REVIEW ARTICLE

Biofield Physiology: A Framework for an Emerging Discipline

Richard Hammerschlag, PhD; Michael Levin, PhD; Rollin McCraty, PhD; Namuun Bat, BA; John A. Ives, PhD; Susan K. Lutgendorf, PhD; James L. Oschman, PhD

Author Affiliations

The Institute for Integrative Health, Baltimore, Maryland; Consciousness and Healing Initiative, San Diego, California; Oregon College of Oriental Medicine, Portland (Dr Hammerschlag); Tufts Center for Regenerative and Developmental Biology, Tufts University, Medford, Massachusetts (Dr Levin); Institute of HeartMath, Boulder Creek, California (Dr McCraty); The Center for Brain, Mind, and Healing, Samueli Institute, Alexandria, Virginia (Ms Bat, Dr Ives); Departments of Psychology, Obstetrics and Gynecology, and Urology, University of Iowa, Iowa City (Dr Lutgendorf); Nature's Own Research Association, Dover, New Hampshire (Dr Oschman).

Citation
Global Adv Health Med. 2015;4(suppl):35-41. DOI: 10.7453/gahmj.2015.015.suppl

Correspondence
Richard Hammerschlag, PhD
rhammerschlag@ocom.edu

Key Words
Biofield, electromagnetic fields, biophotons, physiological regulation, biofield physiology

Disclosures
The authors completed the ICMJE Form for Disclosure of Potential Conflicts of Interest, and Dr Oschman disclosed consultancy to and employment by EarthFx Inc as well as payment for lectures, all outside the submitted work. The other authors had no conflicts to disclose.

ABSTRACT

Biofield physiology is proposed as an overarching descriptor for the electromagnetic, biophotonic, and other types of spatially-distributed fields that living systems generate and respond to as integral aspects of cellular, tissue, and whole organism self-regulation and organization. Medical physiology, cell biology, and biophysics provide the framework within which evidence for biofields, their proposed receptors, and functions is presented. As such, biofields can be viewed as affecting physiological regulatory systems in a manner that complements the more familiar molecular-based mechanisms. Examples of clinically relevant biofields are the electrical and magnetic fields generated by arrays of heart cells and neurons that are detected, respectively, as electrocardiograms (ECGs) or magnetocardiograms (MCGs) and electroencephalograms (EEGs) or magnetoencephalograms (MEGs). At a basic physiology level, electromagnetic activity of neural assemblies appears to modulate neuronal synchronization and circadian rhythmicity. Numerous nonneural electrical fields have been detected and analyzed, including those arising from patterns of resting membrane potentials that guide development and regeneration, and from slowly-varying transepithelial direct current fields that initiate cellular responses to tissue damage. Another biofield phenomenon is the coherent, ultraweak photon emissions (UPE), detected from cell cultures and from the body surface. A physiological role for biophotons is consistent with observations that fluctuations in UPE correlate with cerebral blood flow, cerebral energy metabolism, and EEG activity. Biofield receptors are reviewed in 3 categories: molecular-level receptors, charge flux sites, and endogenously generated electric or electromagnetic fields. In summary, sufficient evidence has accrued to consider biofield physiology as a viable scientific discipline. Directions for future research are proposed.

INTRODUCTION AND OVERVIEW

The impetus to frame a new area of physiology often arises at the interface of existing fields of inquiry. As prime examples, neuroendocrinology emerged when nerve endings in the hypothalamus, near the base of the brain, were observed to release hormones that cue the anterior pituitary to regulate an array of endocrine tissues[1]; psychoneuroimmunology emerged when the phenomenon of conditioned immunosuppression was observed and when nerve endings were discovered adjacent to lymphocytes in secondary lymphoid tissue[2]; cognitive neuroscience came into its own when correlates of mental processes began to be identified by means of increasingly sensitive brain imaging techniques.[3] We suggest that biofield physiology, with its initial focus on the characterization of endogenous electrical and magnetic fields as indices of health and illness—eg, via electroencephalography or magnetoencephalography (EEG and MEG) or electrocardiography and magnetocardiography (ECG and MCG)—represents another such confluence of disciplines, integrating concepts and information from cell biology, biophysics, and medical physiology.

Biologically-generated fields (biofields) are a spatially distributed set of forces and physical properties that have the capacity to encode information and exert instructive influences on cells and tissues capable of perceiving and being modified by them.[4,5] As such, biofields complement molecular processes as key contributors to what biophysicist Mae-Wan Ho, PhD, describes as global coherence—the multilevel integration of diverse biological activities across time and scale.[6] In her view, global coherence—the defining quality of living organisms—accounts for their most salient properties such as long-range order and coordination, rapid and efficient energy transfer, and extreme sensitivity to specific signals.

Although we focus in this paper on fields generated by living systems, there is substantive scientific literature demonstrating that physiological regulatory systems in humans and animals are also affected by and even synchronized to environmentally generated fields, eg, of geomagnetic and solar origin.[7-11] Of additional interest, disruptions in these fields have been observed to create adverse effects on health and behavior.[12] A

companion paper in this supplement reviews evidence for the therapeutic use of externally applied electrical and magnetic fields (see Muehsam, et al, this issue). For example, a recent Cochrane review concludes that pulsing electromagnetic field therapy "may offer some benefit in the treatment of delayed union and nonunion of long bone fractures,"[13] a finding supportive of the US Food and Drug Administration approval of such therapeutic usage.[14]

Given that electrical and magnetic fields,[15] as well as biophotons in the full range from ultraviolet to infrared,[16,17] are detected during normal physiological activity, the question often arises whether such endogenous phenomena are merely epiphenomena of metabolic events or are incompletely understood biological signaling systems. The present paper explores the evidence for the latter view. We suggest physiological regulatory systems are affected by biofields in a manner that complements the more familiar molecular-based mechanisms, by which regulatory systems respond to endogenous biochemical signals and exogenous pharmacological agents.

