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Electromagnetism and Life

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The word "bioelectricity" appears to be a contradiction in terms, implying a connection between biology and electricity. The established textbooks of biology seem to ignore electricity while the electrical texts seem equally unaware that biology exists. To compound the confusion, there are now a number of competing terms used to describe this field: biomagnetics, electrobiology, bioelectromagnetics, magnetobiology, bioelectrochemistry, and so on. Quite apparently something is happening at the interface between the life sciences and electromagnetism that is new and exciting, and that is ignored by the scientific establishment. The situation is typical of what Kuhn called a revolution in scientific concepts (1), and it is my belief that this is exactly what is occurring. It is the purpose of this chapter to introduce this new scientific paradigm by providing a brief historical perspective. As such, it can only touch on what I perceive to be the significant links in the chain of events that have led to the development of this new scientific discipline.

Bioelectricity, defined broadly, is the study of the electromagnetic forces generated by living organisms, and the effects of external electromagnetic forces and fields upon living organisms. This new term is compounded of two Greek roots, and it is fitting that *bios* comes before *elektron*, since in the historical perspective most of the major turning points can be attributed to biological scientists motivated by a recognition of the deep uncertainties in their understanding of life. The history of bioelectricity can be divided into three epochs , the first and second separated by the monumental contributions of Galvani, the second divided from the third by the scientific explosion that accompanied the global conflict of World War II, which has led to our modern technological world.

Any history of electricity and magnetism must begin with the publication in 1600 of *DeMagnete* by William Gilbert, physician to Queen Elizabeth. For the first time these two forces were removed from the realm of mystery, clearly separated from each other and subjected to logical experimentation. While static electricity was the only kind then known, the following century saw the development of methods for generating, measuring, and storing this energy, as well as the appearance of possibly the greatest collection of scientific minds ever existing in one century—Bacon, Harvey, Descartes and Newton. Nevertheless, biology and medicine were still enmeshed in the longest running scientific dispute on record: the question of vitalism versus mechanism. This controversy, dating back to the early Greek philosophers, pitted the vitalists who believed that living things possessed an "anima" or vital spirit inaccessible to physical analysis, against the mechanists who thought that this was simply nonsense and that living entities were merely more complex than non-living things. Electricity became the prime candidate for the "anima," and when Galvani published his findings in 1791 he thought he had identified the vital spirit as "animal electricity." What Galvani actually had discovered was another much more useful form of electricity, direct current, constantly generated by the apposition of two dissimilar metals in a conducting solution. Volta's attack upon Galvani, which occurred two years later, clearly demonstrated this fact and appeared to conclusively exclude electricity as being produced by living tissues. Galvani's answer (later published anonymously), demonstrated that under certain conditions living tissue could produce electricity without the intervention of metallic contacts. However, it was largely ignored in the excitement over Volta's electrical pile which produced a continuous supply of electrical current. Thirty years later, Matteucci demonstrated that what Galvani actually had shown in his later work was the production of electrical current by injured tissue, the "current of injury." In the meantime, Oersted had demonstrated that direct current flowing in a wire produced a magnetic field that extended out in space from the wire, and Davy had shown that the electricity produced by the Voltaic pile was the result of chemical events in the two metals and the conducting solution. Following Matteucci's observations, Du Bois-Raymond demonstrated that stimulation of a nerve produced an electrically measurable impulse that traveled along the nerve from the point of stimulation, and concluded that he had confirmed "the identity of the nervous principle with electricity." However, this was conclusively disproven by von Helmholtz in 1850 when he measured the speed of the nerve impulse at about 30 meters per second, a figure far below that previously obtained by Cavendish and others using a Leyden jar discharged into a wire more than 12,000 feet long. While the nerve impulse could be measured electrically, it could not be electrical in nature. What was it?

The answer was provided by Julius Bernstein, one of Du Bois-Raymond's students. Bernstein published his hypothesis in 1868, proposing that the nerve membrane is polarized, with the interior having a different electrical polarity than the exterior, based upon some mechanism that enabled the membrane to selectively admit ions of only one sign. The nerve impulse was then postulated to be a localized breakdown of this polarity which then propagated along the nerve fiber. Thus, while the nerve impulse could be measured with electrical instruments, it was definitely not the actual passage of electrical current longitudinally along the nerve fiber. This "Bernstein hypothesis" of cell membrane polarization has become the cornerstone of modern electrophysiology and is invoked to explain all electrically measurable phenomena in living organisms, including the current of injury.

