HANDBOOK OF BIOLOGICAL EFFECTS OF
ELECTROMAGNETIC FIELDS

THIRD EDITION

Biological and Medical Aspects of Electromagnetic Fields

EDITED BY

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biological and medical aspects of these three. Bioelectromagnetics first emerged as a separate scientific subject because of interest in studying possible hazards from exposure to electromagnetic fields and setting exposure limits. A second interest is in the beneficial use of fields to advance health, both in diagnostics and in treatment, an interest that is as old as the discovery of electricity itself. Finally, the interactions between electromagnetic fields and biological systems raise some fundamental, unanswered scientific questions and may also lead to fields being used as tools to probe basic biology and biophysics. Answering basic bioelectromagnetic questions will not only lead to answers about potential electromagnetic hazards and to better beneficial applications, but they should also contribute significantly to our basic understanding of biological processes. Both strong fields and those on the order of the fields generated within biological systems may become tools to perturb the systems, either for experiments seeking to understand how the systems operate or simply to change the systems, such as by injecting a plasmid containing genes whose effects are to be investigated. These three threads are intertwined throughout bioelectromagnetics. Although any specific chapter in this work will emphasize one or another of these threads, the reader should be aware that each aspect of the research is relevant to a greater or lesser extent to all three.

The reader should note that the chapter authors have a wide variety of interests and backgrounds and have concentrated their work in areas ranging from safety standards and possible health effects of low-level fields to therapy through biology and medicine to the fundamental physics and chemistry underlying the biology. It is therefore not surprising that they have different and sometimes conflicting points of view on the significance of various results and their potential applications. Thus authors should only be held responsible for the viewpoints expressed in their chapters and not in others. We have tried to select the authors and topics so as to cover the scientific results to date that are likely to serve as a starting point for future work that will lead to the further development of the field. Each chapter's extensive reference section should be helpful for those needing to obtain a more extensive background than is possible from a book of this type.

Some of the material, as well as various authors' viewpoints, are controversial, and their importance is likely to change as the field develops and our understanding of the underlying science improves. We hope that this volume will serve as a starting point for both students and practitioners to come up-to-date with the state of understanding of the various parts of the field as of late 2004 or mid-2005, when authors contributing to this volume finished their literature reviews.

The editors would like to express their appreciation to all the authors for the extensive time and effort they have put into preparing this edition, and it is our wish that it will prove to be of value to the readers and lead to advancing our understanding of this challenging field.

Frank S. Barnes
Ben Greenebaum

Preface

We are honored to have been asked to carry on the tradition established by Dr. Postow and the late Dr. Polk in the first two editions of the *Handbook of Biological Effects of Electromagnetic Fields*. Their editions of this handbook were each recognized as the authoritative standards of their time for scientists working in bioelectromagnetics, the science of electromagnetic field effects on biological systems, and for others seeking information about this field of research.

In revising and updating this edition of the *Handbook of Biological Effects of Electromagnetic Fields*, we have expanded the coverage to include more material on diagnostic and therapeutic applications. At the same time, in updating and expanding the previous editions' coverage of the basic science and studies related to the possible biological effects of the electromagnetic fields, we have added new material on the related physics and chemistry as well as reviews of the recent developments in the setting standards for exposure limits. Following the previous edition's lead, we have charged the authors of the individual chapters with providing the reader, whom we imagine is fairly well founded in one or more of the sciences underlying bioelectromagnetics but perhaps not in the others or in the interdisciplinary subject of bioelectromagnetics itself, with both an introduction to their topic and a basis for further reading. We asked the chapter authors to write what they would like to be the first thing they would ask a new graduate student in their laboratory to read. We hope that this edition, like its two predecessors, will be useful to many as a reference book and to others as a text for a graduate course that introduces bioelectromagnetics or some of its aspects.

As a "handbook" and not an encyclopedia, this work does not intend to cover all aspects of bioelectromagnetics. Nevertheless, taking into account the breadth of topics and growth of research in this field since the last edition, we have expanded the number of topics and the number of chapters. Unavoidably, some ideas are duplicated in chapters, sometimes from different viewpoints that could be instructive to the reader; and different aspects of others are presented in different chapters. The increased amount of material has led to the publication of the handbook as two separate, but inter-related volumes: *Biological and Medical Aspects of Electromagnetic Fields (BMA)* and *Bioengineering and Biophysical Aspects of Electromagnetic Fields (BBA)*. Because there is no sharp dividing line, some topics are dealt with in parts of both volumes. The reader should be particularly aware that various theoretical models, which are proposed for explaining how fields interact with biological systems at a biophysical level, are distributed among a number of chapters. No one model has become widely accepted, and it is quite possible that more than one will in fact be needed to explain all observed phenomena. Most of these discussions are in the *Biological and Medical* volume, but the *Bioengineering and Biophysics* volume's chapters on electroporation and on mechanisms and therapeutic applications, for example, also have relevant material. Similarly, the chapters on biological effects of static magnetic fields and on endogenous electric fields in animals could equally well have been in the *Biological and Medical* volume. We have tried to use the index and cross-references in the chapters to direct the reader to the most relevant linkages, and we apologize for those we have missed.

