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Electromagnetic Forces and Life Processes

The concept that electromagnetic forces might have any effect upon living organisms—other than the thermal effect due to Joule heating—was for many years rejected by the organized biomedical community. But under the weight of experimental evidence this attitude is changing; indeed, the medical community is now expressing considerable interest in the possible therapeutic effects of direct application of small amounts of electrical energy. Within the past year reports of clinically useful effects have appeared in the scientific and the popular press. Thus the arguments over the electrical nature of life processes, which extend back at least to the work of Luigi Galvani, the Italian physician who wrote on "animal electricity" in 1791, are reaching a new and very promising resolution.

My own laboratory began working in this area in 1958, and the response to our reports has changed from complete rejection just over a decade ago through amused disbelief to—at present—enthusiastic acceptance. I believe the field has now reached a stage of understanding where it is important to assess the present stage of knowledge, the implications of that knowledge, and—especially—the possible dangers in premature acceptance of electromagnetic forces as a therapeutic modality suitable for human use.

My own work began with the premise, derived primarily from Albert Szent-Györgyi's theories, that cells and other biological components might have various electronic solid-state physical properties such as semiconduction. We have asked two basic questions:

☐ Are there control systems in living organisms based upon electronic conduction mechanisms that regulate important life processes?

☐ If such control systems exist, may they be perturbed in a clinically useful fashion by the application of appropriate levels of externally generated electromagnetic energy?

Both questions have now been answered in the affirmative, and it may truly be said that we are on the threshold of a new era in medicine in which bioelectronics offers the clinician control over basic life processes which even a decade ago could not have been anticipated.

Already it is established that electromagnetic forces can be used to change three fundamental life processes in mammals—and probably in man:

☐ Stimulation of bone growth.

☐ Stimulation of partial multi-tissue regenerative growth.

☐ Influence on the basic level of nerve activity and function.

All of these effects appear to be mediated through perturbations in naturally pre-existing electronic control systems. All are produced by low levels of direct current (continuous or pulsed) administered directly to the organism. At this time there appears to be a power-density relationship centered at an extremely low power level.

The discussion which follows relates only to the effects of continuous or pulsed direct current. Evidences for non-thermal effects of radiofrequency energy can be explained on the basis of its rectification into some form of direct current within the organism, with the subsequent effects then being by the mechanisms to be discussed.

Several of the effects of electromagnetic energy to be discussed are of considerable interest in the clinical practice of medicine, and we are currently witnessing several initial clinical applications:

☐ To promote healing of bone fractures and bone conditions involving inadequate growth.

☐ To promote rapid healing of skin ulcers and burns.

☐ To produce general anesthesis (electronarcosis).

☐ To produce sleep (electrosleep).

☐ As an adjuvant to acupuncture (electroacupuncture), for producing regional anesthesia and to stimulate healing.

The first two of these are achieved by application of direct currents of 1 to 3 mμamp. to the organ affected, the third and fourth by application of unmodulated or modulated (to 700 Hz.) direct currents of 1 to 5 mamp., the fifth by using pulsed direct currents (variable frequency to 100 Hz.) of no more than 1 mamp.

I have little doubt that a number of these will prove to be exceedingly useful and that enthusiastic acceptance will follow. But one must understand that, despite its pretentions to the contrary, medicine is not a science but an art founded in empiricism—a random search for tools that produce a desired effect on the patient. The history of medicine reveals enthusiastic acceptance of almost all treatment modalities