In 1864, Maxwell postulated mathematically the existence of a continuous spectrum of electromagnetic fields arranged on a scale of increasing frequency and decreasing wave length. About 20 years later Hertz demonstrated the reality of such fields and their ability to transmit signals through space without wires. Less than 10 years later, Roentgen, experimenting with electrical discharges in partially evacuated tubes, discovered X-rays.

By the turn of the century, Hertz's discovery was being used to transmit messages across the Atlantic ocean, and Roentgen's discovery was being used by the medical profession in the diagnosis and reduction of fractures in humans. During the same time the position of the vitalists had been slowly whittled away as electricity was excluded from more and more physiological functions until, by the beginning of the 20th century, only the transmission of the nerve impulse across the synaptic gap was left. In 1920, this last straw was removed by Otto Loewi's demonstration of the production of the chemical acetylcholine by the arrival of the impulse at the nerve termination. There was no "vital spirit" and no place for electricity as such in living organisms, they were simply complex chemical machines, nothing more.

The mechanistic-reductionist philosophy that the total organism was simply the sum of its parts, and that one could isolate and study any part with the resultant data applicable to the whole organism, took firm control of all biological thinking. This approach has led to such advances in all aspects of biology and medicine that it has gained the status of unimpeachable dogma.

One result of this triumph of mechanistic concepts was the total debunking of electromedicine. This method of therapy had arisen not long after Galvani's observations, developing in a completely empirical fashion until by the late 1800's it was in common use for the treatment of a wide variety of ailments. In view of the lack of basic knowledge in both biology and physics during this time, it is not surprising that much of this was sheer nonsense, and medicine was better off for having discarded it. We now know, however, that in at least one instance a valuable method of treatment was also discredited. The method in use at that time for treatment of non-unions of human bone fractures with electrical currents was remarkably similar to that employed and accepted today.

It appeared that the last word had been said with Loewi's demonstration in 1920, but this was actually not the case. In 1929 Berger reported the human electroencephalogram (EEG), with a characteristic frequency range and pattern. It was then, and it still is now, impossible to relate this electrical phenomenon entirely to the nerve impulse. Other neurophysiologists, chiefly, Gerard and Libet, were convinced that the simplistic concept of the nerve impulse being the sole neural mechanism was inadequate to explain the complex functions of the brain. During the 1930's and 40's they reported evidence for actual electrical currents flowing outside of the nerve cells proper in the brain. They demonstrated that such currents influenced the way in which the neurons operated, but their work evoked little interest, not only because it flew in the face of established dogma but also because the measurement of direct currents of such small magnitude was extremely difficult. Thus, few neurophysiologists were interested in exploring what appeared to be a nonproductive backwater. During the same period of time, several biologists, primarily Burr and Lund, similarly convinced that the whole was greater than the sum of the parts, continued to search for evidences of electrical forces playing a role in the actions and processes of the total living organism. Their observations consisted chiefly of measuring the DC electrical potentials from a wide variety of living organisms, and correlating them with functional changes. They interpreted their observations as indicating a total body "bioelectrical field," a simple dipole oriented along the head-tail axis of the body. While they both published their data, their reports elicited no interest from the great majority of scientists and their work was criticized on the basis of inadequate instrumentation, with considerable truth to the latter point. The measurement tools available to them certainly introduced major errors into whatever data was obtained primarily because of their low impedance.

While reductionist biology was consolidating and strengthening its gains, enthusiastic and expanding usage was being made of the discoveries in electricity and electromagnetism. Electrical power was being made available in increasing amounts and was accompanied by increasing development in the use of radio transmissions. Progress in biology and medicine reinforced this development, providing both reassurances that this energy had nothing whatsoever to do with living organisms, and, further evidences of the utility of these discoveries in the form of high-frequency heating for clinical use (diathermy), and the use of X-rays for treatment of a wide variety of conditions ranging from acne to cancer. It was not until well into the second quarter of the 20th century that this development first demonstrated some undesirable side effects in the form of the production of cancers, particularly in those physicians who had made great use of X-rays. This was rapidly attributed to the ability of radiation higher in frequency than light to produce ionization of the tissues and cell structures. Since radiation that was below light in frequency lacked this property, it was concluded that it had no biological effects.