Research in bioelectromagnetics stems from three sources, all of which are important; and various chapters treat both basic physical science and engineering aspects and the

Editors

Frank Barnes received his B.S. in electrical engineering in 1954 from Princeton University and his M.S., engineering, and Ph.D. degrees from Stanford University in 1955, 1956, and 1958, respectively. He was a Fulbright scholar in Baghdad, Iraq, in 1958 and joined the University of Colorado in 1959, where he is currently a distinguished professor. He has served as chairman of the Department of Electrical Engineering, acting dean of the College of Engineering, and in 1971 as cofounder/director with Professor George Codding of the Political Science Department of the Interdisciplinary Telecommunications Program (ITP).

He has served as chair of the IEEE Electron Device Society, president of the Electrical Engineering Department Heads Association, vice president of IEEE for Publications, editor of the *IEEE Student Journal* and the *IEEE Transactions on Education*, as well as president of the Bioelectromagnetics Society and U.S. Chair of Commission K—International Union of Radio Science (URSI). He is a fellow of the AAAS, IEEE, International Engineering Consortium, and a member of the National Academy of Engineering.

Dr. Barnes has been awarded the Curtis McGraw Research Award from ASEE, the Leon Montgomery Award from the International Communications Association, the 2003 IEEE Education Society Achievement Award, Distinguished Lecturer for IEEE Electron Device Society, the 2002 ECE Distinguished Educator Award from ASEE, The Colorado Institute of Technology Catalyst Award 2004, and the Bernard M. Gordon Prize from National Academy of Engineering for Innovations in Engineering Education 2004. He was born in Pasadena, CA, in 1932 and attended numerous elementary schools throughout the country. He and his wife, Gay, have two children and two grandchildren.

Ben Greenebaum retired as professor of physics at the University of Wisconsin–Parkside, Kenosha, WI, in May 2001, but was appointed as emeritus professor and adjunct professor to continue research, journal editing, and university outreach projects. He received his Ph.D. in physics from Harvard University in 1965. He joined the faculty of UW–Parkside as assistant professor in 1970 following postdoctoral positions at Harvard and Princeton Universities. He was promoted to associate professor in 1972 and to professor in 1980. Greenebaum is author or coauthor of more than 50 scientific papers. Since 1992, he has been editor in chief of *Bioelectromagnetics*, an international peer-reviewed scientific journal and the most cited specialized journal in this field. He spent 1997–1998 as consultant in the World Health Organization's International EMF Project in Geneva, Switzerland. Between 1971 and 2000, he was part of an interdisciplinary research team investigating the biological effects of electromagnetic fields on biological cell cultures. From his graduate student days through 1975, his research studied the spins and moments of radioactive nuclei. In 1977 he became a special assistant to the chancellor and in 1978, associate dean of faculty (equivalent to the present associate vice chancellor position). He served 2 years as acting vice chancellor (1984–1985 and 1986–1987). In 1989, he was appointed as dean of the School of Science and Technology, serving until the school was abolished in 1996.

On the personal side, he was born in Chicago and has lived in Racine, WI, since 1970. Married since 1965, he and his wife have three adult sons.

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Introduction

Charles Polk[*]

Revised for the 3rd Edition by Ben Greenebaum

Much has been learned since this handbook's first edition, but a full understanding of biological effects of electromagnetic fields has is to be achieved. The broad range of what must be studied has to be a factor in the apparent slow progress toward this ultimate end. The broad range of disciplines involved includes basic biology, medical science and clinical practice, biological and electrical engineering, basic chemistry and biochemistry, and fundamental physics and biophysics. The subject matter ranges over characteristic lengths and timescales from, at one extreme, direct current (dc) or $\sim 10^4$ km-wavelengths, multimillisecond ac fields and large, long-lived organisms to, at the other extreme, submillimeter wavelength fields with periods below 10^{-12} s and subcellular structures and molecules with subnanometer dimensions and characteristic times as short as the 10^{-15} s or less of biochemical reactions.

This chapter provides an introduction and overview of the research and the contents of this handbook.

0.1 Near Fields and Radiation Fields

In recent years it has become, unfortunately, a fairly common practice—particularly in nontechnical literature—to refer to the entire subject of interaction of electric (E) and magnetic (H) fields with organic matter as biological effects of nonionizing radiation, although fields that do not vary with time and, for most practical purposes, slowly time-varying fields do not involve radiation at all. The terminology had its origin in an effort to differentiate between relatively low-energy microwave radiation and high-energy radiation, such as UV and x-rays, capable of imparting enough energy to a molecule or an atom to disrupt its structure by removing one or more electron\s with a single photon. However, when applied to dc or extremely low-frequency (ELF), the term "nonionizing radiation" is inappropriate and misleading.