We begin our article by describing known and postulated biofields, including how they are generated and which physiological systems may be affected. Next, we consider receptor systems that may detect, integrate, and trigger responses to both biofields and environmental fields. We conclude by identifying areas for future research aimed at clarifying form and function of biofields. Overall, a case will be made that sufficient evidence has accrued to consider biofield physiology as a viable, if nascent-stage, scientific discipline that is likely to expand the current biomedical model of health and disease.

BIOFIELDS: FORM AND FUNCTION

Every region of the body, however superficial or deep, is crisscrossed with well-studied communication and regulatory systems, including neural pathways, blood-borne hormones and exosomes (cell-derived vesicles), and immune surveillance. Yet the existence of fluctuating endogenously generated electromagnetic and other fields, which also suffuse all our cells and comprise an additional rich source of biological information and regulation, remains an underappreciated aspect of physiology.[18,19]

Electrical activity, in the form of charge separation, is a fundamental feature of every living cell. As single cell and multicellular organisms evolved in a primordial sea, the ability to maintain a low-sodium/high-potassium intracellular milieu, in the face of the high-sodium/low-potassium concentrations in sea water, served as a source of energy to enable uptake of metabolites and discharge of waste products across the cell surface. Proteins, evolved to serve as specific ion channels and pumps, maintain this ionic gradient (the "resting potential") between inside and outside of each cell.

But evolution found greater promise for the resting potential than merely as an energy source for ion pumps and crossmembrane transport of molecules. As multicellular organisms evolved, patterns of resting potentials of cells throughout the body became designated as instructive scaffolding to guide pattern formation and stem cell behavior during embryogenesis and organ regeneration.[20-23] For example, endogenous arrays of bioelectric potentials are now known to instruct left-right patterning,[24-26] eye induction,[27] size regulation,[28,29] and patterning during complex organ regeneration.[30-33] New tools allow these bioelectric gradients to be directly observed noninvasively in vivo[34,35] and to be specifically altered to assess effects on intercellular communication and tissue-level or organ-level outcomes.[36,37] Importantly, the molecular mechanisms that couple changes in bioelectric gradient distribution to downstream transcriptional and epigenetic targets are also being characterized.[27,34,36,38,39]

Further, as the advent of multicellular organisms led to increased cellular specialization, muscle and nervous tissue developed mechanisms to turn their resting potentials into high-speed action potentials, propagating along the cell surface with frequencies and other characteristics that encode information.[40] Passage of this information from cell to cell via chemical and electrical synapses expanded the effective area of these electrical fields. Transmembrane currents in neurons also produce local electric fields that induce "ephaptic coupling" (nonsynaptic electrical coupling) between adjacent axons, which influences the synchronization and timing of action potential firing in neurons.[41] As further examples, various types of electrical fields—created by either mechanical stress (piezoelectricity) or streaming potentials—in bone, tendons, skin, and fascia are thought to regulate the functioning of osteocytes and fibroblasts to adjust the density of supporting tissues in response to loads.[42] Also, electric fields generated by the intracellular network of microtubules, centrosomes, and chromosomes appear to play fundamental roles in regulating the dynamics of mitosis, meiosis, and a variety of other cellular activities.[43]

In addition to the high-speed electrical signals conducted along nerve axons, a second communication network, based in ubiquitous epithelial cells, conducts information as slowly varying direct currents.[44,45] The DC fields generated by this system, which spread across considerable distances, play key roles in recognizing damage and guiding cell migration necessary for wound healing (especially in skin, heart, and cornea) as well as in regulating the migration of neuronal path-finding.[46-51] Recent research has identified numerous molecular signaling pathways that mediate the interactions of these bioelectric fields, first described decades ago,[52,53] with the plasma membrane and cytoskeletal mechanisms to facilitate tissue repair.[55-59]

Although the transepithelial DC fields and the gradients of resting membrane potentials (V_{mem}) share functional similarities, the DC fields are produced only by epithelial layers in a relatively standardized form,[60] while V_{mem} are generated by all cells in a wide variety

of patterns.[23,36] A further difference lies in the transduction mechanisms of these systems. The V_{mem} patterns are sensed by a different set of membrane proteins from those that respond to the DC fields.[39,61] Cells use both systems during morphogenesis: the DC fields set directionality of growth and positional information[62-64] and the V_{mem} gradients control differentiation and proliferation and establish anatomical identity of whole regions.[23,28,65]

Since electric charge in motion, whether along a wire or a nerve axon, produces a magnetic field in the surrounding space, this phenomenon represents a further type of biofield. Magnetic fields emanating from the body, although extremely weak relative to the geomagnetic field of the earth, are readily detected by superconducting quantum interference device (SQUID)–based magnetometers.[66] Evidence has recently been summarized that nonthermal electromagnetic fields of amplitude similar to the cardiac field can affect a wide variety of biological functions, including gene expression, particularly in stem cells.[54]

The strongest rhythmic electrical and magnetic fields in the body are produced by synchronous activity of heart muscle cells. While the ECG is readily detected via surface electrodes, the heart's magnetic field can be recorded up to several feet from the body surface as an MCG.[67] Magnetic fields produced by the heart appear to carry information that can also be detected by other persons or animals.[68] An example of the informational potential (bioeffectiveness) of these heart fields is cardiac-induced entrainment, or frequency locking, detected when the R-waves of one subject's ECG become precisely synchronized with the onset of EEG alpha waves of another subject at a distance of up to 5 feet.[69] Heart fields may also encode psychoemotional information, as indicated by the 75% accuracy rate in detecting discrete emotional states from patterns of heart rate variability.[70]

The electrical and magnetic fields generated by the composite activity of thousands of brain cells are detected as an EEG and MEG, respectively. At a functional level, the electromagnetic activity of neural assemblies has been proposed to modulate neuron synchronization[71] and circadian rhythmicity[72] and to underlie the computational and cognitive processes of the brain.[73,74] More specifically, weak sinusoidal electric fields appear to enhance and entrain physiological neocortical network activity.[75] Thus, in a feedback loop, the local fields help to synchronize the neural network that generates them.

