposition and development of Drosophila modified by magnetic fields, Bioelectromagnetics, 4, 315, 1983.

109. Ubeda, A., Leal, J., Trillo, M. A., Jimenez, M. A., and Delgado, J. M. R., Pulse shape of magnetic fields influences chick embryogenesis, J. Anat., 137, 513, 1983.

110. Archer, C. W. and Ratcliffe, N. A., The effects of pulsed magnetic fields on chick embryo cartilaginous skeletal rudiments in vitro, J. Exp. Zool., 225, 243, 1983.

111. Liboff, A. R., Williams, T., Jr., Strong, D. M., and Wistar, R., Jr., Time-varying magnetic fields: effect on DNA synthesis, Science, 223, 818, 1984.

112. Coate, W. B., Project Biological Effects Test Program, Pilot Studies, Final Report, Hazelton Laboratories, NTIS Rep. No. AD75058, Springfield, Virginia, 1970.

113. Marron, M. T., Goodman, E. M., and Greenebaum, B., Mitotic delay in the slime mold Physarum polycephalum induced by low intensity 60 and 75 Hz electromagnetic fields, Nature, 254, 66, 1975.

114. Polk, C., Time varying magnetic fields and DNA synthesis: magnitude of forces due to magnetic fields on surface bound counterions, presented at 6th Ann. Meeting Bioelectromagnetics Society, Atlanta, July 15-19, 1984.

115. Kolin, A., An alternating field induction flow meter of high sensitivity, Rev. Sci. Instrum., 16, 109, 1945.

116. Tenforde, T. S., Mechanisms for biological effects of magnetic fields, in Biological Effects and Dosimetry of Non-ionizing Radiation: Static and ELF Electromagnetic Fields, Grandolfo, M., Michaelson, S. M., and Rindi, A., Eds., Plenum, New York, 1984, in press.

117. Kolin, A., Improved apparatus and technique for electromagnetic determination of blood flow, Rev. Sci. Instrum., 23, 235, 1952.

118. Okai, O. and Oshima, M., Magnetorheography: calculation of blood flow from surface induced potentials, Jpn. Heart J., 16, 694, 1975.

119. Conti, F., Stefanoni, G., and Donadelli, G., A new method for measuring venous blood flow with the aid of an electromagnetic flowmeter, J. Cardiovasc. Surg., 17, 363, 1976.

120. Portnoi, V. F. and Dvortsin, G. F., Experimental basis of a new method of determination of coronary blood flow with the aid of electromagnetic flowmeter, Kardiol., 16, 118, 1976.

121. Kolin, A. and MacAlpin, R. N., Induction angiometer. Electromagnetic magnification of microscopic vascular diameter variations in vivo, Blood Vessels, 14, 141, 1977.

122. Gooszen, H. G., Van Schilfgaarde, R., and Terpstra, J. L., Arterial blood supply of the left lobe of the canine pancreas. II. Electromagnetic flow measurements, Surgery, 93, 549, 1983.

123. Mills, C. J., The electromagnetic flowmeter, Med. Instrum., 11, 136, 1977.

124. Beischer, D. E. and Knepton, J. C., Influence of strong magnetic fields on the electrocardiogram of squirrel monkeys (Saimiri sciureus), Aerosp. Med., 35, 939, 1964.

125. Beischer, D. E., Vectorcardiogram and aortic blood flow of squirrel monkeys (Saimiri sciureus) in a strong superconductive electromagnet, in Biological Effects of Magnetic Fields, Barnothy, M., Ed., Plenum, New York, 1969, 241.

126. Tenforde, T. S., Gaffey, C. T., Moyer, B. R., and Budinger, T. F., Cardiovascular alterations in Macaca monkeys exposed to stationary magnetic fields: experimental observations and theoretical analysis, Bioelectromagnetics, 4, 1, 1983.

127. Gaffey, C. T., Tenforde, T. S., and Dean, E. E., Alterations in the electrocardiograms of baboons exposed to DC magnetic fields, Bioelectromagnetics, 1, 209, 1980.