All controversy had ceased by the beginning of World War II. There were no biological effects of electrical currents below the level at which shock was produced, and living organisms made no use of electrical currents in their physiological functions. All actions of living organisms were best explained on the basis of chemical and molecular actions and polarized cell membranes. Electromagnetic fields had no biological effects, and this concept appeared to be borne out by our operating experience. We had been employing these fields at frequencies from the 60-Hz power frequency to short-wave radio with no obvious (or even demonstrable) effects occurring either in those persons most exposed or in the general population. The possibility that magnetic fields had any biological effect was assigned to the realm of charlatanism or worse. Classical concepts of physics simply did not allow for any meaningful interaction between any form of nonionizing electromagnetic radiation and living organisms. Wave lengths of the frequencies then available were far too long to produce resonance with any biological structure, and the energy delivered to the living system was far below kT. Reductionist and physiochemical concepts of biology were poised to deliver the answers to all of our questions about life, and to provide effective controls for all of our ills.

Yet disquieting problems remained. In the rush to embrace these new concepts that had emerged victorious after their long struggle with vitalism, any biological property or function that did not fit the established paradigm was either glossed over or ignored. On close examination it appeared that we did know a lot about those functions that could be well understood by chemical and molecular concepts, but we simply had no ideas about such basic issues as the nature of life, or even lesser ones such as what controlled growth, structure and embryonic development, the nature of cerebral activity, or the mechanisms involved in biological cyclic patterns. In 1941 a spokesman for this view appeared; Albert Szent Gyorgyi who had won the Nobel prize in medicine in 1937 for his work on biological oxidation and Vitamin C, presented the now famous Koranyi Lecture in which he proposed the radical concept of the transfer of energy within living cells by excited electrons moving within semiconducting matrices (2). Commenting on the failure of reductionist philosophy to explain basic problems, he said, “It looks as if some basic fact about life were still missing, without which any real understanding is impossible.” Szent Gyorgyi went on to publish numerous other papers and books on the same theme, after the war, among which “An Introduction to Submolecular Biology,” published in 1960, has become a classic. Yet his greatest achievement may well turn out to be that single lecture delivered in 1941. From the point of view of bioelectricity it must be considered a classical turning point of as great an import as Galvani’s discoveries 150 years earlier.

The roots of the modern concepts of bioelectricity can be traced to the period following World War II when a great expansion in science occurred based upon the technological advances stimulated by the conflict. This had been the first major war ever fought in which electrical and electromagnetic forces played a major, perhaps pivotal, role in the outcome. Great advances in communications technology were made and rapidly put into use. The ability to generate higher and higher frequencies appeared and the development of the cavity magnetron enabled the first effective use of radar. To the public, this represented a new and novel form of energy, and as technology progressed, the power produced in a radar beam became far greater than that from any other type of field-generating equipment. This fact, coupled with some reports of health effects among radar workers, stimulated a debate beginning in the late 1950’s over the possible biological effects of this new electromagnetic modality. The debate was thought to have been concluded in the early 1960’s with the confirmation of the classical concept that heating effects were the only ones possible, and the subsequent adoption of the thermal effects standard for exposure of humans to microwave radiation. That this is very much not the case is clearly presented in Steneck’s latest book, *The Microwave Debate* (3).

Also in the post-War period, Szent Gyorgyi’s prescient concepts of electron flow were confirmed in the physical sciences with the development of the transistor and other solid state technology. Increasingly sophisticated electronic instrumentation required more sensitive and stable methods for measuring and recording electrical currents and potentials. It was the availability of such devices, which were much more sensitive and much less subject to artifact than those used by Burr and Lund, that effectively re-opened the controversy over the role of electricity in living systems and led to the modern era in the study of bioelectricity.

The initial application of this type of instrumentation occurred in 1960 with the reevaluation of the bioelectric field concept of Burr and Lund. A moist-skinned vertebrate, the salamander, was used, and rather than the simple head to tail dipole field previously described, a complex potential field was found that correlated spatially with the anatomical complexity of the central nervous system (4). Further evidence suggesting the involvement of the nervous system in the generation of these DC potentials was the observation that the strength of individual DC vectors in the field varied directly with the level of consciousness of the experimental animal. The same techniques were later applied to the measurement of the current of injury in animals capable of limb regeneration compared with a closely related species that did not have such capability. The results were significant from two points of view (5). First, the polarity of the potentials at the site of a limb amputation in a regenerating animal while initially positive became strongly negative, this polarity coinciding in time with the regrowth of the limb. The polarity at a similar site in a non-regenerating animal was initially positive and remained so throughout the period of healing by scarification. The observation was unambiguous, indicating a definite relationship between the electrical phenomenon and the type of healing that occurred.