Another type of biofield phenomenon is the coherent, ultraweak photon emissions (UPE), detected from cell cultures and from the body surface.[16,76,77] Since the initial observations of UPE or biophotons were detected from inflammation-producing reactive oxygen species, the level of these emissions has been explored as a noninvasive marker of "metabolic stress" and a measure of overall health.[17] More broadly, such UPE, instead of being considered as metabolic epiphenomena, may serve important physiological roles.

A role for ultraweak light signaling in normal physiological regulation is suggested by evidence of intercellular communication under chemically separated but optically coupled in vitro conditions, eg, through a thin glass film.[78-80] These studies have identified infrared as a primitive source of "cellular vision" to guide migration and other behaviors.[78,81] More recently, a role for biophotons in neural activity was based on observations that fluctuations in UPE correlate with cerebral blood flow and cerebral energy metabolism[82] as well as with EEG activity.[83] Moreover, photonic stimulation at one end of a nerve appears to elicit increased UPE at the other end.[84] As a means of information transfer, biophotons have the advantages of extremely high speed and the ability to penetrate into and through cell membranes and organs that present barriers to the diffusion of molecular signals. Nonconventional means of UPE-mediated biosignaling include wave propagation within longitudinally-oriented neuronal microtubules[85] and passage through membrane-spanning regions of proteins that may serve as "light pipes."[86]

Considerations of physiological activity of biofields also include resonance signaling, ie, the modulation of cell function by specific electromagnetic frequencies.[87] Involvement of nonclassical and quantum forms of energy[5,88] (eg, A-fields and scalar waves[89]) has not been explored to the same level of rigorous detail as the bioelectric gradients and fields discussed above, and physiological roles for such phenomena have not yet been demonstrated. (See the article "Biofield Science: Current Physics Perspectives" in this Supplement for a more extensive discussion of nonclassical and quantum forms of energy.)

BIOFIELD RECEPTOR SYSTEMS

A further challenge for framing a physiology of biofields is to identify endogenous receptor systems that detect electromagnetic or other types of fields and trigger responses to these nonmolecular stimuli. While the concept of receptor brings to mind the conformational matching invoked to characterize receptor-mediated responses to hormones and drugs, biofield reception may be better described by phenomena from physics, such as resonance and impedance matching, based on tuning to signal frequencies. As previously proposed, 3 overlapping categories of biofield receptors can be considered: molecular-level receptors, charge flux sites, and endogenously generated electric or electromagnetic fields.[90,91]

An important series of studies on cultured cells identified 2 examples of the first type of receptor sites—deoxyribonucleic acid (DNA) and the cell membrane—at which exogenous electromagnetic signals exert specific biological effects.[92,93] Just as steroid hormones upregulate transcription of particular genes by binding to hormone response elements of DNA, so do low-frequency (<300 Hz) electromagnetic fields appear

to increase transcription of select genes by acting at upstream regions of DNA designated as electromagnetic response elements (EMRE).[94] Deletion of the EMRE eliminates the ability of the applied electromagnetic field to regulate the target genes, while other genes can be converted from electromagnetic nonresponders to responders by inserting the EMRE at upstream regions. Similar electromagnetic fields, as demonstrated by the same researchers, appear to increase the activity of several membrane-bound enzymes.[93]

Charge flux sites, the second type of receptor as exemplified by the perturbation of transmembrane calcium fluxes, have been proposed as a generic mechanism by which weak electromagnetic fields affect biological systems.[95,96] If voltage sensitivity of calcium ion (Ca^{2+}) channels facilitates the targeting of these sites by electromagnetic fields, voltage-modulated channels for other ions should also be tested as potential target sites. Low-frequency electromagnetic fields have also been proposed to interact with DNA by accelerating the movement of electrons within the helical arrays of base pairs.[97] Changes in charge separation in small DNA regions occur during aggregation, so that interactions may be more pronounced in specific active segments of DNA.[93]

While ion channels and ion pumps have major roles in establishing the resting potential of an individual cell, it is gap junctions, the specialized electrical connections between adjacent cells, that allow voltage and current-mediated signals to be propagated across groups of cells.[98] In this manner, spatiotemporal patterns of resting potentials arise to provide bioelectrical guidance during tissue development, regeneration, and cancer suppression.[20,23,99] Although it is not yet apparent that applied weak electromagnetic fields can alter resting potentials, let alone affect multicellular patterns of membrane voltage, applied weak electrical currents do appear to induce regeneration of adult frog limbs. These exogenously applied currents are comparable in direction and density to the outward electrical currents detected from regenerating amphibian limbs, and it is possible that some of the reported effects of applied electromagnetic fields are due to modification of endogenous bioelectric gradients.[15,100]

A final candidate for a receptor system for endogenous and exogenous biofields is a body-wide network that appears to exhibit all 3 types of potential receptor sites: molecular, charge flux, and endogenous field. Unspecialized "loose" connective tissue, often referred to as fascia, forms a continuous head to toe network surrounding and permeating all tissues and organs.[101] As an extracellular matrix, structured mainly by collagen fibers, fascia provides a supportive and regulatory framework for all organs of the body as it coordinates cellular perception and interpretation of mechanical forces. This extracellular system reaches into the interior of cells via transmembrane bridging molecules known as integrins, which allow information from the fascia to modify cell metabolism and genetic activity.[102] Speculation on the nature of such collagen-signaling focuses on water molecules hydrogen-bonded along the outer shell of the collagen triple helix, oriented in a manner that supports the rapid jump conduction of protons along the length of the collagen fibers.[103,104] Since collagen structures both conduct and modify photon pulses emitted from biological sources,[104] it is conceivable that signaling along collagen fibers serves as a surveillance system of endogenous biofield emission to complement the immune and nervous systems in monitoring tissue health.

