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The Significance of Bioelectric Potentials *

by ROBERT O. BECKER
Medical Investigator Veterans Administration Hospital, Syracuse, New York and Research Professor, Upstate Medical Center Department of Orthopedic Surgery, Syracuse, New York (USA)

Summary

A complete, operational system is proposed to exist in living organisms which controls such basic functions as growth, healing and biological cycles. The system is described in anatomical detail. It functions as a data transmission system in an analog fashion using varying levels of *d. c.* as its signal. The system interlocks physically with the nervous system and is postulated to be its percursor. There are two electrochemical links of great significance in the operation of the system. One is between the *d.c.* system and the nervous system ; the other is between the *d.c.* system and all body cells. The concept explains all of the diverse effects reported for the biological effects of applied electrical currents including : electrical anesthesia, electrical growth control and electro-acupuncture. It also furnishes a testable hypothesis for predicting other effects that might be of clinical significance.

The significance of bioelectric potentials

According to the present concepts of physiology, the mechanisms of data transmission and control in living organisms are limited to the neural action potential and various chemical agents such as hormones and the well known DNA–RNA systems. These have been powerful tools and have provided medical science with insight into many highly sophisticated functions including vision, coordinated muscular activity, the transmission of inherited characteristics and the controls over the multitudinous chemical and metabolic activities of living organisms. They have not, however, succeeded in providing us with knowledge of, or even furnished an adequate frame of reference for, the most basic life functions, including the sensation of pain and the controls over tissue growth and healing. It is unfortunate that these are the areas presenting

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us with the greatest problems in the daily practice of medicine. Since the advent of antibiotics and effective control over exogenous diseases, the bulk of medical practice is now occupied with diseases resulting from inadequate growth and healing or abnormal growth. The former category includes arthritis and heart disease, while the latter is obviously cancer. Man appears to have " traded off " effective growth control systems such as are present in lower animals for cognitive ability. The development of medical science over the last 200 years has been characterized by increasing knowledge of complex second order phenomena and almost total ignorance of prime causes.

The initial observations that furnished the basis for much of biomedical science, including neurophysiology (and for electrochemistry as well) were made by GALVANI in the late 1700's. He observed electrical currents being generated by injured tissue, a phenomenon now known as the current of injury. This potential was steady state or *d.c.* in character and was both difficult to measure and poorly understood. Following GALVANI, much work was done on *d.c.* potentials in living organisms, however, except for that of MATTEUCCI, it was of poor quality and contributed little to our understanding of how biological systems functioned. The observation of the nerve action potential in 1849 by DU BOIS REYMOND provided an easily measurable phenomenon that was obviously related to important physiological functions. Since then the vast majority of neurophysiology has been related to this property and little attention had been paid to the *d.c.* potentials, which were relegated to the status of second order phenomena arising somehow as a result of metabolic gradients. However, the failure of the action potential system to explain basic causes and a steady progression of observations on the origin and functions of biological *d.c.* potentials have recently provided us with a theoretical framework by which basic functions such as growth control may be understood. This framework furthermore, has made possible explanations for such recent empirical observations such as electronarcosis, electrical growth stimulation and electro-acupuncture.

It is now known that the *d.c.* potentials measurable on the intact surfaces of all living animals demonstrate a complex field pattern that is spatially related to the anatomical arrangement of the nervous system (Fig. 1, 2 A). [1-3] The surface potentials appear to be directly associated with some element of the nervous system and they can be measured directly on peripheral nerves themselves where they demonstrate polarity differences depending upon whether the nerve is primarily motor or sensory in function (Fig. 2 B). [4]

The existence of standing electrical potentials in a conducting medium implied the existence of a steady current flow and experiments have demonstrated that such a current exists, longitudinally in the neural elements (Fig. 2 C) and demonstrating several aspects of a solid state or semiconduction type phenomena. [5,6] These potentials were noted to accurately reflect by means of their amplitude and polarity the general level of neural activity (*i.e.*, sleep–wakefulness, anesthesia–consciousness, etc.) and it was demonstrated that the *d.c.* potentials ***determined*** the

