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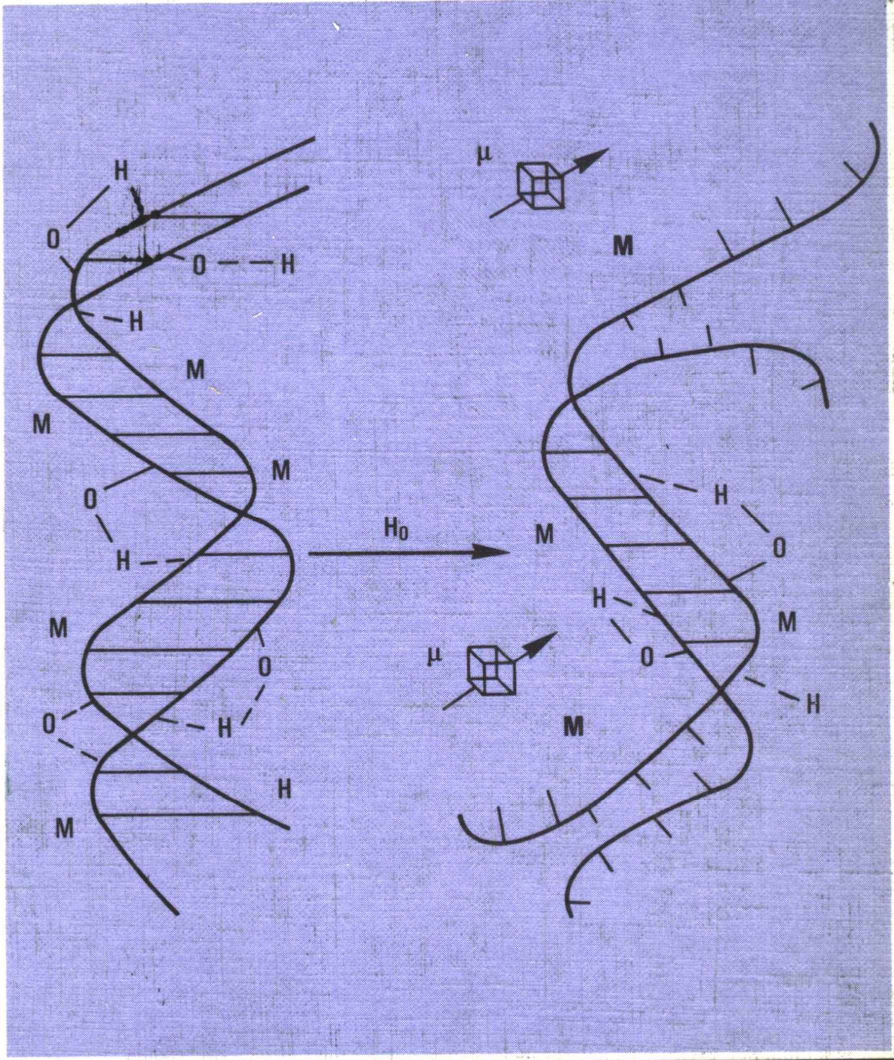
Bioelectromagnetics: Biophysical Principles in Medicine and Biology



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Bioelectromagnetics: Biophysical Principles in Medicine and Biology

Frank John Papatheofanis, Chicago, Ill.

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Drug Dosage

The authors and the publisher have exerted every effort to ensure that drug selection and dosage set forth in this text are in accord with current recommendations and practice at the time of publication. However, in view of ongoing research, changes in government regulations, and the constant flow of information relating to drug therapy and drug reactions, the reader is urged to check the package insert for each drug for any change in indications and dosage and for added warnings and precautions. This is particularly important when the recommended agent is a new and/or infrequently employed drug.

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Dedication

For my parents,
John and Rina Papatheofanis

Symbols and Abbreviations

Electronic charge	$e = 1.602 \times 10^{-19}$ coulombs (c)
Electron mass unit	emu = 1 gauss cm^{-3} (Gs cm^{-3})
Planck's constant divided by 2π	$\hbar = 1.055 \times 10^{-34}$
Boltzmann constant	$k = 1.381 \times 10^{-23}$ joule $kelvin^{-1}$ (J K^{-1})
Gradient	$\overline{\nabla}$
Divergence	$\overline{\nabla} \cdot$
Curl	$\overline{\nabla} \times$
Magnetic field intensity	1 tesla (T) = 1 weber m^{-2} (Wb m^{-2})
	= 10^4 gauss (Gs)
	= 1 volt s m^{-2} (V s m^{-2})
	= 1 kg s^{-2} $ampere^{-1}$ (kg s^{-1} A^{-1})
	1 A m^{-1} = $4\pi \times 10^{-3}$ oersted (Oe)
	= 0.0125 Oe