Further speculation based on the water-protein relationship along collagen fibers invokes quantum coherence, a state that can occur when all water molecules in a particular domain or region are spinning synchronously, emitting spin or torsion waves. Such spin coherence and quantum coherence enable the collagen matrix to be ultrasensitive to electromagnetic fields in a manner that can be frequency selective due to a quantum phenomenon known as the Larmor Precession.[105,106] This effect, resulting from the torque of an external magnetic field exerted on the spin of subatomic particles, is the basis of magnetic resonance imaging (MRI).[107]

Known sensitivities of organisms to extremely small environmental cues, including visible light and electromagnetic fields, merit consideration in this overview of biofield receptors.[108] These sensitivities—which evolved, for example, to locate prey, avoid predators, navigate, and sense changing weather patterns—often operate at or near limits set by physics. An exemplar is the ability of the retina to detect a single photon of light,[109] which occurs via calcium channel–mediated signal amplification and allows thousands of calcium ions enter a retinal rod in response to an individual photon.[110] The public health debate concerning potentially harmful effects of electromagnetic fields was influenced for decades by the conventional physics doctrine that living systems could only be affected by energy strong enough to cause ionization or heating of tissues. In contrast, evidence that very weak, nonionizing electromagnetic fields exert biological effects is well documented,[96,111] and the history of the shift away from the thermal model has been chronicled.[112] Finally, German researchers have demonstrated that individual molecules can act as transmitting and receiving antennae in the mediation of efficient intermolecular communication via single photons.[113]

CONCLUSIONS

Sufficient evidence has accrued to consider biofield physiology as a viable scientific discipline, based on nonlocal, integrated, information-conveying phenomena as well as on emerging molecular details of localized biophysical interactions. Endogenously generated pulses of ultraweak photons, electromagnetic fields directly related to cardiac activity, and patterns of distributed membrane voltage are varied forms of physiological activity designated as biofields, each with established properties and proposed biological

functions. Several receptor systems have been identified that mediate responses to these biofields. By analogy with the hormones, receptors, and regulatory functions that comprise endocrinology, components of the biofield physiology framework are in place.

In seeking to define biofield physiology as an area of research, it is helpful to distinguish it from the existing discipline of bioelectromagnetics and to consider the 2 approaches as different phases of a continuum. If bioelectromagnetics is more about defining mechanisms of local interactions, then biofield physiology is more about understanding the integrated, longer-range functions within the whole organism: the former more reductive, the latter more integrative.

Biofield physiology is still at an early stage of formation. While it is incontrovertible that biological systems emit and react to a wide range of energetic influences, we have not achieved a detailed understanding or mathematical modeling of the essential field aspect of such interactions (a prerequisite for exploiting their long-range organizing properties). Moreover, many of the experimental findings are preliminary, while the biofields studied are varied in form and cannot yet be considered as interrelated representatives of a clearly defined system of biological self-regulation. Further, much of the research appears guided by existing paradigms of biochemistry and physiology. As one example, evidence of DNA response elements that respond to specific electromagnetic frequencies, analogous to DNA regions responsive to specific hormones, is an important finding. However, biofields may also act in a more dispersive, nonspecific manner to activate self-regulatory systems that, in turn, stimulate surveillance to detect the source of tissue imbalance or disease. As future research is likely to reveal, such imbalances may be understood via models based on either molecular-level or biofield-level dysfunction, a perspective that will further expand diagnostics, treatment options, and our concepts of physiology.

DIRECTIONS FOR FUTURE RESEARCH

Interrelation of Endogenous Biofields With Major Physiological Systems

While there is broad acceptance that the nervous, endocrine, immune, and cardiovascular systems are in continuous intercommunication via electrical and molecular signals,[114] the possibility must also be considered that endogenous biofields act as carriers of information between these systems. An exemplar is heart-brain interaction, where several types of cardiac-initiated signals appear to exert sequential effects on brain activity. Electromagnetic signals from the heart reach the brain in a relatively instantaneous manner, followed first by a range of neural signals arriving in millisecond timeframes and subsequently by pressure waves and hormonal signals arriving with delays of seconds.[68] In general, different types of signals mediate rapid/short-acting vs slower/longer-lasting responses, eg, neurally-released adrenaline and hormonally released corticosteroids, respectively, coordinate the stress response. Physiological requirements for ultrarapid responses may be met by biofields. As research continues to identify physiological roles of endogenous biofields, a wider lens should be used to examine whether and how biofields may have intersystem integrative roles in physiological regulation.