A structure is capable of efficiently radiating electromagnetic waves only when its dimensions are significant in comparison with the wavelength λ. But in free space $\lambda = c/f$, where c is the velocity of light in vacuum (3×10^8 m/s) and f is the frequency in hertz (cycles/s); therefore the wavelength at the power distribution frequency of 60 Hz, e.g., is 5000 km, guaranteeing that most available human-made structures are much smaller than one wavelength.

The poor radiation efficiency of electrically small structures (i.e., structures whose largest linear dimension $L \ll \lambda$ can be illustrated easily for linear antennas. In free space the radiation resistance, R_r of a current element, i.e., an electrically short wire of length ℓ carrying uniform current along its length [1], is

$$R_r = 80\pi^2 \left(\frac{\ell}{\lambda}\right)^2 \tag{0.1}$$

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[*] Deceased.

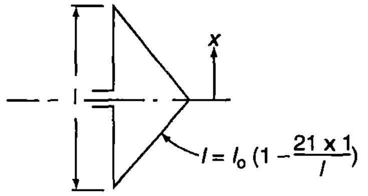

FIGURE 0.1
Current distribution on short, thin, center-fed antenna.

whereas the R_r of an actual center-fed radiator of total length ℓ with current going to zero at its ends, as illustrated in Figure 0.1, is

$$R_r = 20\pi^2 \left(\frac{\ell}{\lambda}\right)^2 \tag{0.2}$$

Thus, the R_r of a 0.01 λ antenna, 50 km long at 60 Hz, would be 0.0197 Ω. As the radiated power $P_r = I^2 R_r$ where I is the antenna terminal current, whereas the power dissipated as heat in the antenna wire is $I^2 R_d$; when I is uniform, the P_r will be very much less than the power used to heat the antenna, given that the ohmic resistance R_d of any practical wire at room temperature will be very much larger and R_r. For example, the resistance of a 50-km long, 1/2-in. diameter solid copper wire could be 6.65 Ω. At dc, of course, no radiation of any sort takes place, as acceleration of charges is a condition for radiation of electromagnetic waves.

The second set of circumstances, which guarantees that any object subjected to low-frequency E and H fields usually does not experience effects of radiation, is that any configuration that carries electric currents sets up E and H field components which store energy without contributing to radiation. A short, linear antenna in free space (short electric dipole) generates, in addition to the radiation field E_r, an electrostatic field E_s and an induction field E_i. Neither E_s nor E_i contribute to the P_r [2,3]. Whereas E_r varies as $1/r$, where r is the distance from the antenna, E_i varies as $1/r^2$, and E_s as $1/r^3$. At a distance from the antenna of approximately one sixth of the wavelength ($r = \lambda/2\pi$), the E_i equals the E_r, and when $r \ll \lambda/6$ the E_r quickly becomes negligible in comparison with E_i and E_s. Similar results are obtained for other antenna configurations [4]. At 60 Hz the distance $\lambda/2\pi$ corresponds to about 800 km and objects at distances of a few kilometers or less from a 60-Hz system are exposed to nonradiating field components, which are orders of magnitude larger than the part of the field that contributes to radiation.

A living organism exposed to a static (dc) field or to a nonradiating near field may extract energy from it, but the quantitative description of the mechanism by which this extraction takes place is very different than at higher frequencies, where energy is transferred by radiation:

1. In the near field the relative magnitudes of E and H are a function of the current or charge configuration and the distance from the electric system. The E field may be much larger than the H field or vice versa (see Figure 0.2).
2. In the radiation field the ratio the E to H is fixed and equal to 377 in free space, if E is given in volt per meter and H in ampere per meter.
3. In the vicinity of most presently available human-made devices or systems carrying static electric charges, dc, or low-frequency (<1000 Hz) currents, the E and H fields will only under very exceptional circumstances be large enough to produce heating effects inside a living object, as illustrated by Figure 0.3. (This statement assumes that the living object does not form part of a conducting path

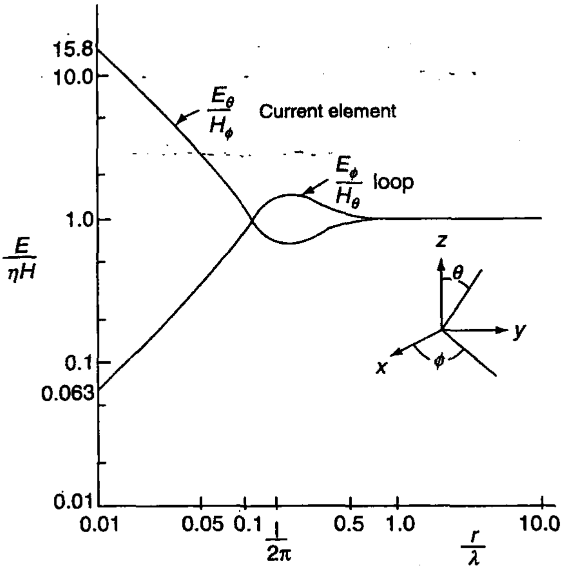

FIGURE 0.2
Ratio of E to H field (divided by wave impedance of free space $\eta = 377\ \Omega$) at $\theta = 90°$ for electric current element at origin along z-axis and for electrically small loop centered at the origin in x–y plane.

that permits direct entrance of current from a wire or conducting ground.) However, nonthermal effects are possible; thus an E field of sufficient magnitude may orient dipoles, or translate ions or polarizable neutral particles (see Chapter 3 and Chapter 4 in *BBA**).

