TOPIC #2: FIELD PARAMETERS

SYNOPSIS

Prepared by
William Bailey
Bailey Research Associates, Inc.
New York, NY

Purpose

The base of firm knowledge about the physical characteristics of electric and magnetic fields began developing more than 100 years ago. As physical forces, the fields are well understood. In the past 25 years there has been increased interest in the potential biological effects of exposure to these fields. This synopsis is designed to provide a taxonomy of characteristics of electric and magnetic fields that have been investigated for their influence on biological systems and the ways in which they are defined for assessing human exposure in the environment and generating fields in the laboratory. Table 2-1, at the end of the synopsis, provides a matrix showing selected magnetic-field parameters, with reference to hypothetical biological mechanisms. Because the recent health-related research and the EMF Rapid Program itself focus principally on magnetic fields, little attention is given to electric fields.

Physical Characteristics

Facilities that generate, transmit, and use electric energy are sources of electric and magnetic fields. In most cases these fields are produced by electric currents and charges on power conductors and related equipment, although other unintentional conductors, e.g., water pipes, may also be sources.

Frequency

Electric and magnetic fields are vector quantities characterized by a magnitude, direction, and frequency. The characteristics of electric and magnetic fields are determined by the characteristics of their sources. The earth’s gravitational field on a unit mass is also described as a vector field. In the U.S., the power oscillates at frequency of 60 Hz; in Europe and some other countries the frequency is 50 Hz. The oscillation of the electricity 60 times per second produces a sinusoidal, or wave-like, rise and fall in the magnitude and vector orientation of the associated fields. Electrified rail transportation is sometimes powered at frequencies of 25 Hz in the U.S. and 16-2/3 Hz in Europe. The operation of some electrical devices in the power system produce fields at other frequencies. Fields that occur at higher frequencies as even multiples of the fundamental frequency (e.g., 120, 180, 240 Hz. . .) are termed harmonics. Typically, harmonics from utility power sources are not greater than 300 Hz; however, some types of electrical equipment (e.g., electric trains) may produce magnetic fields at frequencies up to 3000 Hz. Fields with frequencies between 3 Hz and 3000 Hz are categorized in the Extreme Low Frequency (ELF) range [ANSI/IEEE Std 100-1988 (IEEE 1988)].

At most frequencies electromagnetic fields are coupled, meaning that the magnitude of one field can be calculated exactly if the other is known. In the ELF range, electric and magnetic fields are effectively uncoupled. This is because the wavelengths of ELF electric and magnetic fields at 60 Hz are very large, roughly 5000 km, in relation to the size of objects of interest. Under these "near field" conditions, electric and magnetic fields do not "radiate" away from the source. The field produced by a source is better described as a zone of influence in which the forces on electrical charges oscillate in time and space.

Field Magnitude

Because ELF electric and magnetic fields can be treated as separate forces, the magnitude of the electric field is related directly to the voltage of the source and the magnetic field to the current. Since the voltages of sources remain relatively constant, electric fields remain constant over time. Electric fields are measured in International System of Units (SI) volts/meter (V/m).

The magnitudes of magnetic fields are directly related to variations in current flow; in contrast to electric fields, magnetic fields may be highly variable over time. The magnitude of the flux density of the magnetic field (B), is expressed in SI units of tesla (T)[1]. The older cgs units for expressing magnetic-field magnitude—gauss (G) and milligauss (mG)—are still quite common. Magnetic fields expressed in one unit can be easily converted to other units by the definitions:

$$1 \text{ T} = 1000 \text{ mT} = 10000 \text{ G}$$

$$1 \text{ G} = 1000 \text{ mG and } 1 \text{ mG} = 0.1\ \mu\text{T}$$

The magnitude of electric or magnetic fields varies during each cycle. For a sinusoidal magnetic field:

$$B = B_0 \sin\omega t$$

where B_0 is the peak value of B. For convenience, electric current, voltage field, and magnetic-field values are commonly expressed as the root-mean-square (rms) values. The rms value of a oscillating field is the square root of the average square of the field parameter, e.g., magnetic field, during a complete cycle. For a sinusoidal 60-Hz magnetic field:

$$B_{rms} = B_0/\sqrt{2} = 0.707\ B_0.$$

---

[1] Less frequently, the magnitude of the magnetic field is expressed in terms of field intensity (H-Amperes/m). The relationship between flux density B and magnetic-field strength (H) is $H = B/\mu$, where μ is the magnetic permeability of the medium. For most biological material, the value of μ can be assumed to be the same as air.