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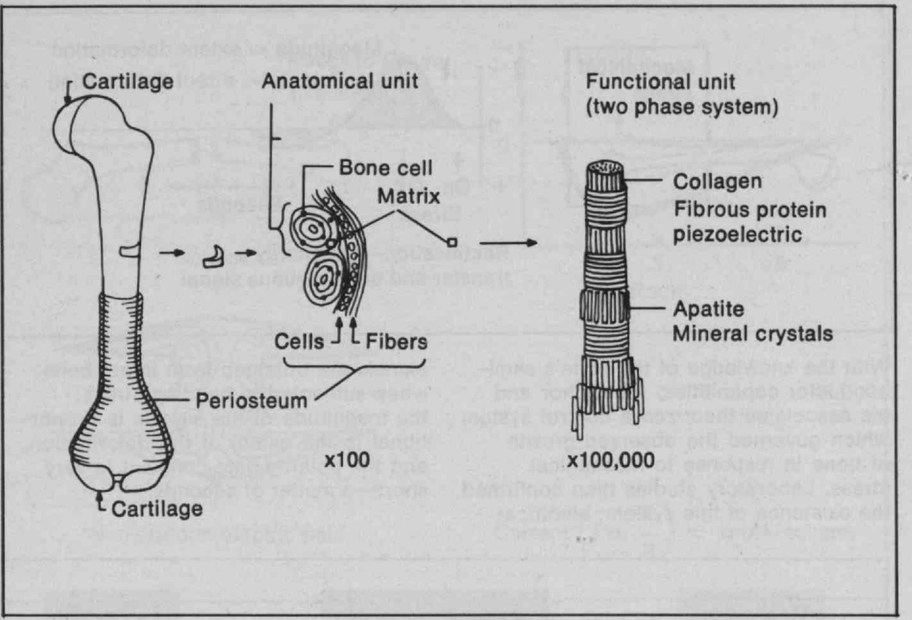
New research has made clear the role of minute electrical currents and voltages in controlling the development of animal structures and the healing of wounds. Detailed understanding of the life systems involved may be the next great advance in biomedical science.



The author's (and others') studies reveal that bone does in fact display solid-state electrical properties, and that these properties are associated with living bone cells—a small percentage of the total bone material. Collagen, the associated fibrous protein in the bone cell matrix, is piezoelectric; it and apatite, the mineral crystals associated with collagen, are both semiconductors.

that are effective without any consideration of the method of working and little consideration of possible deleterious side effects. Though extensive controls now surround the introduction of new drugs, there are few regulations concerning medical devices of the nature of those which deliver electromagnetic forces. Present evidence indicates that such forces have profound effects through the perturbations they induce in the naturally occurring electronic control systems within living organisms, and indeed that in this work we are gaining access to biological control systems of a very basic nature. Several very real dangers are inherent in the premature widespread clinical use of these techniques:

☐ Unrecognized deleterious side effects—such as malignant transformation of cells—may exist, and may not become evident until several years have passed.

☐ Applications involving the central nervous system may induce behavioral or cognitive disorders of a basic nature—again, perhaps not evident for some years.

☐ In the desire for immediate clinical rewards, extremely important applications may be overlooked.

☐ Acceptance of this technique as clinically useful may—without proper regulation—bring forth hordes of charlatans and quacks purveying ineffective but costly "treatment devices."

I believe that the situation is serious, and I urge that, as a first step, a working union should be organized between clinicians, biomedical workers, electronic engineers, electrochemists, and solid-state physicists to help achieve understanding of the uses and dangers of application of low-level electromagnetic forces. I doubt if such a basic question as how such forces influence biological systems can be answered without the multidisciplinary approach I propose.

The "Current of Injury"

The work in my laboratory in investigating this field has been chiefly on the role of small electromagnetic forces in cellular growth and regeneration. We began by studying what is called the "current of injury"—an electrical potential which always appears at a site of injury in a living organism. We measured this "current of injury" in two closely related animal species, one of which could regenerate a limb and one of which could not. (Most readers will be aware that certain animals—salamanders, for example—can regrow an amputated limb; this occurs by a particular growth process characterized by the appearance of a mass of primitive cells, forming themselves gradually into a complete multi-tissue extremity appropriately organized.) We found very specific differences in the "current of injury" which were postulated to be related to the two different processes involved in regeneration and nonregenerative healing.