The second observation was of equal import. Clearly measurable potentials existed in both species throughout the entire healing period of 3–4 weeks. The explanation of the current of injury, based upon the Bernstein hypothesis, was that damaged cell membranes became leaky and, whatever the mechanism was that produced the polarization, it then produced the externally measurable current. It was obviously not logical to conclude that such a mechanism could be operational over such a lengthy period of time. The same measurement techniques were next applied to bone tissue which was then found to be capable of producing electrical potentials when mechanically stressed (6). This capability was theorized to be related to the growth of bone in response to such stress. The relationship of the nerve to the DC potentials was further strengthened by the observation that a Hall effect was measurable from peripheral nerves (7) with the application of high-strength magnetic fields, and later by the observation that similar fields could produce major alterations in the pattern of the electroencephalogram (8). In this latter experiment it was further noted that the shift in the pattern was similar to that observed under deep anesthesia, and that the animals exposed to such fields demonstrated a similar behavioral change. While all of these observations had been suggestive of the existence of functionally significant, organized DC electrical currents existing within living organisms, the first substantiation of this concept form an experimental point of view was Smith's observation that simulation of the negative polarity of the current of injury in animals not normally capable of limb regeneration restored a significant measure of this growth (9). This seminal report stimulated Friedenberg's work, reported in 1970, in which he demonstrated the healing of a non-union of a human fracture by the application of a negative polarity direct current to the site (10). Friedenberg's technique, remarkably similar to that used in the 1880's and subsequently discarded as quackery, has evolved with minor changes into the clinically approved method in wide use today. The importance of this development is frequently overlooked. This was the first time since the beginnings of medicine that a method for *stimulating* growth based upon verifiable scientific concepts was made available to physicians. The fact that the method was derived from basic experimentation in bioelectricity did much to enhance the credibility of the entire concept that electrical forces *did* play a role in life processes.

During the 1960's magnetism also crept back into biology with the first report of the production of an actual, detectable magnetic field produced by the electrical activity of the heart (11). This was shortly followed by Cohen's report in 1968 of a magnetic field produced by the activity of the brain (12). These reports had employed classical Helmholtz coils as detectors for the magnetic field, and the data obtained was minimal until the development of the SQUID magnetometer in 1969. The availability of this device has led to an explosive growth in the detection, measurement and analysis of magnetic fields produced by brain activity (the magnetoencephalogram). Despite the fact that this technology requires the existence of actual electrical current flow in the brain, thus far credit has yet to be extended to Libet and Gerard for their pioneering observations, and no re-evaluation of classical cerebral neurophysiological concepts in this light has taken place.

In 1971 two important conferences were convened both of which materially assisted the development of this discipline. The first was a small gathering at the Lamont-Dougherty Geological observatory in which the evidence for a surprising observation was presented. While it had been known for some time that the Earth's magnetic field was subjected to occasional perturbations of a significant nature during which reversals of the Earth's magnetic poles occurred, the new evidence consisted of correlations of these events with major alterations in the total biota. During the 51000 years required to effect the reversal, major extinction of the most evolutionarily advanced species occurred. The data base in both the physical and biological areas was inadequate at that time to reach any firm conclusions, however, it appeared highly unlikely that a reversal in the direction of the DC field would have any major effect upon any life form except those that migrated possibly via magnetic cues. The suggestion was made that perhaps the micropulsation frequencies changed during reversal periods and that organisms which derived some important information from such frequencies would suffer major physiological and behavioral alterations. This concept had been in part explored for some years by Brown who presented considerable evidence that the tidal fluctuations in the Earth's field could be the timer for the simultaneous cyclic fluctuations in all living organisms known as circadian rhythms or biological cycles (13). His work illustrates well the classic conundrum in science: Brown could demonstrate with careful experimentation that very small magnetic fields (often below 1 gauss) could unquestionably alter the cyclic behavior of various animals, yet, because the hold of dogma was so strong and there was no known linkage mechanism between such small fields and living organisms, his observations were simply not believed. However, the Lamont Conference did much to stimulate interest in the possible role that *normal* electromagnetic fields of the Earth played in biological processes. The second conference was a larger affair held at Princeton University under the aegis of the Electrochemical Society. This organized group had worked primarily in the area of classical electrochemistry, with no interest in its possible application to biological affairs. The Princeton conference represented the formation of a sub-area of electrochemistry, bioelectrochemistry, and provided both the mechanism for the formation of this group and a chance for many of the people working in the area of bioelectricity to exchange ideas. The bioelectrochemical group is not only alive and well but expanding in a most productive fashion. The latest observations and concepts will be detailed in other chapters.