Waveform

If a field continually oscillates over time in a sinusoidal fashion, then the field can be simply characterized by its frequency, as discussed above. However, to be adequately described, fields with non-sinusoidal waveforms and limited durations require additional parameters to be specified. The frequency spectrum of such fields can be complex, and can extend over a frequency range much wider than the nominal frequency of the source. If the field contains pulses, it may be characterized by the rise time, decay time, pulse duration, and pulse repetition rate, and, if the pulses are oscillating, by the frequency of the oscillation. Alternatively, the field may be characterized by the frequency spectrum. There are methods such as Fourier and wavelet analysis that can characterize the frequency spectrum of such complex fields; however, to use these methods requires that the measurement instruments be capable of faithfully capturing very high frequencies.

Transients or field “spikes” are of interest because they may transfer to biological systems significant amounts of energy (in relation to background electrical and thermal “noise” in biological systems), and therefore may be expected to be more likely to affect biological systems. This expectation is supported by research on the effects of devices used for bone healing and other therapeutic applications. The waveform or frequency content of “pulsed” fields is critical for these devices to elicit biological responses.

One field characteristic that relates both the magnitude and frequency of the magnetic field is the time rate of change of B (dB/dt). For a sinusoidal magnetic field, dB/dt is obtained from the expression 2 x π x frequency x B_0. The importance of this relationship derives from Faraday’s law, which states that an *electric field* is induced in conductive loop (including objects like the body) by alternating magnetic fields. The magnitude of this field is proportional to the time rate of change (dB/dt). Hence, a magnetic field with a waveform characterized by high dB/dt will couple to the body more strongly (i.e., induce larger electric fields) than a field of lower flux density and frequency. Field parameters that produce exposures characterized by high dB/dt have been shown to cause stimulation of neural and cardiac tissues by induced electric fields and current density. Although there is consensus that the induced electric field is the parameter most closely related to tissue stimulation, internal exposures are frequently referenced in terms of current density (J) and amperes per meter (A/m), where J (A/m^2) = σE (σ = tissue conductivity in siemens/m and E = electric field in V/m. However, exposures to power frequency magnetic fields with high dB/dt are not found in residential or even in most occupational environments in which exposures to strong magnetic fields are likely.

Field Polarization

The magnetic-field vector surrounding a single conductor is oriented in a plane perpendicular to the conductor and does not change its direction during a cycle. This field is said to be linearly polarized. Even though the current and the resulting B-field vary over time, the direction of the field is fixed. Currents flowing on other parallel conductors will not change the polarization of the field as long as their currents are electrically in phase. More commonly, three-phase distribution or transmission lines are the source of environmental magnetic fields, and the currents are out of phase. In these cases, the locus of the magnetic-field vector is not a straight line but traces out an ellipse and is said to be elliptically polarized. When the major and minor axes of the ellipse are the same, the field has a circular polarization.