Professor Marcus Singer had previously reported on a direct relationship between the extent of innervation to a limb—its integration into the nervous system—and the ability of the animal to regenerate that appendage after amputation. We therefore next investigated the relationship of the nervous system to this phenomenon, and we found that nerves (or their closely related supporting tissues) generated longitudinal electrical potentials which appeared to have their origin in semiconducting properties of some element of the nerve itself. After several years of studying this phenomenon, we developed the thesis that this property was organized into a primitive data transmission and control system that dealt with such modalities as the receipt of pain sensations (indicative of an injury) and the control of subsequent repair processes (to insure that they were appropriate and adequate).

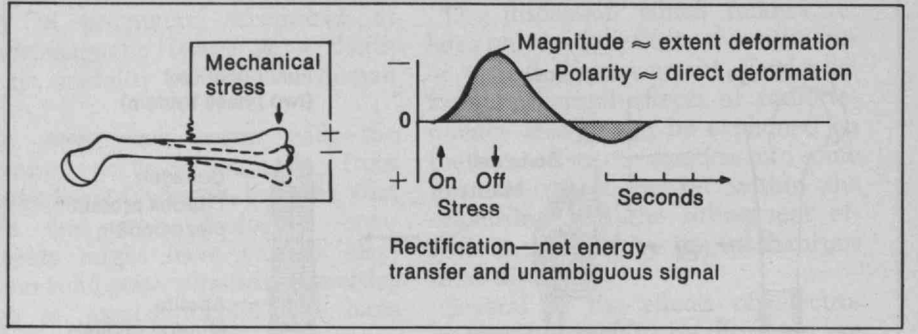
The neural electronic system also seemed to be related to levels of consciousness and biological cycles, and we have developed the thesis that this system furnishes the linkage mechanism between electromagnetic forces in the environment and biological cyclic behavior. Thus we may for the first time have a basis for understanding such interesting, generally accepted phenomena as these:

☐ Reversals of earth's magnetic field are related to the extinctions of various animal species.

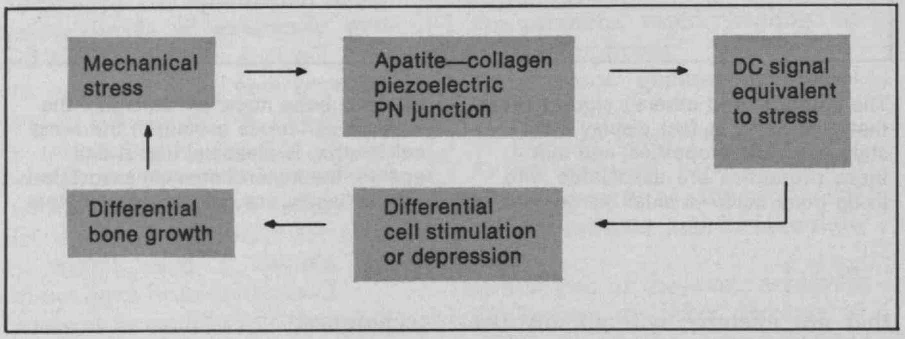
☐ Cyclic patterns in the earth's field are related, perhaps causally, to biological cycles.

☐ Disturbances in the earth's field (magnetic storms, etc.) are statistically related to behavior disturbances in the human population.

☐ There is a direct link between the earth's magnetic field and the migratory and homing activity of animals and birds.



With the knowledge of the bone's semiconductor capabilities, the author and his associates theorized a control system which governed the observed growth of bone in response to mechanical stress. Laboratory studies then confirmed the existence of this system; electrical signals are obtained from intact bone when subjected to bending stress; the magnitude of the signals is proportional to the extent of the deformation, and the polarity time-constant is very short—a matter of seconds.