Preface

This short book represents the effort of many individual investigators attempting to creatively contribute to the discipline of bioelectromagnetics. The book is directed at scientists and clinicians from every branch of the physical and biological sciences. This treatise is meant to serve as a brief introduction to the discipline for the research scientist and the advanced student. Arranged with the basic structure of a scientific paper as a model, the text begins with a brief historical review relevant to bioelectromagnetics. The second chapter is a general restatement of relevant sections from the classical work of Paul Lorrain and Dale Corson, *Electromagnetic Fields and Waves* [32]. Chapter 3 introduces some of the methods used to obtain the data reviewed in Chapter 4. Finally, Chapter 5 provides a discussion of theoretical models of biological systems and their interactions with electromagnetic fields. Altogether, this book attempts to outline an intellectual approach or orientation to bioelectromagnetics which should serve to stimulate further experimentation in consideration of a logical progression and development of method.

The treatise was critically reviewed by William Negendank, Wayne State University, Detroit, Mich. His thoughtful comments and assistance are greatly appreciated. Bill J. Papatheofanis, Los Alamos National Laboratory, Los Alamos, New Mexico, provided discussion and technical knowledge of electromagnetic theory with cheerful wit and enthusiasm. Alexander Wolsky (Series Editor) and Marilyn Noz of New York University carefully reviewed the text and provided helpful suggestions and criticism. Altogether, the editorial members at Karger were patient and helpful throughout the course of completion of this treatise.

Chicago, Illinois

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1. Introduction

A sense of the interconnectedness of man and his environment has been maintained and evidenced since the earliest historical records. The ancients considered the environment an inextricable linkage between each other and forces beyond their understanding. Perhaps the earliest and most familiar observer of man's relationship to his environment was the legendary Father of Medicine, Hippocrates. Accounts of the life of Hippocrates can be traced from Plato in his discussions from the *Protagoras* and the *Phaedrus* in which Hippocrates is introduced as a contemporary of Socrates and an inhabitant of the Aegean island of Cos. In addition, Alexandrian scholars traced Hippocrates' presumable linkage to Hercules and Aesculapius, and recorded his date of birth in 460 BC and his death between 375 and 351 BC. Plato had founded his Academy in 387 BC and the geographical domain of antiquity consisted of cities in Greece, Italy and Egypt. At the time, communication between cities was poor and although the great thinkers studied and wrote, civilization based its sacred trust on beliefs unrelated to human control or destiny. The scientific community of that epoch presaged the natural philosophers of the later centuries. Gedanken (thought) experiments proved to have a much more significant role in classical science than any empirical observation. Hippocrates stood out because of his method – he observed, recorded and summarized his experiences. Acutely aware of his physical environment, he proposed that human disease was influenced by that environment, by the weather. He wrote:

With regard to the states of the weather which continue but for a day, that which is northerly, braces the body, giving it tone, agility, and color, improves the sense of the hearing, dries up the bowels, pinches the eyes, and aggravates any previous pain which may have been seated in the chest. But the southerly relaxes the body, and renders it humid, brings on dullness of hearing, heaviness of the head, and vertigo, impairs the movements of the eyes and the whole body, and renders the alvine discharges watery. With regard to the seasons, in spring and in the commencement of summer, children and those next to them are most comfortable, and enjoy best health; in summer and during a certain portion of autumn, old people; during the remainder of autumn and in winter, those of the intermediate ages.

All diseases occur at all seasons of the year, but certain of them are more apt to occur and be exacerbated at certain seasons.

Thus, Hippocrates stated a causal linkage between environment and human health. He outlined how specific diseases and maladies were more prevalent during certain seasons. From this early Greek physician, centuries of scientific inquiry have attempted to explain whether and by what mechanism human beings were connected to their environment. In many ways, most of the scientific research conducted since antiquity has been aimed at understanding man's connectedness to his environment so as to better regulate that environment to his advantage.