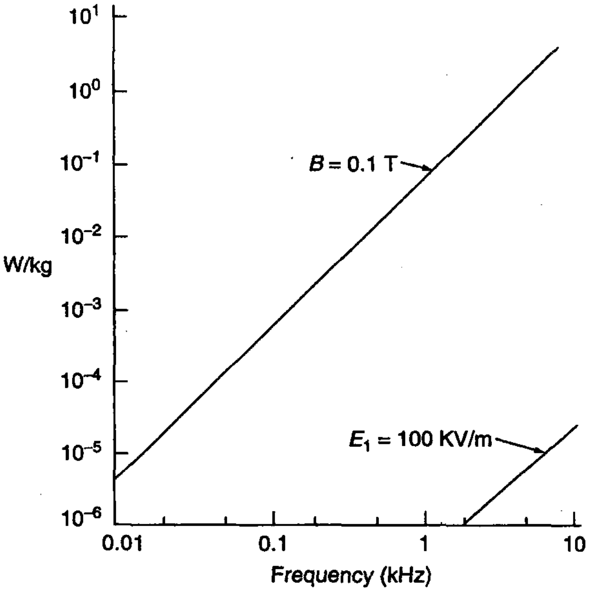

FIGURE 0.3
Top line: Eddy current loss produced in cylinder by sinusoidally time-varying axial H field. Cylinder parameters are conductivity $\sigma = 0.1\,\mathrm{S/m}$, radius 0.1 m, density $D = 1100\,\mathrm{kg/m^3}$, RMS magnetic flux density $0.1\,\mathrm{T} = 1000\,\mathrm{G}$. Watt per kilogram $= \sigma B^2 r^2 w^2 / 8D$; see Equation 0.15 and use power per volume $= J^2/\sigma$, *Lower line:* loss produced by 60-Hz E field in Watt per kilogram $= \sigma\, E_{\mathrm{int}}{}^2 / D$, where external field E_1 is related to E_{int} by Equation 0.9 with $\varepsilon_2 = \varepsilon_0 \times 10^5$ at 1 kHz and $\varepsilon_0 = 8 \times 10^4$ at 10 kHz.

**BBA*: *Bioengineering and Biophysical Aspects of Electromagnetic Fields* (ISBN 0-8493-9539-9); *BMA*: *Biological and Medical Aspects of Electromagnetic Fields* (ISBN 0-8493-9538-0).

4. With radiated power it is relatively easy to produce heating effects in living objects with presently available human-made devices (see Chapter 10 in *BBA* and Chapter 5 in *BMA*). This does not imply, of course, that all biological effects of radiated radio frequency (RF) power necessarily arise from temperature changes.

The results of experiments involving exposure of organic materials and entire living organisms to static E and ELF E fields are described in *BBA*, Chapter 3. Various mechanisms for the interaction of such fields with living tissue are also discussed there and in *BBA*, Chapter 5. In the present introduction, we shall only point out that one salient feature of static (dc) and ELF E field interaction with living organisms is that the external or applied E field is always larger by several orders of magnitude than the resultant average internal E field [5,6]. This is a direct consequence of boundary conditions derived from Maxwell's equations [1–3].

0.2 Penetration of Direct Current and Low-Frequency Electric Fields into Tissue

Assuming that the two materials illustrated schematically in Figure 0.4 are characterized, respectively, by conductivities σ_1 and σ_2 and dielectric permittivities ε_1 and ε_2, we write E-field components parallel to the boundary as E_P and components perpendicular to the boundary as $E_\perp$. For both static and time-varying fields

$$E_{P1} = E_{P2} \tag{0.3}$$

and for static (dc) fields

$$\sigma_1 E_{\perp 1} = \sigma_2 E_{\perp 2} \tag{0.4}$$

as a consequence of the continuity of current (or conservation of charge). The orientations of the total E fields in media 1 and 2 can be represented by the tangents of the angles between the total fields and the boundary line

$$\tan\theta_1 = \frac{E_{\perp 1}}{E_{P1}}, \quad \tan\theta_2 = \frac{E_{\perp 2}}{E_{P2}} \tag{0.5}$$

From these equations it follows that

$$\tan\theta_1 = \frac{\sigma_2}{\sigma_1}\frac{E_{\perp 1}}{E_{P1}} = \frac{\sigma_2}{\sigma_1}\frac{E_{\perp 2}}{E_{P2}} = \frac{\sigma_2}{\sigma_1}\tan\theta_2 \tag{0.6}$$

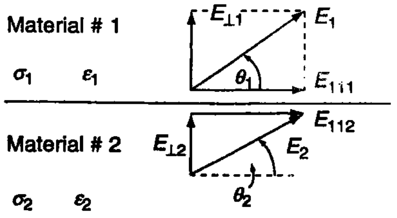

FIGURE 0.4
Symbols used in description of boundary conditions for E-field components.