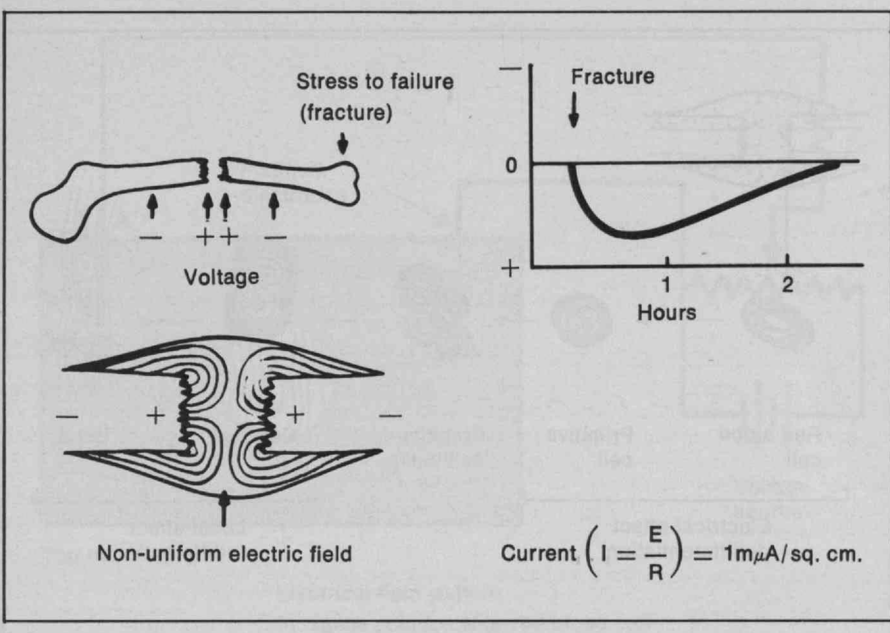
This simple block diagram illustrates the control system which regulates the growth of bone in response to mechanical stress (short of failure) in all mammals, as postulated by the author. The author confirmed this hypothesis by finding differential bone growth resulting from appropriate electrical signals introduced into nonstressed areas of bone.

Fracture Healing

We encountered considerable difficulties in adapting to nerve tissue the type of solid-state physical analysis that we wished to apply in order to establish the effects of electromagnetic forces. So we then turned to a study of bone from this point of view. This was a fortuitous choice, since—though bone has no nerve supply—it still evidences several types of clearly identifiable growth response which could be subject to control systems analysis. One such growth process in bone is its ability to anatomically restructure itself to best resist the mechanical stresses applied to it—an ideal input-output system. Another growth phenomenon of interest is fracture healing—the only true regenerative growth process still available to the mammal.

A portion of the bone matrix, the collagen fiber, had already been shown by Professor Eiichi Fukada to have piezoelectric properties; we extended this study and were able

Disturbances in the earth's electromagnetic field are statistically related to behavior disturbances in the human population



Mechanical stress to failure—the fracture of bone—leads to electrical activity of a kind very different from that involved in the gradual response to mechanical stress. In the former case, the stimulus stems from an interaction of electrical potentials in the damaged bone matrix and in damaged nerves in the extremity. The result is basically an opposed dipole which persists for several hours, in contrast to the signals from stressed but undamaged bone with time-constants in the range only of seconds.

to demonstrate that the collagen molecule, in addition to being piezoelectric, was an N-type semiconductor, while the mineral crystals closely applied to the collagen were P-type semiconductors. (These two semiconductors differ in the following way: current will flow from a P-type to an N-type material but not in the reverse direction.) With this knowledge, we could theorize a control system governing the growth of bone in response to mechanical stress that utilized a rectified electrical signal produced by the bone matrix when stressed. Such signals were found, and when devices which simulated such signals were inserted into non-stressed areas of bone, appropriate differential bone growth ensued. We have made many studies of the solid-state properties of bone and have reported a considerable amount of interesting data to support this view of how bone growth responds to physical stress.