128. Togawa, T., Okai, O., and Oshima, M., Observation of blood flow E.M.F. in externally applied strong magnetic fields by surface electrodes, Med. Biol. Engin., 5, 169, 1967.

129. Gaffey, C. T. and Tenforde, T. S., Alterations in the rat electrocardiogram induced by stationary magnetic fields, Bioelectromagnetics, 2, 357, 1981.

130. Bassett, C. A. L., Pulsing electromagnetic fields: a new approach to surgical problems, in Metabolic Surgery, Buchwald, H. and Varco, R. L., Eds., Grune and Stratton, New York, 1978, 255.

131. Fukada, E. and Yusuda, I., On the piezoelectric effect in bone, J. Phys. Soc. Jpn., 12, 1158, 1957.

132. Bassett, C. A. L. and Becker, R. O., Generation of electric potentials by bone in response to mechanical stress, Science, 137, 1063, 1962.

133. Bassett, C. A. L., Pawluk, R. J., and Pilla, A. A., Acceleration of fracture repair by electromagnetic fields. A surgically noninvasive method, Ann. N. Y. Acad. Sci., 238, 242, 1974.

134. Lunt, M. J., Magnetic and electric fields produced during pulsed-magnetic-field therapy for non-union of the tibia, Med. Biol. Engin. Comput., 20, 501, 1982.

135. Bassett, C. A. L., Pilla, A. A., and Pawluk, R. J., A non-operative salvage of surgically-resistant pseudoarthroses and non-unions by pulsing electromagnetic fields, Clin. Orthop., 124, 128, 1977.

136. Watson, J. and Downes, E. M., The application of pulsed magnetic fields to the stimulation of bone healing in humans, Jpn. J. Appl. Phys., 17, 215, 1978.

137. Hinsenkamp, M. G., Electromagnetic stimulation of nonunion, Rev. Med. Brux. Nouv., Ser. 3 (1), 19, 1982.

138. Bassett, C. A. L., Mitchell, S. N., and Gaston, S. R., Pulsing electromagnetic field treatment in ununited fractures and failed arthrodeses. J. Am. Med. Assoc., 5, 623, 1982.

139. Bigliani, L. U., Rosenwasser, M. P., Caulo, N., Schink, M. M., and Bassett, C. A. L., The use of pulsing electromagnetic fields to achieve arthrodesis of the knee following failed total knee arthroplasty. A preliminary report, J. Bone Joint Surg., 65, 480, 1983.

140. Barker, A. T. and Lunt, M. J., The effects of pulsed magnetic fields of the type used in the stimulation of bone fracture healing, Clin. Phys. Physiol. Meas., 4, 1, 1983.

141. Watson, J. and Downes, E. M., Light-weight battery-operable orthopaedic stimulator for the treatment of long-bone nonunions using pulsed magnetic fields, Med. Biol. Engin. Comput., 21, 509, 1983.

142. Hinsenkamp, M. G. and Rooze, M. A., Morphological effect of electromagnetic stimulation on the skeleton of fetal or newborn mice, Acta Orthop. Scand., Supp. 196, 39, 1982.

143. Frank, C., Schachar, N., Dittrich, D., Shrive, N., Dehaas, W., and Edwards, G., Electromagnetic stimulation of ligament healing in rabbits, Clin. Orthop., May (175), 1983, 263.

144. Wilson, D. H. and Jagadeesh, P., Experimental regeneration in peripheral nerves and the spinal cord in laboratory animals exposed to a pulsed electromagnetic field, Paraplegia, 14, 12, 1976.

145. Raji, A. R. M. and Bowden, R. E. M., Effects of high peak pulsed electromagnetic field on degeneration and regeneration of the common peroneal nerve in rats, Lancet, 2 (8295), 444, 1982.

146. Raji, A. R. and Bowden, R. E., Effects of high-peak pulsed electromagnetic field on the degeneration and regeneration of the common peroneal nerve in rats, J. Bone Joint Surg., 65, 478, 1983.

147. Bassett, C. A. L., Becker, R. O., Brighton, C. T., Lavine, L., and Rowley, B. A., Panel discussion: to what extent can electrical stimulation be used in the treatment of human disorders? Ann. N. Y. Acad. Sci., 238, 586, 1974.