If material 1 is air with conductivity [7] $\sigma_1 = 10^{-13}$ S/m and material 2 a typical living tissue with $\sigma_2 \approx 10^{-1}$ S/m (compare Chapter 3 in *BBA*), $\tan\theta_1 = 10^{12}\tan\theta_2$, and therefore even if the field in material 2 (the inside field) is almost parallel to the boundary so that $\theta_2 \cong 0.5°$ or $\tan\theta_2 \approx (1/100)$, $\tan\theta_1 = 10^{10}$ or $\theta_1 = (\pi/2 - 10)^{-10}$ radians. Thus an electrostatic field in air, at the boundary between air and living tissue, must be practically perpendicular to the boundary. The situation is virtually the same at ELF although Equation 0.4 must be replaced by

$$\sigma_1 E_{\perp 1} - \sigma_2 E_{\perp 2} = -\mathrm{j}\omega\rho_s \tag{0.7}$$

and

$$\varepsilon_1 E_{\perp 1} - \varepsilon_2 E_{\perp 2} = \rho_s \tag{0.8}$$

where $\mathrm{j} = \sqrt{-1}$, ω is the radian frequency ($= 2\pi \times$ frequency), and ρ_s is the surface charge density. In Chapter 3 in *BBA* it is shown that at ELF the relative dielectric permittivity of living tissue may be as high as 10^6 so that $\varepsilon_2 = 10^6\ \varepsilon_0$, where ε_0 is the dielectric permittivity of free space $(1/36\ \pi)\ 10^{-9}$ F/m; however, it is still valid to assume that $\varepsilon_2 \leq 0^{-5}$. Then from Equation 0.7 and Equation 0.8

$$E_{\perp 1} = \frac{\sigma_2 + \mathrm{j}\omega\varepsilon_2}{\sigma_1 + \mathrm{j}\omega\varepsilon_1} E_{\perp 2} \tag{0.9}$$

which gives at 60 Hz with $\sigma_2 = 10^1$ S/m, $\sigma_1 = 10^{-13}$ S/m, $\varepsilon_2 \approx 10^{-5}$ F/m, and $\varepsilon_1 \approx 10^{-11}$ F/m

$$E_{\perp 1} = \frac{10^{-1} + \mathrm{j}_4 10^{-3}}{10^{-13} + \mathrm{j}_4 10^{-9}} E_{\perp 2} \approx \frac{\sigma_2}{\mathrm{j}\omega\varepsilon_1} = -\mathrm{j}\,(2.5 \times 10^7) E_{\perp 2} \tag{0.10}$$

This result, together with Equation 0.3 and Equation 0.5, shows that for the given material properties, the field in air must still be practically perpendicular to the boundary of a living organism: $\tan\theta_1$: $2.5(10^7)\tan\theta_2$.

Knowing now that the living organism will distort the E field in its vicinity in such a way that the external field will be nearly perpendicular to the boundary surface, we can calculate the internal field by substituting the total field for the perpendicular field in Equation 0.4 (dc) and Equation 0.9 (ELF). For the assumed typical material parameters we find that in the static (dc) case

$$\frac{E_{\text{internal}}}{E_{\text{external}}} \approx 10^{-12} \tag{0.11}$$

$$\rho_f = \frac{3(\sigma_2\varepsilon_1 - \sigma_1\varepsilon_2)E_0}{2\sigma_1 + \sigma_2}\cos\vartheta\ \mathrm{C/m^2}$$

and for 60 Hz

$$\frac{E_{\text{internal}}}{E_{\text{external}}} \approx 4(10^{-8}) \tag{0.12}$$

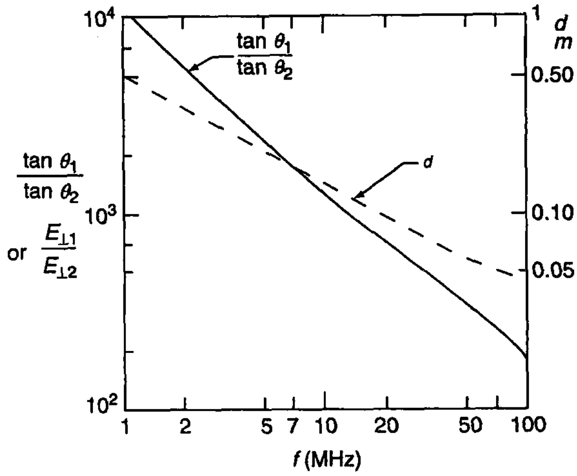

FIGURE 0.5
Orientation of E-field components at air–muscle boundary (or ratio of fields perpendicular to boundary); depth (d) at which field component parallel to boundary surface decreases by approximately 50% ($d = 0.693\delta$).