The healing of bone fractures is a completely different growth process. Our first effort was to seek an electrical signal that resulted from stressing-to-failure of bone material, and such a signal was indeed identified. When applied *in vitro* to cells that produce new bone, a similar electrical signal in fact induced changes identical to those observed at the fracture site. We were soon able to integrate these observations into a control system that regulated fracture healing.

It should now be emphasized that both of these control systems are essentially self-contained; they fit the category of self-organizing systems, and they are in fact relatively simple closed-loop, negative feedback systems.

Toward Human Regeneration

The distinction between bone response to stress and to fracture lies in cellular changes which seem to be of great importance. In the case of fracture repair, we found that certain cells under appropriate electrical stimulation (direct current in μμamp. ranges) would undergo reversion to a more primitive cell type (dedifferentiated), and that this primitive material was subsequently redifferentiated into those cell types needed for the particular tissue repair process required. We were able to study some of the electrical parameters of importance; the most outstanding was that the effective levels of voltage and current had both upper and lower limits. In other words, voltages or currents above an upper limit were nonproductive of cellular changes until current densities became high enough to produce heating effects.

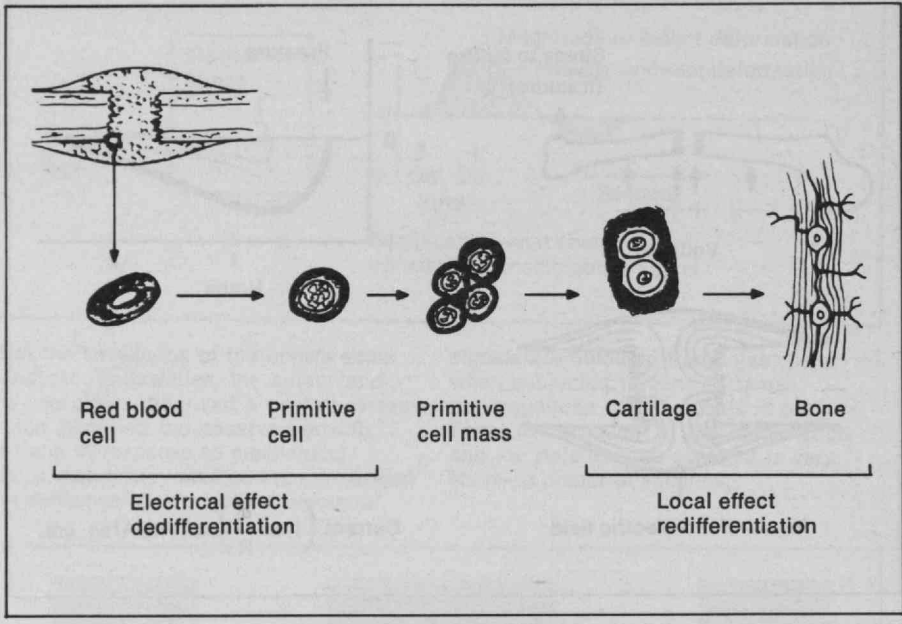
The fracture healing process is an example of regenerative-type growth; new *bone* tissue is regrown, and no scar tissue is formed. Thus we were able to use the information gathered in the fracture study to synthesize a theoretical control system regulating regenerative growth in general. On that basis we postulated several points in the control system where mammals, including man, might be deficient and so unable to achieve regenerative growth—except in the limited case of bone fracture repair. Correcting one or more of these theorized deficiencies might lead to the capability for regenerative growth in man. The clinical importance of this concept lies not in the possibility of achieving limb regrowth for humans, but rather in the possibilities it opens for the control of growth processes to achieve more effective healing.

For example: a heart attack results in the death of a portion of the heart muscle; the normal healing process is the production of scar tissue across the area. Multiple scar formation obviously results in diminished functional ability of the heart as a pump. At the present time only three therapeutic methods seem to be available: grafting of additional blood vessels to the heart with the intent of preventing additional attacks, heart transplant, and—possibly—mechanical hearts of various types. None of these is particularly efficient, most are experimental in nature, and one can reasonably predict great difficulties in developing these as effective, large-scale therapeutic methods.