148. Baum, S. J., Ekstrom, M. E., Skidmore, W. D., Wyant, D. E. and Atkinson, J. L., Biological measurements in rodents exposed continuously throughout their adult life to pulsed electromagnetic radiation, Health Phys., 30, 161, 1976.

149. Seipel, J. H. and Morrow, R. D., The magnetic field accompanying neuronal activity: a new method for the study of the nervous system, J. Wash. Acad. Sci., 50, 1, 1960.

150. Gengerelli, J. A., Holter, N. J., and Glassock, W. R., Magnetic fields accompanying transmission of nerve impulses in the frog's sciatic, J. Psych., 57, 202, 1961.

151. Baule, G. M. and McFee, R., Detection of the magnetic field of the heart, Am. Heart J., 66, 95, 1963.

152. Cohen, D., Magnetic fields around the torso: production by electrical activity of the human heart, Science, 156, 652, 1967.

153. Cohen, D., Magnetoencephalography: evidence of magnetic fields produced by alpha rhythm currents, Science, 161, 784, 1968.

154. Cohen, D., Magnetic fields of the human body, Phys. Today, Aug., 1975, 34.

155. Zimmerman, J. E., Thiene, P., and Harding, J. T., Design and operation of stable rf-biased superconducting point-contact quantum devices, and a note on the properties of perfectly clean metal contacts, J. Appl. Phys., 41, 1572, 1970.

156. Cohen, D., Magnetoencephalography: detection of the brain's electrical activity with a superconducting magnetometer, Science, 175, 664, 1972.

157. Romani, G. L., Williamson, S. J., and Kaufman, L., Biomagnetic instrumentation, Rev. Sci. Instrum., 53, 1815, 1982.

158. Williamson, S. J. and Kaufman, L., Biomagnetism, J. Mag. Mag. Mat., 22, 129, 1981.

159. Williamson, S. J., Romani, G.-L., Kaufman, L., and Modena, I., Eds., Biomagnetism, Plenum, New York, 1982.

160. Awano, I., Muramoto, A., and Awano, N., An approach to clinical magnetocardiology, Tohoku J. Exp. Med., 138, 367, 1982.

161. Savard, P., Cohen, D., Lepeschkin, E., Cuffin, B. N., and Madias, J. E., Magnetic measurement of S-T and T-Q segment shifts in humans. Part I: Early repolarization and left bundle branch block, Circ. Res., 53, 264, 1983.

162. Cohen, D., Savard, P., Rifkin, R. D., Lepeschkin, E., and Strauss, W. E., Magnetic measurement of S-T and T-Q segment shifts in humans. Part II. Exercise-induced S-T segment depression, Circ. Res., 53, 274, 1983.

163. Reite, M. and Zimmerman, J., Magnetic phenomena of the central nervous system, Ann. Rev. Biophys. Bioeng., 7, 167, 1978.

164. Cohen, D. and Cuffin, B. N., Demonstration of useful differences between magnetoencephalogram and electroencephalogram, Electroencephalogr. Clin. Neurophysiol., 56, 38, 1983.

165. Reite, M., Zimmerman, J. E., Edrich, J., and Zimmerman, J., The human magnetoencephalogram: some EEG and related correlations, Electroencephalogr. Clin. Neurophysiol., 40, 59, 1976.

166. Gutman, A. M. and Morgenshtern, V. Ya., Possible mechanism of the genesis of the magnetoencephalogram, Biofiz., 22, 529, 1977.

167. Plonsey, R., The nature of sources of bioelectric and biomagnetic fields, Biophys. J., 39, 309, 1982.

168. Brenner, D., Williamson, S. J., and Kaufman, L., Visually evoked magnetic fields of the human brain, Science, 190, 480, 1975.

169. Brenner, D., Kaufman, L., and Williamson, S. J., Application of a squid for monitoring magnetic response of the human brain, IEEE Trans. Mag., MAG-13, 365, 1977.