When measurements are made of magnetic fields, their polarization must be considered. If the magnetic field is measured with a single-axis meter, then the magnitude of the field along the major axis of the ellipse is reported (maximum field B_{max}). These are the magnetic-field values frequently reported in spot measurement surveys of homes and work places, particularly before three-axis meters became available. A three-axis meter, as the name implies, records the magnitude of the projection of the magnetic flux density vector on the axes of three orthogonal coils. The measurements of B in the x, y and z planes are combined as the resultant field by the expression $B_{resultant} = [(B_x)^2 + (B_y)^2 + (B_z)^2]^{1/2}$. Epidemiological and other surveys to characterize exposures of individuals in residential and occupational environments often use three-axis meters because measurements can be taken and stored in the electronic memory of the meter quickly and efficiently. The relationship between B_{max} and $B_{resultant}$ is not always clear-cut. For example, if the field is elliptically polarized, then $B_{resultant}$ can be up to $\sqrt{2}$ greater than B_{max}, But if linearly polarized, $B_{resulant} = B_{max}$. A further complexity is that field polarization changes with distance from the source. The magnetic-field resultant coincides with the rms value of the vector B, regardless of the waveform of the three orthogonal components and the polarization of each frequency component.

As discussed above, environmental fields may be quite complex. In laboratory studies, however, it is difficult and expensive to re-create all the characteristics of environmental fields. Therefore, the fields to which animals, tissues, and cells have been exposed in the laboratory are a simplified subset of exposures in residential and occupational environments. The frequency is usually fixed at 50 or 60 Hz, and the independent variable controlled by the experimenter is the magnetic flux density or electric field strength. Most laboratory exposure systems produce linearly polarized fields. For studies of cells and tissues *in-vitro*, single-phase electric fields in the culture medium produce exposures that simulate electric fields produced by a three-phase power line at ground level (Misakian et al., 1993). However, elliptically polarized magnetic fields are difficult and expensive to generate in the laboratory.

A group of laboratory studies that is notable for the effort that went into simulating real-world exposures was funded by the New York State Power Lines Project (NYSPLP). In many of these studies the animals and cell/tissue cultures were exposed to circularly polarized magnetic fields (Ahlbom et al., 1987). In most environments people are exposed simultaneously to both electric and magnetic fields. Therefore, most of the laboratory studies supported by the NYSPLP designed exposure systems to generate both electric and magnetic fields. Moreover, a component of the magnetic-field vector was specified to be perpendicular to that of the alternating electric field. In this configuration, the force (F) on moving charges, as predicted by the Lorenz equation $F = qv \times B$, is greatest.

Experimental interest in the idea that field polarization might be an important field parameter comes from a series of studies of rats exposed to 1.4-μT 50-Hz magnetic field in which responses tothe magnetic field were reported to vary with polarization (circular, linear, or elliptical) (Kato and Shigemitsu, 1997).

Spatial Variability

Many field parameters vary markedly with distance from services and so there is considerable variability in measures of these parameters for this reason. Attempts to reduce this source of variability have focused on averaging field parameters over smaller locations of interest, e.g., bedrooms in residential studies or work locations in occupational studies. Because persons encounter spatial variations in field parameters as they move about in the environment, spatial variations in exposure are translated into temporal variances in exposure.

DC Magnetic Field

The static magnetic field has also been suggested as important in determining the sensitivity of some organisms to alternating magnetic fields. For example, several investigators have proposed theories predicting that the biological responses to ac magnetic fields at specific frequencies are predicted to occur *only* when combined with dc magnetic-field vectors of particular alignment and, perhaps, specific intensities. The strengths and weaknesses of these and other theories have been reviewed in the context of *in-vitro* studies (NIEHS, 1997).

Duration and Temporal Variability

The duration of exposure may be quite short—a few milliseconds or less, as for a transient excursion of the field—or well-nigh continuous exposure over much of the day. In between these two extremes are intermittent fields where the field is periodically turned on or off. Over the years, data from Dr. Graham's laboratory at the Midwest Research Institute has suggested that continuous and intermittent exposure of humans to 60-Hz electric and magnetic fields might not produce the same biological responses. Apart from studies on intermittence, little research has focused on the effects of temporal variability in exposure. In epidemiology studies where specific locations, e.g. bedrooms, or personal exposures have been measured over one or two days with recording magnetic field meters, this aspect of exposure could be analyzed to test specific hypotheses.