But we have found that some animals capable of regrowing limbs can also regrow portions of the heart muscle. The control mechanisms for both these types of regenerative growth appear to be the same. If we could gain access to these control systems in an effective fashion, we would be able to bring about the repair of damaged heart muscle by growing new heart muscle instead of scar. Similar applications can be envisioned in many other areas of clinical medicine; probably the most fruitful for early application would be in the bones and joints.

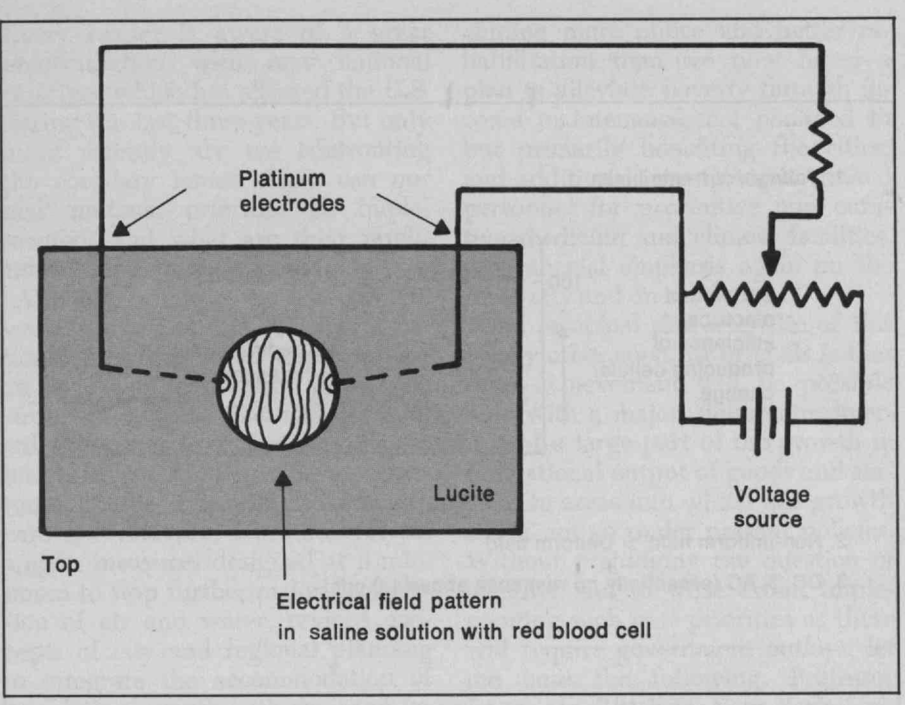
We theorize that one reason why mammals cannot achieve many kinds of regenerative growth is the absence of adequate electrical factors at the injury site. Acting on that hypothesis, my laboratory initially undertook a study of limb regeneration in the white rat. The theoretical current/voltage requirements were small enough so that we could consider bimetallic electrogenic couplings as a power source; similar devices had been used by Professor Stephen Smith in 1967 to restore some measure of limb regeneration in the frog, an amphibian capable of limb regeneration when in the tadpole stage but lacking this ability in adulthood. We investigated these devices and found that Smith's simple, silver-platinum junctions produced currents approximately five times those required. We resolved this problem by inserting miniature carbon resistors of various values between the silver and platinum, encapsulating the entire device in silicon.