Thus, a 60-Hz external field of 100 kV/m will produce an average E_{internal} field of the order of 4 mV/m.

If the boundary between air and the organic material consists of curved surfaces instead of infinite planes, the results will be modified only slightly. Thus, for a finite sphere (with ε and σ as assumed here) embedded in air, the ratios of the internal field to the undisturbed external field will vary with the angle θ and distance r as indicated in Figure 0.5, but will not deviate from the results indicated by Equation 0.7 and Equation 0.8 by more than a factor of 3 [3,8]. Long cylinders ($L \ll r$) aligned parallel to the external field will have interior fields essentially equal to the unperturbed external field, except near the ends where the field component perpendicular to the membrane surface will be intensified approximately as above (see Chapter 9 and Chapter 10 in this volume).

0.3 Direct Current and Low-Frequency Magnetic Fields

Direct current H fields are considered in more detail in the Chapter 3, Chapter 5, and Chapter 8 in *BBA*. ELF H fields are considered in various places, including Chapter 5 and Chapter 7 in *BBA* and Chapter 2 and Chapter 11 in *BMA*. As the magnetic permeability μ of most biological materials is practically equal to the magnetic permeability μ_0 of free space, $4\pi(10^{-7})$ H/m, the dc or ELF H field "inside" will be practically equal to the H field "outside." The only exceptions are organisms such as the magnetotactic bacteria, which synthesize ferromagnetic material, discussed in Chapter 8 of *BBA*. The known and suggested mechanisms of interaction of dc H fields with living matter are:

1. Orientation of ferromagnetic particles, including biologically synthesized particles of magnetite.
2. Orientation of diamagnetically or paramagnetically anisotropic molecules and cellular elements [9].
3. Generation of potential differences at right angles to a stream of moving ions (Hall effect, also sometimes called a magnetohydrodynamic effect) as a result of the magnetic force $F_m = qvB \sin \theta$, where q is the the electric charge, v is the

velocity of the charge, B is the magnetic flux density, and $\sin\theta$ is the sine of the angle θ between the directions v and B. One well-documented result of this mechanism is a "spike" in the electrocardiograms of vertebrates subjected to large dc H fields.

4. Changes in intermediate products or structural arrangements in the course of light-induced chemical (electron transfer) reactions, brought about by Zeeman splitting of molecular energy levels or effects upon hyperfine structure. (The Zeeman effect is the splitting of spectral lines, characteristic of electronic transitions, under the influence of an external H field; hyperfine splitting of electronic transition lines in the absence of an external H field is due to the magnetic moment of the nucleus; such hyperfine splitting can be modified by an externally applied H field.) The magnetic flux densities involved not only depend upon the particular system and can be as high as 0.2 T (2000 G) but also <0.01 mT (100 G). Bacterial photosynthesis and effects upon the visual system are prime candidates for this mechanism [10,11].
5. Induction of E fields with resulting electrical potential differences and currents within an organism by rapid motion through a large static H field. Some magnetic phosphenes are due to such motion [12].

Relatively slow time-varying H fields, which are discussed in the basic mechanisms and therapeutic uses chapters (Chapter 5 of *BBA* and Chapter 11 in *BMA*), among others, may interact with living organisms through the same mechanisms that can be triggered by static H fields, provided the variation with time is slow enough to allow particles of finite size and mass, located in a viscous medium, to change orientation or position where required (mechanism 1 and 2) and provided the field intensity is sufficient to produce the particular effect. However, time-varying H fields, including ELF H fields, can also induce electric currents into stationary conducting objects. Thus, all modes of interaction of time-varying E fields with living matter may be triggered by time-varying, but not by static, H fields.

In view of Faraday's law, a time-varying magnetic flux will induce E fields with resulting electrical potential differences and "eddy" currents through available conducting paths. As very large external ELF E fields are required (as indicated by Equation 0.9 through Equation 0.12) to generate even small internal E fields, many human-made devices and systems generating both ELF E and H fields are more likely to produce physiologically significant internal E fields through the mechanism of *magnetic* induction.