William Gilbert (1540–1603) was the first scientist to give magnetism a specific, quantitative description and detailed studies along the lines of a structured, purposeful effort. Gilbert obtained his bachelor's degree in 1560 from St. John's College, Cambridge. He served as a mathematical examiner before obtaining his medical degree in 1569 from Cambridge. Gilbert toured the Continent extensively before returning to London in 1573. By 1599, his reputation as a successful physician had earned him the presidency of the College of Physicians. Aside from his achievements in medicine, Gilbert devoted his energy to the study of the natural sciences and was, for example, an early advocate of Copernican thought concerning the relationship of the earth to the cosmos. He published his monumental treatise *De Magnete Magneticisque Corporibus et de Magno Magnete Tellure Physiologia Nova* in 1600. His discussion of physical science stimulated European scientists including Galileo and Bacon, and earned him widespread influence and acclaim. Gilbert attracted the great thinkers of his epoch, and a group met regularly to discuss scientific questions. This group is thought by many historians to have preceded the Royal Society of London. While his duties as a physician brought him to the Royal Court as Royal Physician, he soon died of plague during the reign of James I on November 30, 1603. In his great work, Gilbert reviewed the medicinal applications of the loadstone or magnet (named after Magnesia in Macedonia, a region reportedly rich in loadstone):

It is given chiefly in cases of lax and overhumid liver, and in cases of tumid spleen after suitable evacuations; hence young women of pale, muddy, blotchy complexion are by it restored to soundness and comeliness, for it is highly exsiccative and harmlessly astringent. But some, who in every internal disorder always recognize obstructions of liver and spleen, think it beneficial in some cases, as removing obstructions; and herein they accept the opinions of certain Arabic writers. Hence in cases of dropsy, schirrus of the liver, of chronic jaundice, and hypochondriac melancholia, or complaints of the oesophagus, they prescribe it, or add it to electuaries, often to the sure destruction of many a patient. Fallopius recommends a preparation of iron of his own for schirrus of the spleen; but, he is much mistaken, for though loadstone is exceedingly beneficial where the spleen is lax and tumid on account of humours, so far is it from curing a spleen thickened to a schirrus, that it makes the mischief far worse; for agents that are greatly siccative and that absorb humours, transform viscera that have been thickened by schirrus, into the hardness almost of a stone.

Gilbert went on to describe the earth as a great loadstone. In addition to the physical properties of the loadstone, he described the magnetic horizon, parallels, axes and poles. He detailed the properties of the loadstone in such a way that the environment as a whole could be thought of as governed by the rules and properties of the loadstone. In fact, he predicted geomagnetism and the action of bodies in the presence of magnetic lines of force or fields.

The great English scientist Michael Faraday (1791–1867) took up where his countryman Gilbert left off in the study of magnetism. Whereas generations of scientists or natural philosophers studied magnetism by concentrating on the hardware needed to generate electricity and magnetism, Faraday concentrated on the physical events associated with the surrounding magnetic fields. He was born and educated under conditions of extreme poverty. At the age of 12, Faraday was apprenticed to a bookbinder. While learning that trade, he read the *Encyclopaedia Britannica* and any other book on science that he could find. At the same time, Faraday set up a small laboratory to repeat the classical experiments in chemistry and physics that he read about. In 1813, Faraday became a laboratory assistant to Humphrey Davy, the leading English scientist of the period, and accompanied him on his European travels. After years of careful laboratory investigation, he wrote his great work, *Experimental Researches in Electricity*. Faraday gained wide scientific popularity and prestige, and became an influential member of the Royal Society. The major thrust of his lifetime as a scientist was his detailed study of electricity and magnetism. Faraday studied the electric and magnetic fields generated by a variety of living systems, and wrote:

351. After an examination of the experiments of Walsh, Ingenhousz, Cavendish, Sir H. Davy, and Dr. Davy, no doubt remains on my mind as to the identity of the electricity of the torpedo with common and voltaic electricity; and I presume that so little

will remain on the minds of others as to justify my refraining from entering at length into the philosophical proofs of that identity. The doubts raised by Sir H. Davy have been removed by his brother Dr. Davy: the results of the latter being the reverse of the former. At present the sum of the evidence is as follows:

354. ii. Magnetism. Perfectly distinct. According to Dr. Davy, the current deflected the needle and made magnets under the same law, as to direction, which governs currents of ordinary and voltaic electricity.

357. iv. Physiological Effects. These are so characteristic, that by them the peculiar powers of the torpedo and *Gymnotus* are principally recognized.

Clearly, Faraday had identified another linkage between an animal's physiological function and the electromagnetic fields that it generated. Faraday was largely self-taught and could not interpret his results in strict physical language and definition as could Ampère before him. Nonetheless, he was an outstanding experimenter and studied electromagnetic field theory with precision and simplicity. Faraday defined electricity and magnetism unlike any scientist before him and thereby set the stage for modern electromagnetics.