170. Brenner, D., Lipton, J., Kaufman, L., and Williamson, S. J., Somatically evoked magnetic fields of the human brain, Science, 199, 81, 1978.

171. Okada, Y. C., Williamson, S. J., and Kaufman, L., Magnetic field of the human sensorimotor cortex, Int. J. Neurosci., 17, 33, 1982.

172. Okada, Y. C., Kaufman, L., and Williamson, S. J., The hippocampal formation as a source of the slow endogenous potentials, Electroencephalogr. Clin. Neurophysiol., 55, 417, 1983.

173. Cohen, D., Ferromagnetic contamination in the lungs and other organs of the human body, Science, 180, 745, 1973.

174. Farrell, D. E., Tripp, J. H., Zanaucchi, P. E., Harris, J. W., Brittenham, G. M., and Muir, W. A., Magnetic measurement of human iron stores, IEEE Trans. Mag., MAG-16, 818, 198, 1980.

Table 1

BEHAVIORAL EFFECTS OF EXPOSURE TO TIME-VARYING ELF MAGNETIC FIELDS

A. POSITIVE FINDINGS

Reference	Subject	Exposure Conditions[a]	Results
38: Friedman et al., 1967	Human	0.1 and 0.2 Hz, 0.5-1.1 mT; acute exposures	Increased reaction time in 0.2 Hz field
39: Caldwell and Russo, 1968	Honeybee	60 Hz, 2.2-30 mT; 10-min exposures	Altered exploratory behavior
40: Persinger, 1969	Rat	0.5 Hz, 0.3-3.0 mT, rotating field; exposure during entire gestational period	Decreased open-field activity and increased defecation when tested postnatally at 21-25 days
41: Persinger and Foster, 1970	Rat	Same as Ref. 40	Decreased avoidance of aversive electrical shock when tested postnatally at 30 days
42: Persinger and Pear, 1972	Rat	Same as Ref. 40	Suppressed rate of response to a conditioned stimulus preceding an aversive shock when tested postnatally at 70 days
43: Persinger et al., 1972	Rat	Same as Ref. 40, but with adult animals exposed for 21-30 days	Increased ambulatory activity after removal from field
44: Ossenkopp and Shipiro, 1972	Duck eggs	0.5 Hz, 2-10 and 10-30 mT, rotating field; exposure for entire prenatal period	Increased ambulation and defecation rate when tested postnatally
45: Medvedev et al., 1976	Human	50 Hz, 10-13 μT; acute exposures	Increased latency of sensorimotor reactions
46: Smith and Justeson, 1977	Mouse	60 Hz, 1.4-2.0 mT 2-min aperiodic exposures over 2 days	Increased locomotor activity and aggression-related vocalization
47: Brown and Scow, 1978	Hamster	10^{-5} Hz, 0.8-26 μT; 26-h schedule of high (14 h) to low (12 h) field switching over period of 4-5 months	Modified circadian rhythm in locomotor activity

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Table 1 (continued)

BEHAVIORAL EFFECTS OF EXPOSURE TO TIME-VARYING ELF MAGNETIC FIELDS

A. POSITIVE FINDINGS (continued)

Reference	Subject	Exposure Conditions[a]	Results
48: Clark and Justesen, 1979	Chicken	60 Hz, 2.4 mT; aperiodic exposures during 1-h interval for 10 days	Increased variability of response to electric shock stimulus when 60-Hz magnetic field used as conditional stimulus
49: Delgado, 1983	Monkey	9-500 Hz, 0.1 mT (applied to cerebellum); 9-h daily exposures for maximum of 19 days	Modification of threshold for excitation of motor neurons

B. NEGATIVE FINDINGS

Reference	Subject	Exposure Conditions[a]	Results
56: Beischer et al., 1973	Human	45 Hz, 0.1 mT; 22.5-h exposure	No effect on reaction time
57-62: DeLorge, 1972, 1973, 1974, 1979, 1984	Monkey	10, 15, 45, 60 and 75 Hz, 0.8-1.0 mT; fields applied in 4-13 daily sessions of 2-8 h duration	No consistent influence on motor activity, reaction time, inter-response time, overall lever responding, or match-to-sample performance
63: Tucker and Schmitt, 1978	Human	60 Hz, 1.06 mT over whole body, or 2.12 mT over head region; repetitive acute exposures	No perception of field
64: Davis et al., 1984	Mouse	60 Hz, 2.33 mT; 3-day continuous exposure	No change in memory retention, locomotor activity, or sensitivity to a neuropharmacologic agent

[a] The magnetic fields were sinusoidal unless otherwise indicated.