The induced voltage V around some closed path is given by

$$V = \oint E \cdot \mathrm{d}\ell = -\iint \frac{\partial B}{\partial t}\,\mathrm{d}s \tag{0.13}$$

where E is the induced E field. The integration $\oint E\,\mathrm{d}\ell$ is over the appropriate conducting path, $\partial B/\partial t$ is the time derivative of the magnetic flux density, and the "dot" product with the surface element, ds, indicates that only the component of $\partial B/\partial t$ perpendicular to the surface, i.e., parallel to the direction of the vector ds, enclosed by the conducting path, induces an E field. To obtain an order-of-magnitude indication of the induced current that can be expected as a result of an ELF H field, we consider the circular path of radius r, illustrated by Figure 0.6. Equation 0.13 then gives the magnitude of the E field as

$$E = \frac{\omega B r}{2} \tag{0.14}$$

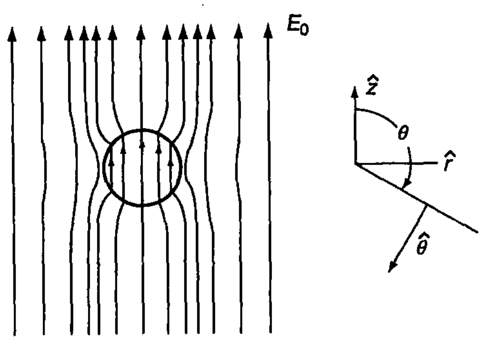

FIGURE 0.6
E field when sphere of radius R, conductivity σ_2, and dielectric permittivity ε_2 is placed into an initially uniform static field ($E = 2E_0$) within a medium with conductivity σ_1 and permittivity ε_1. The surface charge density is $\rho_r = \frac{3(\sigma_2\varepsilon_1 - \sigma_1\varepsilon_2)E_0}{2\sigma_1 + \sigma_2}\cos\theta$ C/m^2.

$$r < R \quad \bar{E} = \frac{3\sigma_1 E_0}{2\sigma_1 + \sigma_2}\hat{z} \qquad \varepsilon_2, \sigma_2$$

$$r < R \quad \bar{E} = E_0 \cos\theta\left[1 + \frac{2R^3(\sigma_2 \propto \sigma_1)}{r^3(2\sigma_1 + \sigma_2)}\right]\hat{r} \qquad \varepsilon_1, \sigma_1$$

$$- E \sin\theta\left[1 - \frac{R^3(\sigma_2 \propto \sigma_1)}{r^3(2\sigma_1 + \sigma_2)}\right]\hat{\theta}$$

where ω is the $2\pi f$ and f is the frequency. The magnitude of the resulting electric current density J in ampere per square meter is*

$$J = \sigma E = \frac{\sigma \omega B r}{2} \tag{0.15}$$

where σ is the conductivity along the path in Siemens per meter. In the SI (Systeme Internationale) units used throughout this book, B is measured in tesla ($T = 10^4$ G) and r in meters. Choosing for illustration a circular path of 0.1 m radius, a frequency of 60 Hz, and a conductivity of 0.1 S/m, Equation 0.14 and Equation 0.15 give $E = 18.85$ B and $J = 1.885$ B. The magnetic flux density required to obtain a current density of 1 mA/m^2 is 0.53 mT or about 5 G. The E field induced by that flux density along the circular path is 10 mV/m. To produce this same 10 mV/m E_{internal} field by an external 60 Hz E_{external} field would require, by Equation 0.12, a field intensity of 250 kV/m.

As the induced voltage is proportional to the time rate of change of the H field (Equation 0.13), implying a linear increase with frequency (Equation 0.14), one would expect that the ability of a time-varying H field to induce currents deep inside a conductive object would increase indefinitely as the frequency increases; or conversely, that the magnetic flux density required to induce a specified E field would decrease linearly with frequency, as indicated in Figure 0.7. This is not true however, because the displacement current density $\partial D/\partial t$, where $D = \varepsilon E$, must also be considered as the frequency increases. This leads to the wave behavior discussed in Part III, implying that at sufficiently high frequencies the effects of both external E and H fields are limited

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*Equation 0.15 neglects the H field generated by the induced eddy currents. If this field is taken into account, it can be shown that the induced current density in a cylindrical shell of radius r and thickness Δ is given by $\Delta r < 0.01$ m^2/[$1 + j\Delta r/\delta^2$], where $H_0 = B_0/\mu_0$ and δ is the skin depth defined by Equation 0.17 below. However, for conductivities of biological materials ($\sigma < 5$ s/m) one obtains at audio frequencies $\delta > 1$ m and as for most dimensions of interest $\Delta r < 0.01$ m^2 the term $j\Delta r/\delta^2$ becomes negligible. The result $-jrH_0/\delta^2$ is then identical with Equation 0.15.

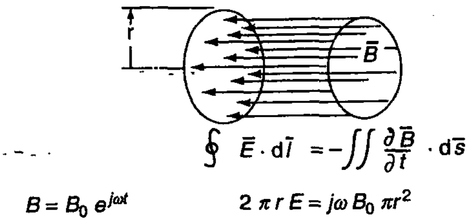

FIGURE 0.7
Circular path (loop) of radius r enclosing uniform magnetic flux density perpendicular to the plane of the loop. For sinusoidal time variation $B = B_0 e^{j\omega t}$.

by reflection losses (Figure 0.8 through Figure 0.10) as well as by skin effect [13], i.e., limited depth of penetration d in Figure 0.5.