The history of bioelectromagnetics is replete with the inclusion of pivotal thinkers in science and medicine. Some of the most important physical discoveries set the groundwork for an investigative consideration of how living systems might be interconnected or related to the electromagnetic environment around them. As noted in Faraday's comments about the reports of the two Davys, however, conflicting and often contradictory results have been reported in the study of that relationship. Often, such disparity has been ignored and discussions about bioelectromagnetics have bordered on interpretive opinion rather than scientific evidence and evaluation. *The fundamental challenge to bioelectromagnetics remains the clear exposition of experimental and theoretical findings in light of previous reports and the existing body of scientific knowledge.*

2. Principles of Electromagnetic Fields

Nature is composed of substances, including cells and tissues, which interact with magnetic fields in a number of ways. Most materials are slightly repelled by a magnet and are termed diamagnetic. The extent or degree of diamagnetism of a substance is independent of the applied field intensity and temperature. Other substances are termed paramagnetic and are slightly attracted to a magnet. Transition metals, those elements having incompletely filled energy levels, are common examples of this class of materials. Paramagnetism is associated with the presence of an unpaired electron. As a result, paramagnetic substances generally include atoms, ions or molecules with an odd number of electrons. Paramagnetism is independent of applied field intensity but frequently is inversely related to the absolute temperature. Some substances are powerfully attracted to a magnet and are termed ferromagnetic. Up to a million times as strong as paramagnetism or diamagnetism, ferromagnetism is present in iron, cobalt, nickel and a few assorted alloys. Ferromagnetism is a function of both applied field strength and temperature. The transition temperature at which ferromagnetism decreases to zero and the material becomes paramagnetic is the Curie point.

The natural coordination of biological function is governed by interrelated events between cells and organ systems. The basic result of such linkage permits an organism to regulate activities in a myriad of ordered events. Underlying the apparent simplicity of functional performance there remains an intricate array of biochemical and biophysical associations. In cells, ion fluxes permit transmembranal transport of nutrients but also regulate electrostatic surface changes that may eventually lead to total functional integrity or cell survival. Seen as an interconnected system, biological tissues bear striking similarities to conductive circuits and permit, thereby, from such a comparison, an understanding of the interaction of electromagnetic fields with viable, compartmented living tissues.

Magnetic Forces and Magnetic Induction

When two electric circuits carry electric currents, the currents in one circuit exert forces on the other and vice versa. In the simplest case, two straight, parallel wires, which are carrying currents I_a and I_b are proportionally related as $I_a I_b/\varrho$, where the distance between each wire is represented as r. The force exerted is attractive when the currents flow in the same direction and repulsive if in the opposite direction. The force between two currents, otherwise, is again related to the product $I_a I_b$ with the expression of force ($\bar{F}_{ab}$) as:

$$\bar{F}_{ab} = \frac{\mu_o}{4\pi} I_a I_b \oint_a \oint_b \frac{\overline{dl}_b \times (\overline{dl}_a \times \bar{r}_l)}{r^2}. \qquad (2.1)$$

This relationship is called the magnetic force law and applies to the force exerted by I_a on I_b. The direction of current flow is evident in the vectors $\overline{dl}_a$ and $\overline{dl}_b$ (fig. 1) where the unit vector $\bar{r}_l$ points from $\overline{dl}_a$ to $\overline{dl}_b$ and r is the distance between these elements. When viewed in consideration of the meaning of the constant μ_o, the permeability of free space ($\mu_o = 4\pi \times 10^{-7}$ NA^{-2}), equation 2.1 can be used as a definition of current (in ampere or coulomb/second). In order to express the symmetrical nature of $\overline{dl}_a$ and $\overline{dl}_b$, the triple vector product must be expanded:

$$\frac{\overline{dl}_b \times (\overline{dl}_a \times \bar{r}_l)}{r^2} = \frac{\overline{dl}_a (\overline{dl}_b \cdot \bar{r}_l)}{r^2} - \frac{\bar{r}_l (\overline{dl}_a \cdot \overline{dl}_b)}{r^2}. \qquad (2.2)$$

As the circuits represent a closed loop, the second integral is zero because of identical upper and lower evaluations. Thus, only the second term of the vector product remains and, therefore:

$$\bar{F}_{ab} = -\frac{\mu_o}{4\pi} I_a I_b \oint_a \oint_b \frac{\bar{r}_l (\overline{dl}_a \cdot \overline{dl}_b)}{r^2}. \qquad (2.3)$$

Thus, $\bar{r}_l$ is directed in one direction for $\bar{F}_{ab}$ and another for $\bar{F}_{ba}$, so that $\bar{F}_{ab} = -\bar{F}_{ba}$.