Relation of Biofield-mediated Physiological Changes to Health and Healing

In regard to human health, biofield research has taken 2 broad directions aimed at establishing salutary and detrimental effects of biofields and biofield therapies. Caution is recommended regarding attempts to draw correlations between biofields and health based on present data. For example, a recent review of biophoton detection as a potential noninvasive means of health assessment stresses the need for standardization of devices and conditions used to monitor this UPE.[17] Epidemiological assessments of adverse effects of ambient electromagnetic fields face critiques common to such long-term correlational studies. Future research on biofields and health needs to include state-of-the-science physiological endpoints that best reflect clinical conditions. Such research will benefit from advances in "calibrating" biofield therapy practitioners and biofield devices as well as from improved methodology for designing and implementing appropriate controls.

At the Frontier

Many of the hypotheses gathered for this paper are, at present, at the leading edge of speculation, but they are offered with confidence that emerging technologies will eventually be able to either validate or refute them. As an instructive example, Pienta and Coffey stated in 1991 that "Cells and intracellular elements are capable of vibrating in a dynamic manner with complex harmonics, the frequency of which can now be measured and analyzed in a quantitative manner by Fourier analysis."[115] In the decades since that statement, other technologies have been developed to characterize ultrafast activities in the molecular fabric of the fascia or living matrix and/or ground regulation systems[102,116] and "wetware."[117]

As a final thought, new insights into the properties of water[118] and applications of quantum field theory[119] will undoubtedly contribute to a deeper understanding of the relationships between biofields and molecular dynamics. Raman and infrared spectroscopic techniques are now enabling rapid and sensitive chemical characterization of samples based strictly on the vibrational signatures of the molecules present in a sampling volume. When applied to biological systems, the techniques provide highly complex spectra that document changes taking place in the entire genome, proteome, and metabolome; real time in-vivo applications are possible. The January 2013 issue of the *Journal of Photonics* was devoted to the most recent developments, with commentary on possible future directions.

Acknowledgments

Many thanks to David Muehsam, PhD, and Lee Hullender Rubin, DAOM, for their helpful feedback on earlier drafts of this paper.