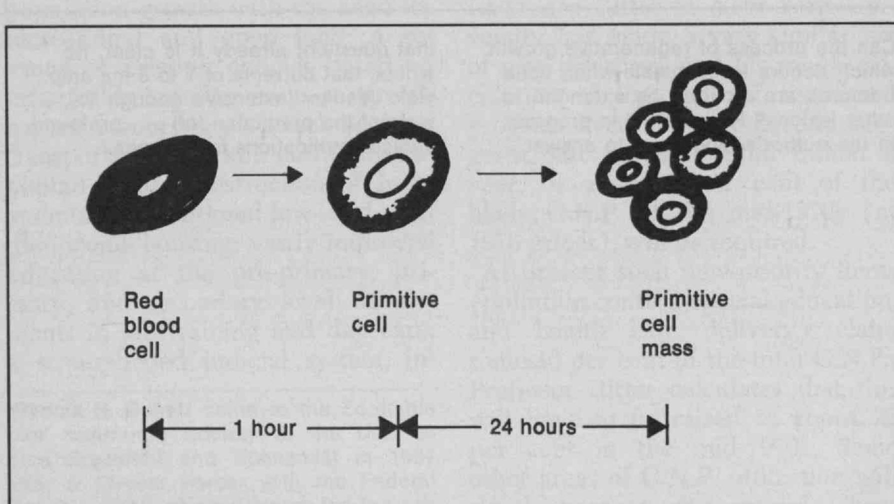
Such devices inserted into the amputated forelimbs of 21-day-old white rats resulted, in a high percentage of cases, in the regrowth of an organized, multi-tissue portion of the mission extremity. Bone cartilage, bone marrow, muscle, nerve, and blood vessels all were regenerated. While a complete extremity was not formed in any case, the amount and organizational pattern of the units formed far exceeded any growth naturally seen or previously obtained by any technique.



Distinctive cellular events stemming from nerve/bone electrical potentials are associated with fracture healing in all vertebrates other than mammals, and the author proposes that they also occur in bone marrow cells in the fracture healing process in mammals. The events of interest consist first of dedifferentiation of red blood cells into primitive cells and cell masses, and then the redifferentiation of the latter into cartilage and bone. The fracture healing process is the only example of regenerative growth known in mammals.

Successful experimental regrowth of a cell population by electrical energy application warrants a prediction of profound clinical implications for humans





This diagrammatic representation (top) shows the author's method of obtaining primitive regenerative growth by simulating the levels of electrical currents and fields which he found to in fact prevail at the site of a bone fracture in a laboratory mouse. Direct currents in amp. ranges are used to create an electrical field in a saline solution containing red blood cells.

Within an hour these cells have begun a process of redifferentiation into more primitive cells (below), and within 24 hours large numbers of such primitive cells are available. Then can begin the process of their redifferentiation into the various cell types required for the tissue repairs.

The importance of this observation is two-fold. The growth pattern makes it clear that the effect of the electrical energy was to bring about dedifferentiation of a cell population and its subsequent regrowth and re-differentiation, with the expression of multiple genetic pathways (i.e., the controlled reading-out and application of the all-purpose structural information that all cells possess—the process which occurs in its most complete form during the development of an embryo). And the results produced in response to the level of current used (a total of 1 to 3 mμamp.) were extensive enough to warrant the prediction that similar-level currents could have profound clinical implications for humans.