0.4 RF Fields

At frequencies well below those where most animals and many field-generating systems have dimensions of the order of one free space wavelength, e.g., at 10 MHz where $\lambda = 30$ m, the skin effect limits penetration of the external field. This phenomenon is fundamentally different from the small ratio of internal to external E fields described in Equation 0.4 (applicable to dc) and Equation 0.9.

Equation 0.9 expresses a "boundary condition" applicable at all frequencies, but as the angular frequency ω increases (and in view of the rapid decrease with frequency of the dielectric permittivity ε_2 in biological materials—see Chapter 3 of *BBA*, the ratio of the normal component of the external to the internal E field at the boundary decreases

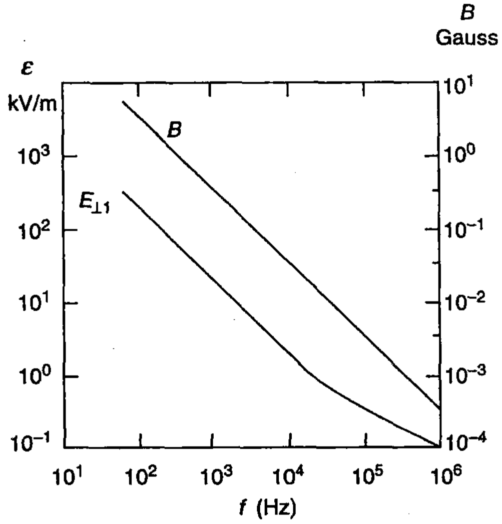

FIGURE 0.8
External E and H field required to obtain an internal E field of 10 mV/m (conductivity and dielectric permittivity for skeletal muscle from Foster, K.R., Schepps, J.L., and Schwan, H.P. 1980. *Biophys. J.*, 29:271–281. H-field calculation assumes a circular path of 0.1-m radius perpendicular to magnetic flux).

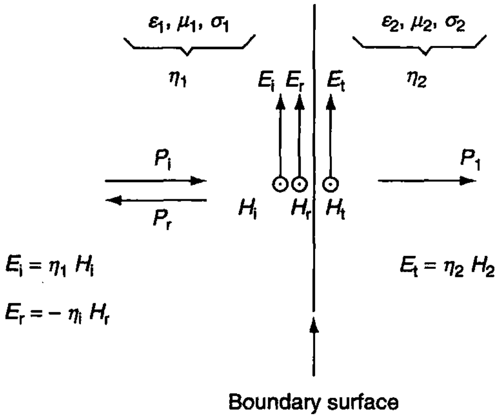

FIGURE 0.9
Reflection and transmission of an electromagnetic wave at the boundary between two different media, perpendicular incidence; P_i = incident power, P_r = reflected power, P_t = transmitted power.

with increasing frequency. This is illustrated by Figure 0.10 where $\tan\theta_1/\tan\theta_2$ is also equal to $E_{\perp 1}/E_{\perp 2}$ in view of Equation 0.3, Equation 0.5, and Equation 0.9. However, at low frequencies the total field inside the boundary can be somewhat larger than the perpendicular field at the boundary; and any field variation with distance from the boundary is not primarily due to energy dissipation, but in a homogeneous body is a consequence of shape. At RF, on the other hand, the E and H fields of the incoming

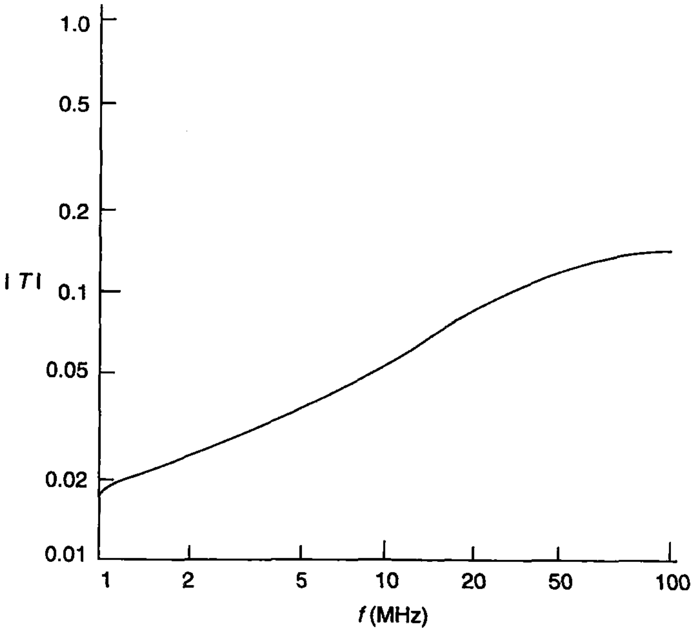

FIGURE 0.10
Magnitude of transmission coefficient T for incident E field parallel to boundary surface. $T = E_t/E_i$: reflection coefficient $r = E_r/E_i = T-1$. Γ and T are complex numbers; ε_r and σ for skeletal muscle from Chapter 3 in *BBA*.