The TWA magnetic field has been used, most often in epidemiology studies, to relate potentially relevant aspects of exposure to biological responses and health conditions. There are clear advantages to this metric because it provides an estimate of the average exposure and it can be used to obtain total cumulative exposure. These derivative field descriptors are conveniently collected by recording magnetic-field meters, where the goal of the measurement strategy is to collect PE measurements.

A large number of other potential field parameters has been suggested or tested for links to biological responses, in addition to those described above. Listings and descriptions of these field parameters or derivative measures are found in Rapid Engineering Report #1 (Electric

Research and Management, Inc., 1997: 24-42), #2 (Bittner, 1997: 2-9 to 2-11; Appendix A.4[2]), and #4 (Bracken et al., 1997: 2-20).

It is important to note that a number of other field parameters are correlated with the TWA magnetic field and the variability in the TWA (Armstrong et al., 1990; Sahl et al., 1994; Savitz et al., 1994, Villenueve et al., 1997).

The presence of such correlations, however, should not be regarded as a substitute for more rigorous and specific tests for associations with disease end points

Implications for Risk Assessment

A variety of magnetic-field, and some electric-field, parameters have been tested for their effect on biological responses in the laboratory and association with disease in epidemiology studies. Altogether, there is no strong evidence that points to one field parameter or a mechanistically related group of parameters as a factor in producing biological responses. There is as yet no agreement as to what should be defined as a biological “dose.” This lack of agreement poses an obstacle to the further development and refinement of methods to capture relevant characteristics of electric- and magnetic-field exposures.

Nevertheless, there is a need to perform more careful and detailed review and analysis of the existing exposure and biological data. The effort spent in the review and analysis of data has not kept pace with the ability to measure and record magnetic-field data.

Few studies have reported the exposure conditions in sufficient detail that quality control issues can begin to be addressed. The criteria proposed by the National Academy of Sciences in their first review of ELF fields in 1979 should be implemented (NAS, 1979). The greatest weight should be placed on those laboratory studies in which at least three levels of exposure were used, so that exposure-response relationships can be investigated. Studies in which effects of field parameters were tested in a yes/no fashion against sham-controls may not effectively control against artifact and error.

The strong focus in the literature on field magnitude and TWA, supplemented with surveys for other field parameters of interest, has canvassed the most plausible and experimentally supported mechanisms by which fields might adversely affect health. At present, the field parameters that would appear to be most plausibly and consistently related to biological responses are those reflecting field magnitude, perhaps modified by other field parameters.

---

[2] Readers interested in a discussion of field parameters relevant to proposed biological interaction mechanisms should consult this Appendix.

Remaining Questions

1. Should a list of studies in which exposure parameters were well characterized be identified to improve the focus on important "positive" and "negative" studies?
2. Should the scientific community: a) make public recommendations regarding minimum standards for quality in the definition, collection, and analysis of exposure data, and b) make them available to funding agencies and journal editors?
3. What opportunities are there to use converging approaches to reduce the number of potential field parameters that might be biologically relevant? Can we estimate the impact of alternative metric definitions on the interpretation of "positive" studies in the same way that epidemiologists eliminate possible confounding variables?
4. Has the focus on magnetic fields instead of electric fields been fostered by the ease and availability of measurement and calculation technologies rather than by biological and epidemiological evidence?
5. What recommendations can be made to improve the reproducibility of field exposures across laboratories?

References

Armstrong,B.G.; Deadman,J.E.; Thériault,G. Comparison of indices of ambient exposure to 60-hertz electric and magnetic fields. *Bioelectromagnetics* 11(4), 337-347. 1990.

Ahlbom, A.; Albert, E.N.; Fraser-Smith, A.C.; Grodzinsky, A.J.; Marron, M.T.; Martin, A.O.; Persinger, M.A.; Shelanski, M.L.; Wolpaw, E.R. Biological Effects of Power Line Fields. New York State Power Lines Project, Scientific Advisory Panel Final Report, July 1987.

Bittner, P. Development of recommendations for guidelines for environment-specific magnetic-field measurement. RAPID Engineering Project #2. Magnetic Measurements for Oak Ridge National Laboratory EMF Research Program. U.S. Department of Energy. 1997.