REFERENCES

1. Reichlin S. Neuroendocrinology. N Engl J Med. 1963;269:1182-91, 1246-50, 1296-1303.
2. Ader R. Psychoneuroimmunology. 1st ed. New York: Elsevier Academic Press; 1981.
3. Gazzaniga M. The cognitive neurosciences. Cambridge, MA: Massachusetts Institute of Technology Press; 2000.
4. Rubik B. The biofield hypothesis: its biophysical basis and role in medicine. J Altern Complement Med. 2002 Dec;8(6):703-17.
5. Rein G. Bioinformation within the biofield: beyond bioelectromagnetics. J Altern Complement Med. 2004 Feb;10(1):59-68.
6. Ho MW. The rainbow and the worm: The physics of organisms. 3rd ed. Singapore: World Scientific Publishing; 2008.
7. Burch J, Reif J, Yost M. Geomagnetic activity and human melatonin metabolite excretion. Neurosci Lett. 2008;438(1):76-9.
8. Liboff AR. A role for the geomagnetic field in cell regulation. Electromagn Biol Med. 2010;29(3):105-12.
9. Blackman CF, Blanchard JP, Benane SG, House DE, Elder JA. Double blind test of magnetic field effects on neurite outgrowth. Bioelectromagnetics. 1998;19(4):204-9.
10. Eder SH, Cadiou H, Muhamad A, McNaughton PA, Kirschvink JL, Winklhofer M. Magnetic characterization of isolated candidate vertebrate magnetoreceptor cells. Proc Natl Acad Sci U S A. 2012;109(30):12022-7.
11. Wiltschko R, Wiltschko W. Sensing magnetic directions in birds: radical pair processes involving cryptochrome. Biosensors. 2014;4(3):221-42..
12. Shibib K, Brock M, Gosztonyi G, Erne S, Hahlbohm H, Schoknecht G. The geomagnetic field: a factor in cellular interactions? I. Magnetism and Schwann cell-axon interaction in the peripheral nerves of the newborn rat. Neurol Res. 1987;9(4):225-35.
13. Griffin XL, Costa ML, Parsons N, Smith N. Electromagnetic field stimulation for treating delayed union or non-union of long bone fractures in adults. Cochrane Database Syst Rev. 2011;(4):CD008471.
14. Markov MS. Expanding use of pulsed electromagnetic field therapies. Electromagn Biol Med. 2007;26(3):257-74.
15. Funk R, Monsees T, Ozkucur N. Electromagnetic effects—From cell biology to medicine. Prog Histochem Cytochem. 2009;43(4):177-264.
16. Van Wijk R, Schamhart D. Regulatory aspects of low intensity photon emission. Experientia. 1988;44(7):586-93.
17. Ives J, van Wijk E, Bat N, et al. Ultraweak photon emission as a non-invasive health assessment: a systematic review. PLoS One. 2014;9(2):e87401. doi:10.1371/journal.pone.0087401.
18. Cifra M, Fields J, Farhadi A. Electromagnetic cellular interactions. Prog Biophys Mol Biol. 2011;105(3):223-46.
19. Rossi C, Foletti A, Magnani A, Lamponi S. New perspectives in cell communication: Bioelectromagnetic interactions. Semin Cancer Biol. 2011;21(3):207-14.
20. Levin M. Endogenous bioelectrical networks store non-genetic patterning information during development and regeneration. J Physiol. 2014;592(Pt 11):2295-305.
21. Lan J, Williams C, Levin M, Black L 3rd. Depolarization of cellular resting membrane potential promotes neonatal cardiomyocyte proliferation in vitro. Cell Mol Bioeng. 2014;7(3):432-45.
22. Sundelacruz S, Levin M, Kaplan D. Depolarization alters phenotype, maintains plasticity of predifferentiated mesenchymal stem cells. Tissue Eng Part A. 2013;19(17-18):1889-908.
23. Tseng A, Levin M. Cracking the bioelectric code: Probing endogenous ionic controls of pattern formation. Commun Integr Biol. 2013;6(1):e22595.
24. Adams D, Robinson K, Fukumoto T, et al. Early, H+-V-ATPase-dependent proton flux is necessary for consistent left-right patterning of non-mammalian vertebrates. Development. 2006;133(9):1657-71.
25. Levin M, Thorlin T, Robinson K, Nogi T, Mercola M. Asymmetries in H+/K+-ATPase and cell membrane potentials comprise a very early step in left-right patterning. Cell. 2002;111(1):77-89.
26. Morokuma J, Blackiston D, Levin M. KCNQ1 and KCNE1 K+ channel components are involved in early left-right patterning in *Xenopus laevis* embryos. Cell Physiol Biochem. 2008;21(5-6):357-72.
27. Pai V, Aw S, Shomrat T, Lemire J, Levin M. Transmembrane voltage potential controls embryonic eye patterning in *Xenopus laevis*. Development. 2012;139(2):313-23.
28. Beane W, Morokuma J, Lemire J, Levin M. Bioelectric signaling regulates head and organ size during planarian regeneration. Development. 2013;140(2):313-22.
29. Perathoner S, Daane J, Henrion U, et al. Bioelectric signaling regulates size in zebrafish fins. PLoS Genet. 2014;10(1):e1004080.
30. Adams D, Masi A, Levin M. H+ pump-dependent changes in membrane voltage are an early mechanism necessary and sufficient to induce Xenopus tail regeneration. Development. 2007;134(7):1323-35.
31. Adams D, Tseng A, Levin M. Light-activation of the Archaerhodopsin H(+)-pump reverses age-dependent loss of vertebrate regeneration: sparking system-level controls in vivo. Biol Open. 2013;2(3):306-13.