In order to express the force resulting from current b on a, an operation must be performed on equation 2.1 to result in the Biot-Savart law:

$$\bar{F}_{ab} = I_b \oint \overline{dl}_b \times \left(\frac{\mu_o}{4\pi} I_a \oint \frac{\overline{dl}_a \times \bar{r}_l}{r^2} \right) \qquad (2.4)$$

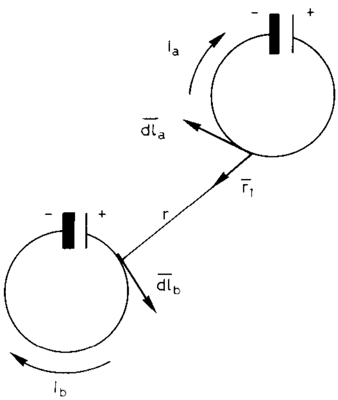

Fig. 1. Interaction of current circuits I_a and I_b.

$$= I_b \oint_b \overline{dl}_b \times \overline{B}_a \tag{2.5}$$

where

$$\overline{B}_a = \frac{\mu_o}{4\pi} I_a \oint_a \frac{\overline{dl}_a \times \bar{r}_1}{r^2} \tag{2.6}$$

defines the magnetic induction due to a. The induction is expressed in teslas [1 tesla (T) = 1 weber per square meter (1 Wb m^{-2}) = 10^4 gauss (Gs)]. This equation can be used to calculate $\overline{B}$ inside a conductor carrying a current or to define the flux of magnetic induction through any given surface (S) where flux (Φ) is expressed in units of webers:

$$\Phi = \int_S \overline{B} \cdot \overline{da}. \tag{2.7}$$

Point Charge Force

To understand the force on a point charge, for example a chemical ion, we assume a charge Q moving within a field ($\overline{B}$) with a velocity of $\bar{v}$, and in this model case, the cross section of the element is da:

$$I = n(da\ v)\ Q, \tag{2.8}$$

where n represents the independent charge carriers per unit of material conductor and v the average drift velocity. The force on the element dl is calculated from:

$$n\,da\,dl\,Q\,\bar{v}\times\bar{B}, \tag{2.9}$$

and for a single charge Q:

$$Q\,\bar{v}\times\bar{B}, \tag{2.10}$$

or in the presence of an applied electric field ($\bar{E}$) (Lorentz force):

$$Q\,[\bar{E}+(\bar{v}\times\bar{B})]. \tag{2.11}$$

Induction through Closed Surface

The induction through any closed surface is zero and may be derived from the Biot-Savart law (2.6) where $\bar{J}_f$ is the current density in amperes per square meter:

$$\bar{B}=\frac{\mu_o}{4\pi}\int_{\tau'}\frac{\bar{J}_f\times\bar{r}_1}{r^2}\,d\tau', \tag{2.12}$$

$$\bar{\nabla}\cdot\bar{B}=\frac{\mu_o}{4\pi}\int_{\tau'}\bar{\nabla}\cdot\frac{\bar{J}_f\times\bar{r}_1}{r^2}\,d\tau'=\frac{\mu_o}{4\pi}\int\bar{\nabla}\cdot\left(\bar{J}_f\times\frac{\bar{r}_1}{r^2}\right)d\tau', \tag{2.13}$$

and τ is any volume-conducting current. However, since $\nabla\cdot(A\times D)=D\cdot(\nabla\times A)-A\cdot(\nabla\times D)$ for any two vectors A and D,

$$\bar{\nabla}\cdot\left(\bar{J}_f\times\frac{\bar{r}_1}{r^2}\right)\equiv\frac{\bar{r}_1}{r^2}\cdot\left(\bar{\nabla}\times\bar{J}_f\right)-\bar{J}_f\left(\bar{\nabla}\times\frac{\bar{r}_1}{r^2}\right), \tag{2.14}$$

and after performing the necessary operation,

$$\bar{\nabla}\cdot\bar{B}=0. \tag{2.15}$$

As this is so, the net flux of magnetic induction through a closed surface remains:

$$\bar{B}\cdot\overline{da}=\int_{\tau}\bar{\nabla}\cdot\bar{B}\,d\tau=0. \tag{2.16}$$