Bracken, T.D., Rankin, R.F., Wiley, J.F., Bittner, P. Recommendations for guidelines for personal exposure field measurements. RAPID Engineering Project #4. T. Dan Bracken, Inc. for Oak Ridge National Laboratory EMF Research Program. U.S. Department of Energy. 1997

Electric Research and Management, Inc. Development of recommendations for guidelines for field source measurement. RAPID Engineering Project #1. For Oak Ridge National Laboratory EMF Research Program. U.S. Department of Energy. 1997.

IEEE. *IEEE Standard Dictionary of Electrical and Electronics Terms.* 4th ed. The Institute of Electrical and Electronics Engineers, Inc., New York, NY. 1988.

Kato, M.; Shigemitsu, T. Effects of 50-Hz magnetic fields on pineal function in the rat. *In* The Melatonin Hypothesis: Breast Cancer and the Use of Electric Power. R.G. Stevens, B.W. Wilson, L. E. Anderson (eds). Columbus, Ohio: Battelle Press, pp. 337-376. 1997.

Misakian, M.; Sheppard, A.R.; Krause, D.; Frazier, M.E.; Miller, D.L. Biological, physical, and electrical parameters for in-vitro studies with ELF magnetic and electric fields: a primer. *Bioelectromagnetics Supplement*. 2:1-73. 1993.

National Academy of Science (NAS). Committee on Biological Effects of Extremely-Low-Frequency Radiation Biological Effects of Electric and Magnetic Fields Associated with Proposed Project Seafarer. 1979.

National Institute of Environmental Health Sciences (NIEHS) and the Electric and Magnetic Fields Research and Public Information Dissemination Program (EMF RAPID). “Ion resonance and Electron Transfer Mechanisms.” Breakout Group Reports for Theoretical Mechanisms and In-vitro Research Findings. EMF Science Review Symposium, March 24-27, pp. 11-54, 1997.

Sahl, J.D.; Kelsh, M.A.; Smith, R.W.; Aseltine, D.A. Exposure to 60-Hz magnetic fields in the electric utility work environment. *Bioelectromagnetics*. 15:21-32. 1994.

Savitz, D.A.; Ohya, T.; Loomis, D.P.; Senior, R.S.; Bracken, T.D.; Howard, R.L.. Correlations among indices of electric and magnetic field exposure in electric utility workers. *Bioelectromagnetics*. 15:193-204. 1994.

Villeneuve,PJ; Agnew,DA; Corey,PN; MillerAB (1998): Alternate indices of electric and magnetic field exposures among Ontario electrical utility workers. Bioelectromagnetics. 19:140-151.

Table 2-1: Selected magnetic-field parameters with reference to selected hypothesized biological mechanisms

Specific Measure	Applicable Research Areas			
	Resonances	Coherence-Intermittency	Induced Currents	Magnetic Moment
AC-DC Angle	x			x
AC-DC Parallel Magnitude	x			x
AC-DC Perpendicular Magnitude	x			x
AC RMS		x		
Analog AC RMS		x		
Coherency Index		x		
DC	x			x
Harmonic Magnitude	x	x	x	x
Harmonic Phase	x	x		x
Intermittency Index		x		
Low Frequency RMS			x	
Maximum Spatial Component	x	x		x
Maximum Spatial Phase	x	x		x
Minimum Spatial Component	x	x		x
Minimum Spatial Phase	x	x		x
Peak Magnitude			x	x
Peak Rate-of-Change			x	
Peak Resultant			x	x
Peak-to-Peak Magnitude			x	x
Polarization	x	x		x
Rate-of-Change Intermittency		x	x	
Resonance Indices	x			x
Resultant	x	x		x
Transient Indices of Rise Time, Over-shoot, Settling Time, Natural Frequency			x	
Transient Peak Rate-of-Change			x	
Very-Low-Frequency RMS			x	

Source: *Recommendations for Guidelines for Source Measurements*, Electric Research & Management, Inc., May, 1997.