32. Monteiro J, Aires R, Becker J, Jacinto A, Certal A, Rodríguez-León J. V-ATPase proton pumping activity is required for adult zebrafish appendage regeneration. PLoS One. 2014;9(3):e92594.
33. Tseng A, Beane W, Lemire J, Masi A, Levin M. Induction of vertebrate regeneration by a transient sodium current. J Neurosci. 2010;30(39):13192-200.
34. Adams D, Levin M. Measuring resting membrane potential using the fluorescent voltage reporters DiBAC4(3) and CC2-DMPE. Cold Spring Harb Protoc. 2012(4):459-64.
35. Adams D, Levin M. General principles for measuring resting membrane potential and ion concentration using fluorescent bioelectricity reporters. Cold Spring Harb Protoc. 2012(4):385-37.
36. Adams D, Levin M. Endogenous voltage gradients as mediators of cell-cell communication: strategies for investigating bioelectrical signals during pattern formation. Cell Tissue Res. 2013;352(1):95-122.
37. Levin M, Stevenson C. Regulation of cell behavior and tissue patterning by bioelectrical signals: challenges and opportunities for biomedical engineering. Annu Rev Biomed Eng. 2012;14:295-323.
38. Chernet B, Levin M. Transmembrane voltage potential is an essential cellular parameter for the detection and control of tumor development in a Xenopus model. Dis Model Mech. 2013;6(3):595-607.
39. Tseng A, Levin M. Transducing bioelectric signals into epigenetic pathways during tadpole tail regeneration. Anat Rec (Hoboken). 2012;295(10):1541-51.
40. Gerstner W, Kreiter A, Markram H, Herz A. Neural codes: firing rates and beyond. Proc Natl Acad Sci U S A. 1997;94(24):12740-1.
41. Jefferys J. Nonsynaptic modulation of neuronal activity in the brain: electric currents and extracellular ions. Physiol Rev. 1995;75(4):689-723.
42. Ahn A, Grodzinsky A. Relevance of collagen piezoelectricity to "Wolff's Law": a critical review. Med Eng Phys. 2009;31(7):733-41.
43. Zhao Y, Zhan Q. Electric fields generated by synchronized oscillations of microtubules, centrosomes and chromosomes regulate the dynamics of mitosis and meiosis. Theor Biol Med Model. 2012 Jul 2;9:26.
44. Nuccitelli R. Endogenous ionic currents and DC electric fields in multicellular animal tissues. Bioelectromagnetics. 1992;Suppl 1:147-57.
45. Robinson K, Messerli M. Electric embryos: the embryonic epithelium as a generator of developmental information. In: McCaig C, ed. Nerve growth and guidance. Portland: Portland Press; 1996:131-41.
46. McCaig C, Song B, Rajnicek A. Electrical dimensions in cell science. J Cell Sci. 2009;122(Pt 23):4267-76.
47. Reid B, Song B, McCaig C, Zhao M. Wound healing in rat cornea: the role of electric currents. FASEB J. 2005;19(3):379-86.
48. Wang E, Zhao M. Regulation of tissue repair and regeneration by electric fields. Chin J Traumatol. 2010;13(1):55-61.
49. Yao L, Shanley L, McCaig C, Zhao M. Small applied electric fields guide migration of hippocampal neurons. J Cell Physiol. 2008;216(2):527-35.
50. Zhao M, Forrester J, McCaig C. A small, physiological electric field orients cell division. Proc Natl Acad Sci. 1999;96(9):4942-6.
51. Guo A, Song B, Reid B, et al. Effects of physiological electric fields on migration of human dermal fibroblasts. J Invest Dermatol. 2010;130(9):2320-7.
52. Burr HS. An electro-dynamic theory of development suggested by studies of proliferation rates in the brain of Amblystoma. J Comp Neurol. 1932;56:347-71.
53. Nordenström B. Impact of biologically closed electric circuits (BCEC) on structure and function. Integr Physiol Behav Sci. 1992;27(4):285-303.
54. Muehsam D, Ventura C. Life rhythm as a symphony of oscillatory patterns: electromagnetic energy and sound vibration modulates gene expression for biological signaling and healing. Global Adv Health Med. 2014;3(2):40-55.
55. Cao L, Graue-Hernandez E, Tran V, et al. Downregulation of PTEN at corneal wound sites accelerates wound healing through increased cell migration. Invest Ophthalmol Vis Sci. 2011;52(5):2272-8.
56. Cao L, McCaig C, Scott R, et al. Polarizing intestinal epithelial cells electrically through Ror2. J Cell Sci. 2014;127(Pt 15):3233-9.
57. Cao L, Pu J, Zhao M, Cao L, Pu J ZM. GSK-3β is essential for physiological electric field-directed Golgi polarization and optimal electrotaxis. Cell Mol Life Sci. 2011;68(18):3081-93.
58. Pullar C, Zhao M, Song B, et al. Beta-adrenergic receptor agonists delay while antagonists accelerate epithelial wound healing: evidence of an endogenous adrenergic network within the corneal epithelium. J Cell Physiol. 2007;211(1):261-72.
59. Zhao M, Song B, Pu J, et al. Electrical signals control wound healing through phosphatidylinositol-3-OH kinase-gamma and PTEN. Nature. 2006;442(7101):457-60.
60. McCaig C, Rajnicek A, Song B, Zhao M. Controlling cell behavior electrically: current views and future potential. Physiol Rev. 2005;85(3):943-78.
61. Levin M. Molecular bioelectricity in developmental biology: new tools and