Table 2

CELLULAR AND TISSUE INTERACTIONS OF TIME-VARYING ELF MAGNETIC FIELDS

Reference	Test Specimen	Exposure Conditions[a]	Results
81: Odintsov, 1965	Mouse	50 Hz, 20 mT; 6.5-h single exposure or 6.5-h daily for 15 d	Increased resistance to *Listeria* infection
82: Riesen *et al.*, 1971	Guinea pig brain mitochondria	60 Hz, 10 mT; 10-110 min exposures	No effect on respiration (oxidative phosphorylation)
82: Riesen *et al.*, 1971	Rat brain synaptosomes	60 Hz, 5-10 mT; 30-min exposure	Decreased uptake of norepinephrine at 0°C, but not at 10, 25 or 37°C
83: Ossenkopp *et al.*, 1972	Rat	0.5 Hz, 0.05-0.30 or 0.3-1.5 mT, rotating field; exposure during entire gestational period	Increased thyroid and testicle weights at 105-130 days of age; no change in thymus or adrenal weights relative to controls
56: Beischer *et al.*, 1973	Human	45 Hz, 0.1 mT; 22.5-h exposure	Elevated serum triglycerides; no other effects on blood cell counts or serum chemistry
59: DeLorge, 1974	Monkey	15 and 45 Hz, 0.82-0.93 mT; fields applied in 5-8 daily sessions of 2-h duration	No alteration in blood cell counts or serum chemistry (including triglycerides)
84: Toroptsev *et al.*, 1974	Guinea pig	50 Hz, 20 mT; 6.5-h single exposure or 6.5-h daily for 24 d	Pathomorphological changes in testes, kidneys, liver, lungs, nervous tissues, eyes, capillaries and lymphatic system
85: Udintsev and Moroz, 1974	Rat	50 Hz, 20 mT; 1-7 days exposure	Increase in adrenal 11-hydroxy corticosteroids
86: Mizushima *et al.*, 1974	Rat	50 Hz, 0.12 T; 3-h exposure	Anti-inflammatory effects of field on carrageenan-induced edema and adjuvant-induced arthritis
87: Beischer and Brehl, 1975	Mouse	45 Hz, 0.1 mT; 24-h exposure	No change in liver triglycerides

CONTINUED ON P. 63

Table 2 (continued)

CELLULAR AND TISSUE INTERACTIONS OF TIME-VARYING ELF MAGNETIC FIELDS

Reference	Test Specimen	Exposure Conditions[a]	Results
88: Udintsev et al., 1976	Rat	50 Hz, 20 mT; 24-h exposure	Increased LDH activity and change in distribution in heart and skeletal muscles
89: Batkin and Tabrah, 1977	Mouse neuroblastoma	60 Hz, 1.2 mT; 13-d exposure	Decreased tumor growth rate
90: Chandra and Stefani, 1979	Mouse mammary carcinoma	60 Hz, 0.16 T; 1-h daily exposures for 1-4 d	No effect on tumor growth rate
91: Goodman et al., 1979 92,93: Greenebaum et al., 1979 and 1982	Slime mold	75 Hz, 0.2 mT 400-d exposure	Lengthened nuclear division cycle and respiration rate (decreased O_2 uptake)
94: Kolodub and Chernysheva, 1980	Rat	50 Hz, 9.4 and 40 mT; 5-h daily for 15 d	Altered brain metabolism at higher field intensity, including decreased rate of respiration, decreased levels of glycogen, creatine phosphate and glutamine, and increased DNA content
95: Fam, 1981	Mouse	60 Hz, 0.11 T; 23 h daily for 7 d	Decreased body weight and increased water consumption; hematology, organ histology and reproduction not affected
96: Aarholt et al., 1981	Bacteria	16.66 and 50 Hz, 0-2.0 mT; 10-12 h exposure	Decreased growth rate
97: Ramon et al., 1981	Bacteria	60 and 600 Hz, 2 mT; 17-64 h exposure	Decreased growth rate and cytolysis
98: Sakharova et al., 1981	Rat	50 Hz, 20 mT; 24-h exposure	Mobilization of adrenal catecholamines
99: Toroptsev and Soldatova, 1981	Rat	50 Hz, 20 mT; 1 to 24 h exposures	Pathomorphological changes in brain