In 1973 an even more significant international conference took place which substantiated bioelectricity as a valid scientific discipline. "Electrically Mediated Growth Mechanisms in Living Systems" was hosted by the New York Academy of Sciences and consisted of 47 formal papers, several panel discussions and an air of excitement over the progress made in this field over the preceding decade. It provided another important link in the chain of events that has led to the present status of this field.

Progress in bioelectricity over the past decade has been even more rapid. It has been characterized by the establishment of several scientific societies and excellent journals, and the one index that a subject "has come of age," the number of papers published per year, clearly indicates a level of maturity that is almost overwhelming. Progress in clinical applications is apparent, and understanding of the extent of the environmental hazards posed by abnormal electromagnetic fields is advancing rapidly and seems destined to become the environmental issue of this decade. In the present context of an introductory chapter, it is impossible to adequately review the progress that has taken place in the past decade and that task will be taken over by the remaining chapters in this volume. However, during the same period of time, great advances have been made in basic biological knowledge that have important consequences for the science of bioelectricity as a whole. These seem destined to provide a means to relate all living organisms to the normal electromagnetic fields of the Earth in a particularly important and vital fashion. They also have provided us with an answer to the question of the linkage mechanism which has prevented even more rapid progress and acceptance of the concepts of bioelectricity by the total scientific establishment.

As noted early in this chapter, the concepts of classical physics provided no mechanism by which low-strength electric or magnetic fields could have any impact upon a living system. Despite the advances made in all aspects of this field and the obvious evidence that low-strength fields *do* have important biological effects, this situation still prevails to some extent. However, these new biological discoveries appear to be capable of resolving this dilemma. In 1975, Blakemore first described the presence of deposits of magnetite mineral in certain magnetotactic bacteria (14), and proposed that it served a useful function in detecting magnetic north. Assisted by SQUID technology, subsequent progress in studying these deposits has been rapid. It is now known that animals, representative of the majority of phyla including the human, have such deposits and that they are organized in such a fashion as to be able to "resolve magnetic field direction to within a few seconds of arc, or magnetic field intensity differences of 1–100 nT" (15). Further, in all higher animals the deposits are intimately related to the central nervous system. The widespread occurrence of these deposits throughout the animal kingdom indicates that they are evolutionarily conserved and that they must serve a useful function for their hosts. What is being described and characterized is a true magnetic organ whose purpose appears to be the detection of the strength and direction of the Earth's field. The pineal gland has, within the past few years, also become identified as another magnetic organ that is responsive to slight changes in the Earth's normal field (16). In addition, the pineal has come to be recognized as probably the true master gland of the body, with its secretions regulating the activity of the pituitary, the thyroid, the adrenal and the reproductive organs. Its major secretion, melatonin, is the regulator for the biological cycles and a potent neurochemical agent acting on the brain (17). Thus, final confirmation of Brown's original thesis is at hand; the cyclic fluctuations of the Earth's normal magnetic field are the timer for circadian rhythms. Whether the action of this weak field upon the cellular systems involved in these two magnetic organs is explicable on the basis of classical physics or involves other mechanisms remains to be elucidated. However, the existence of such specifically designed organs in living systems should not surprise us. Consideration of the normal electromagnetic environment of the Earth (that which pre-existed the present abnormal environment resulting from our usage of this modality) contained two quasi-static components; the DC magnetic field with its associated micropulsation spectrum (0–30 Hz), and visible light. This environment had existed, with the naturally occurring magnetic reversals providing the only perturbations, for the entire period of the genesis and evolution of life. During that time living things had developed a non-classical organ for the detection of light to provide imaging of the environment. It should not then be surprising to find that specific organs were also developed for the detection of the DC and ELF magnetic field fluctuations to provide timing signals for biological cycles (18).

Bioelectricity thus provides us with a totally new scientific paradigm by which to understand the basic physiological mechanisms occurring within living organisms, as well as the basic mechanisms relating all living organisms to the natural electromagnetic field of the Earth. Further exploration of its intricacies will undoubtedly lead to major advances in medical science and an understanding of the basic relationship between all living things and environmental electromagnetic forces.

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