recent discoveries: control of cell behavior and pattern formation by transmembrane potential gradients. Bioessays. 2012;34(3):205-17.
62. Yao L, Pandit A, Yao S, McCaig C. Electric field-guided neuron migration: a novel approach in neurogenesis. Tissue Eng Part B Rev. 2011;17(3):143-53.
63. Zhao M. Electrical fields in wound healing—An overriding signal that directs cell migration. Semin Cell Dev Biol. 2009;20(6):674-82.
64. Chifflet S, Hernández J, Grasso S. A possible role for membrane depolarization in epithelial wound healing. Am J Physiol Cell Physiol. 2005;288(6):C1420-30.
65. Sundelacruz S, Li C, Choi Y, Levin M, Kaplan D. Bioelectric modulation of wound healing in a 3D in vitro model of tissue-engineered bone. Biomaterials. 2013;34(28):6695-705.
66. Lewis M. Biomagnetism: a new tool in sport and exercise science. J Sport Sci. 2003;21(10):793-802.
67. Steinhoff U, Schnabel A, Burghoff M, et al. Spatial distribution of cardiac magnetic vector fields acquired from 3120 SQUID positions. Neurol Clin Neurophysiol. 2004 Nov 30;2004:59.
68. McCraty R, Atkinson M, Tomasino D, Bradley R. The coherent heart, heart–brain interactions, psychophysiological coherence, and the emergence of system-wide order. Integr Rev. 2009;5(2):10-115.
69. McCraty R. The energetic heart: Bioelectromagnetic communication within and between people. In: Rosch P, Markov M, eds. Bioelectromagnetic Medicine. New York: Marcel Dekker; 2004:541-62.
70. Leon E, Clarke G, Callaghan V, Doctor F. Affect-aware behaviour modelling and control inside an intelligent environment. Pervas Mobile Comput. 2010;6(5):559-74.
71. Lestienne R. Spike timing, synchronization and information processing on the sensory side of the central nervous system. Prog Neurobiol. 2001;65(6):545-91.
72. Cajochen C, Wyatt J, Czeisler C, Dijk D. Separation of circadian and wake duration-dependent modulation of EEG activation during wakefulness. Neuroscience. 2002;114:1047-60.
73. Aur D. A comparative analysis of integrating visual information in local neuronal ensembles. J Neurosci Methods. 2012;207(1):23-30.
74. Aur D, Jog M, Poznanski R. Computing by physical interaction in neurons. J Integr Neurosci. 2011;10(4):413-22.
75. Fröhlich F, McCormick D. Endogenous electric fields may guide neocortical network activity. Neuron. 2010;67(1):129-43.
76. Popp F, Nagl W, Li K, Scholz W, Weingartner O, Wolf R. Biophoton emission. New evidence for coherence and DNA as source. Cell Biphys. 1984;6(1):33-52.
77. Rubik B. Natural light from organisms: What, if anything, can it tell us? Noetic Sci Rev. 1993 Summer;26:10.
78. Albrecht-Buehler G. Rudimentary form of cellular "vision." Proc Natl Acad Sci U S A. 1992;89(17):8288-92.
79. Shen X, Mei W, Xu X. Activation of neutrophils by a chemically separated but optically coupled neutrophil population undergoing respiratory burst. Experientia. 1994;50(10):963-8.
80. Scholkmann F, Fels D, Cifra M. Non-chemical and non-contact cell-to-cell communication: a short review. Am J Transl Res. 2013;5(6):586-93.
81. Albrecht-Buehler G. A long-range attraction between aggregating 3T3 cells mediated by near-infrared light scattering. Proc Natl Acad Sci U S A. 2005;102(14):5050-5.
82. Kobayashi M, Takeda M, Sato T, et al. In vivo imaging of spontaneous ultraweak photon emission from a rat's brain correlated with cerebral energy metabolism and oxidative stress. Neurosci Res. 1999;34(2):103-13.
83. Van Wijk R, Bosman S, Ackerman J, Van Wijk E. Correlation between fluctuations in human ultra-weak photon emission and EEG alpha rhythm. Neuroquantology. 2008;6(4):452-63.
84. Sun Y, Wang C, Dai J. Biophotons as neural communication signals demonstrated by in situ biophoton autography. Photochem Photobiol Sci. 2010;9(3):315-22. doi:10.1039/b9pp00125e.
85. Rahnama M, Tuszynski JA, Bókkon I, Cifra M, Sardar P, Salari V. Emission of mitochondrial biophotons and their effect on electrical activity of membrane via microtubules. J Integr Neurosci. 2011;10(1):65-88.
86. Oschman J, Oschman N. Vortical structure of light and space: biological implications. J Vortex Sci Technol. 2015;2:1-3.
87. Foletti A, Grimaldi S, Lisi A, Ledda M, Liboff AR. Bioelectromagnetic medicine: the role of resonance signaling. Electromagn Biol Med. 2013;32(4):484-99.
88. Tiller W. What are subtle energies? J Sci Explor. 1993;7(3):293-304.
89. Swanson C. The torsion field and the aura. Subtle Ener Ener Med. 2008;19(3):43-89.
90. Hintz KJ, Yount GL, Kadar I, Schwartz G, Hammerschlag R, Lin S. Bioenergy definitions and research guidelines. Altern Ther Health Med. 2003;9(3 Suppl):A13-30.
91. Movaffaghi Z, Farsi M. Biofield therapies: biophysical basis and biological regulations? Complement Ther Clin Pract. 2009;15(1):35-7.
92. Blank M, Goodman R. Initial interactions in electromagnetic field-induced biosynthesis. J Cell Physiol. 2004;199(3):359-63.
93. Blank M. Protein and DNA reactions stimulated by electromagnetic fields. Electromagn Biol Med. 2008;27(1):3-23.
94. Lin H, Blank M, Rossol-Haseroth K, Goodman R. Regulating genes with electromagnetic response elements. J Cell Biochem. 2001;81(1):143-8.
95. McLeod K. The role of cell and tissue calcium in transducing the effects of exposure to low-frequency electromagnetic fields. In: Blank M, ed. Electromagnetic fields: Biological interactions and mechanisms. Washington, DC: American Chemical Society; 1995:349-65.
96. Pall M. Electromagnetic fields act via activation of voltage-gated calcium channels to produce beneficial or adverse effects. J Cell Mol Med. 2013;17(8):958-65.
97. Meyl K. DNA and cell resonance: magnetic waves enable cell communication. DNA Cell Biol. 2012;31(4):422-4.
98. Jamora C, Fuchs E. Intercellular adhesion, signalling and the cytoskeleton. Nat Cell Biol. 2002;4(4):E101-8.
99. Yang M, Brackenbury W. Membrane potential and cancer progression. Front Physiol. 2013 Jul 17;4:185.
100. Shupak NM. Therapeutic uses of pulsed magnetic-field exposure: A review. Radio Sci Bull. 2003 Dec;307:9-32.
101. Langevin HM. Connective tissue: a body-wide signaling network? Med Hypotheses. 2006;66(6):1074-7.
102. Oschman JL. Energy medicine in therapeutics and human performance. Edinburgh: Elsevier; 2003.
103. Ho MW, Knight D. The acupuncture system and the liquid crystalline collagen fibers of the connective tissues. Am J Chin Med. 1998;26(3-4):251-63.
104. Van Wijk R, van der Greef J, van Wijk E. Human ultraweak photon emission and the yin yang concept of Chinese medicine. J Acupunct Meridian Stud. 2010;3(4):221-31.
105. Oschman JL. Functional role of quantum coherence in interfacial water. Paper presented at: Water Conference 2013; Sofia, Bulgaria, October 22-25, 2013.
106. Muehsam DJ, Pilla AA. A Lorentz model for weak magnetic field bioeffects. Bioelectromagnetics. 2009;30(6):462-88.
107. Akber SF. The physics of NMR tomography. Nuklearmedizin. 1986;25(1):33-8.
108. Bialek W. Physical limits to sensation and perception. Annu Rev Biophys Biophys Chem. 1987;16:455-78.
109. Baylor DA, Lamb TD, Yau KW. Response of retinal rods to single photons. J Physiol. 1979 Mar;288:613-34.
110. Stryer L. Molecular design of an amplification cascade in vision. Biopolymers. 1985;24(1):29-47.
111. Sage C, Carpenter D. Public health implications of wireless technologies. Pathophysiology. 2009;16(2-3):233-46.
112. Oschman JL. Energy and the healing response. J Bodyw Mov Ther. 2005;9(1):3-15.
113. Lee KG, Chen XW, Eghlidi H, et al. A planar dielectric antenna for directional single-photon emission and near unity collection efficiency. Nat Photon. 2011;5:166-69.
114. Irwin MR. Human psychoneuroimmunology: 20 years of discovery. Brain Behav Immun. 2008;22(2):129-39.
115. Pienta KJ, Coffey DS. Cellular harmonic information transfer through a tissue tensegrity-matrix system. Med Hypotheses. 1991;34(1):88-95.
116. Pischinger A. The extracellular matrix and ground regulation: basis for a holistic biological medicine. Berkeley, CA: North Atlantic Books; 2007.
117. Bray D. Wetware: a computer in every cell. New Haven, CT: Yale University Press; 2009.
118. Pollack GH. The fourth phase of water: beyond solid, liquid, and vapor. Seattle, WA: Ebner & Sons; 2013.
119. Bischof M, Del Giudice E. Communication and the emergence of collective behavior in living organisms: a quantum approach. Mol Biol Int. 2013;2013:987549.