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Table 2 (continued)

CELLULAR AND TISSUE INTERACTIONS OF TIME-VARYING ELF MAGNETIC FIELDS

Reference	Test Specimen	Exposure Conditions[a]	Results
100,101: Delgado et al., 1981, 1982	Chicken embryo	10,100 and 1000 Hz; 0.12, 1.2 and 12 μT; 0.5-ms rectangular pulses; 2-d exposure	Morphological abnormalities in nervous tissue, heart, blood vessels and somites
102: Soldatova, 1982	Rat	50 Hz; 20, 40 and 70 mT; 6.5 h daily and 5 d, or 24-h continuous exposure	Pathomorphological changes in brain tissue
103: Sander et al., 1982	Human	50 Hz, 5 mT; 4-h exposure	No changes in ECG, EEG, hormones, blood cell counts, or blood chemistry
104: Lubin et al., 1982	Mouse osteoblast cultures	Single bidirectional pulses at 72 Hz, or 4-kHz bursts of bidirectional pulses with 15-Hz repetition rate; 2 mT peak intensity; 3-d exposure	Reduced cAMP production in response to parathyroid hormone
105: Conti et al., 1983	Human lymphocytes	1, 3, 50 and 200 Hz; 2.3-6.5 mT; square-wave pulses; 3-d exposure	Inhibition of lectin-induced mitogenesis by 3 and 50 Hz fields
106: Goodman et al., 1983	Drosophila salivary glands	15- and 72-Hz pulses as in Ref. 104 above; 5-90 min exposures	Increased RNA transcription
107: Jolley et al., 1983	Rabbit pancreas	4-kHz bursts of bidirectional pulses with 15-Hz repetition rate; 2 mT peak intensity; 18-h exposure	Reduced Ca^{++} content and efflux; reduced insulin release during glucose stimulation
108: Ramirez et al., 1983	Drosophila eggs	0.5-ms square wave pulses at 100 Hz, or 50-Hz, 1.41-mT sinusoidal field; 2-d exposure	Decreased viability of eggs

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Table 2 (continued)

CELLULAR AND TISSUE INTERACTIONS OF TIME-VARYING ELF MAGNETIC FIELDS

Reference	Test Specimen	Exposure Conditions[a]	Results
109: Ubeda *et al.*, 1983	Chicken embryos	0.5-ms bidirectional pulses at 100 Hz (4 different waveforms); 0.4-104 μT peak intensity; 2-d exposure	Teratogenic changes in nervous system, circulatory system and foregut
110: Archer and Ratcliffe, 1983	Cultured chicken tibiae	1 Hz, 15-60 mT square-wave pulses; 7-d exposure	Decreased collagenous and noncollagenous protein synthesis; no alteration in glycosoaminoglycan and DNA synthesis
111: Liboff *et al.*, 1984	Cultured human fibroblasts	15 Hz-4 kHz; 2.3-560 μT; 18-96 h exposures	Increased DNA synthesis

[a] The magnetic fields were sinusoidal unless otherwise indicated.

FIGURE LEGENDS

Figure 1. The mean threshold magnetic flux densities required to elicit magnetophosphenes are plotted as a function of frequency for 6 subjects with normal color vision and for 9 deutans with defects in color vision. Threshold values were determined at wavelengths of 443, 531 and 572 nm with a luminance of 3 cd/m^2. Error bars represent ± 1 S.E.M. (Reproduced from ref. 24 with permission of the authors and publisher.)