Unravelling the Control of Life

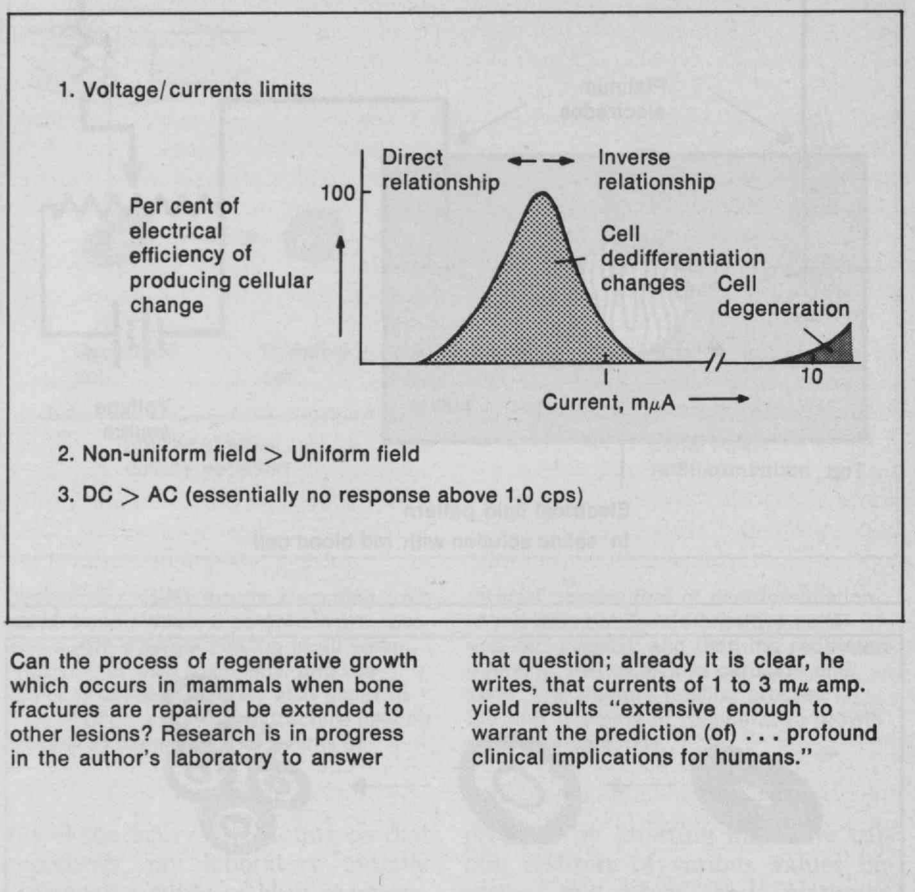
We therefore now believe that low-level electrical currents and potentials, produced either by direct injection or by rectification and induction from a field, have the capability of bringing about very major biological effects of a very basic nature. The changes appear to be based upon perturbations produced in pre-existing biological electronic control systems which regulate very basic life functions. They hold significant promise for better understanding of life control systems and for clinical application to certain diseases.

But the present rapid proliferation of techniques and devices utilizing electrical currents and potentials in the treatment of various clinical conditions seems to be unjustified and indeed alarming; and I am particularly concerned that the very real dangers appear not to have been considered very thoroughly by any of the groups occupied with clinical applications.

I also feel concern for a much broader problem, which is the continuous exposure of the entire North American population to an electromagnetic environment in which is present the possibility of inducing currents or voltages comparable with those now known to exist in biological control systems.

I am not suggesting that all clinical investigation of this modality be terminated; however, I do believe that it should be subject to the same types of controls imposed on the use of experimental drugs. Nor am I suggesting that all use of radio-frequency radiation be terminated; however, the application of energy in new spectral regions or increases in current field densities in metropolitan areas should be carefully evaluated.

What I feel is urgently required is multidisciplinary research on the entire problem of electromagnetic energy and biological systems, covering all areas—the direct injection of electrical current into living systems, their exposure to radio-frequency fields, and pre-existing basic biological electronic control systems. My conviction is that this field holds promise of containing the next great advance in biomedical science.



Can the process of regenerative growth which occurs in mammals when bone fractures are repaired be extended to other lesions? Research is in progress in the author's laboratory to answer that question; already it is clear, he writes, that currents of 1 to 3 mμ amp. yield results "extensive enough to warrant the prediction (of) . . . profound clinical implications for humans."

Suggested Readings

Becker, R. O., and D. G. Murray, "The Electric Control System Regulating Fracture Healing in Amphibians," *Clinical Orthopedics and Related Research,* Vol. 73, pp. 169-98, 1970.

Frost, Harold M. (ed.), *Bone Biodynamics.* Boston: Little Brown and Co., 1964.

Szent-Gyorgyi, Albert, *Introduction to a Submolecular Biology.* New York: Academic Press, 1960.