Figure 2. The mean threshold electric currents and magnetic flux densities for eliciting electro- and magnetophosphenes are plotted as a function of frequency for 10 subjects with normal vision. The data have been normalized relative to the threshold values determined at 20 Hz, the frequency at which maximum sensitivity was observed for the induction of both electro- and magnetophosphenes. The threshold electric current divided by the field frequency has also been plotted (see text for explanation). All studies were conducted with a broad-spectrum white light background at a luminance of 3 cd/m^2. (Reproduced from ref. 23 with permission of the authors and publisher.)

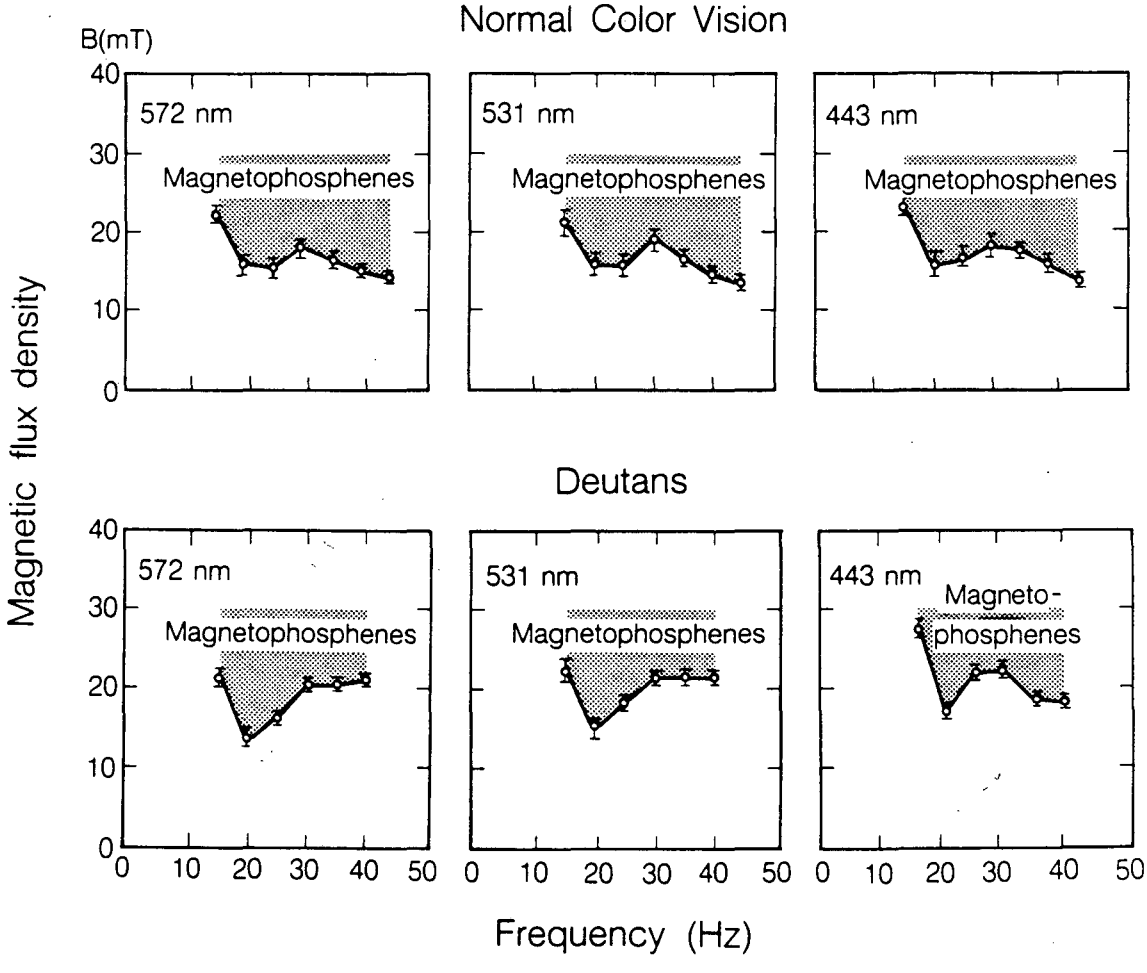

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FIGURE 1

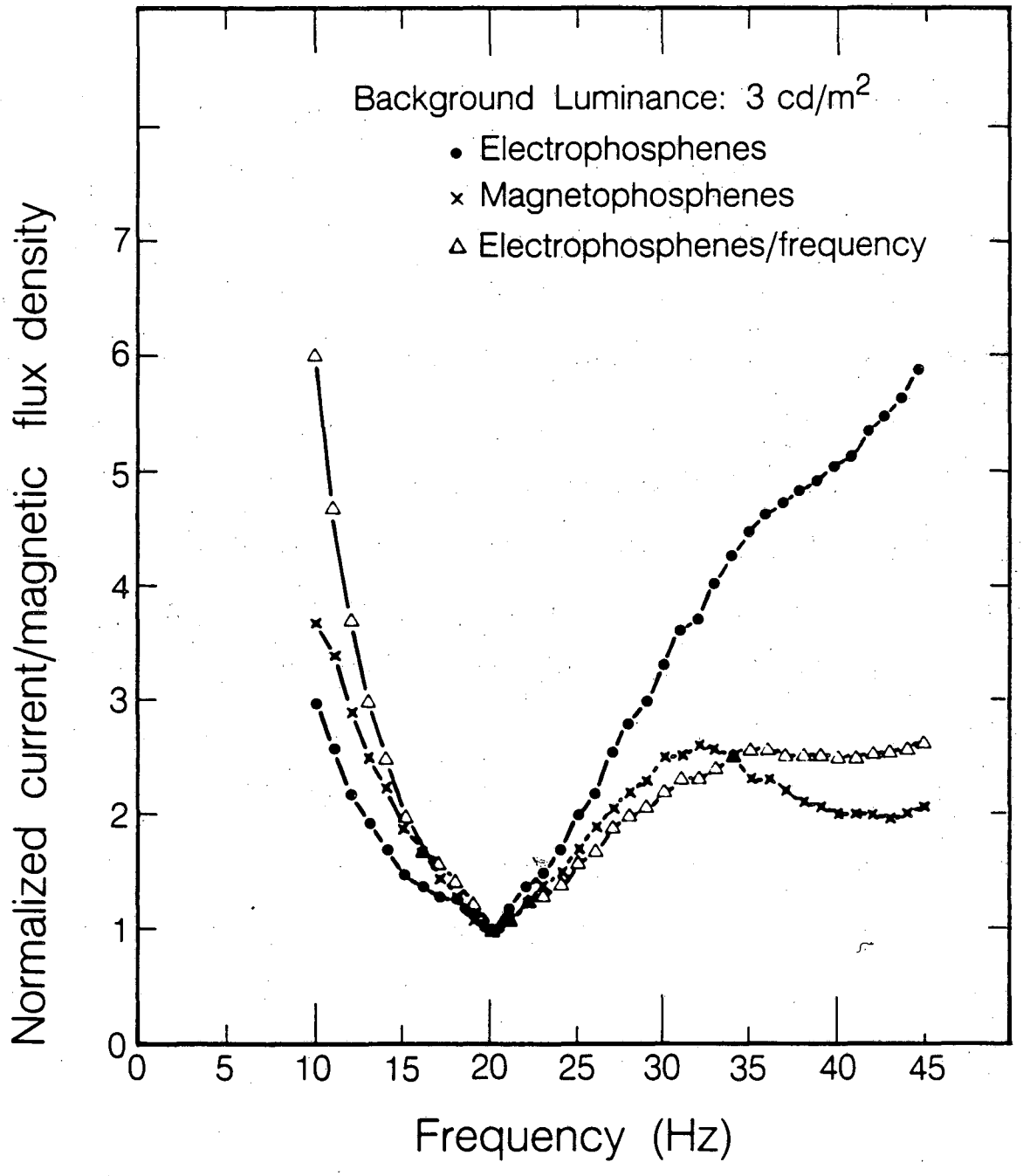

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FIGURE 2

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