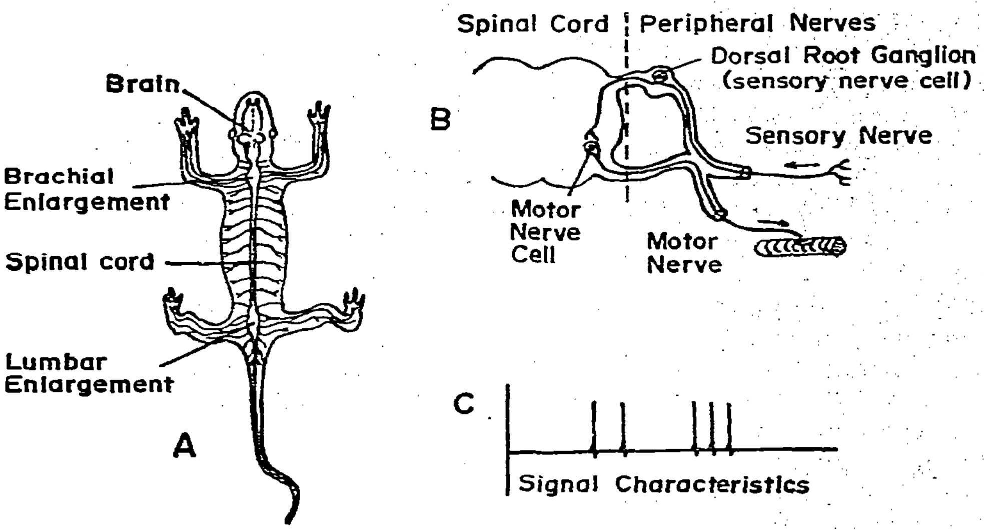

Fig. 1.
A. Gross anatomical arrangement of the CNS of the salamander. The cell bodies of the neurons are located primarily in the brain and in the enlargements of the spinal cord that serve to innervate the extremities.
B. Section through spinal cord and peripheral nerves demonstrating the arrangement of motor (output) and sensory (input) nerves.
C. Characteristics of transmitted signal, action potential.

level of neural activity [7,8] an observation that provides a logical basis for electrical anesthesia and a framework of reference for hypnosis. [9] These observations would appear to indicate that the action potential system existed upon a substratum of *d.c.* potentials which may have antedated the action potentials as a mechanism of data transmission. If this is so, then the pre-existing *d.c.* potentials must have had originally, and may still have, control functions over basic properties of living organisms. Such a function has been determined in the case of the reaction to injury and the self repair processes that follow it.

The property of self repair is obviously well controlled, it is initiated by the injury, is adequate to repair the injury and no more, and in the case of regeneration is capable of transmitting large volumes of data leading to a full anatomical restoration. In the latter instance, those animals capable of regeneration, such as the salamander, have the ability to regrow a missing extremity in its entirety, as much as 30 % of the heart and up to 30 % of the brain. The structures regrown are entirely analagous to their human counterparts and, in the case of extremities, fully as complicated. While it has been well demonstrated that the regenerative process is dependent upon some element of the nervous system, [10] it has not been possible to equate it with any component of the nerve action potential system. It has, however, been

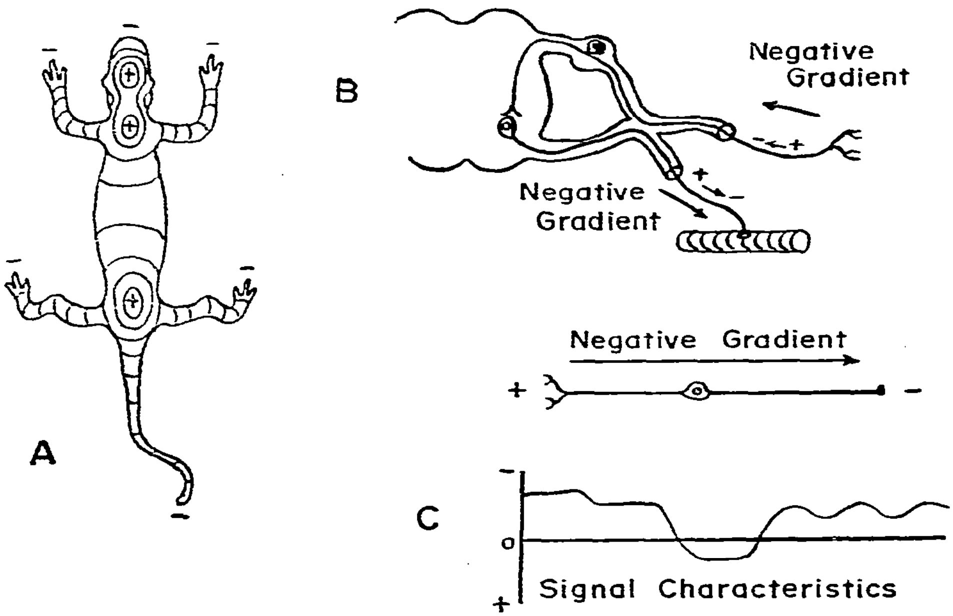

Fig. 2.

A. Gross arrangement of the *d.c.* electrical field on the surface of the intact salamander. The congruence of the field pattern with the gross anatomical arrangement of the central nervous system is obvious.

B. Section through spinal cord identical to Fig. 1 B with the polarity of the peripheral nerve *d.c.* electrical potential indicated.

C. Characteristics of transmitted signal, *d.c.* analog.

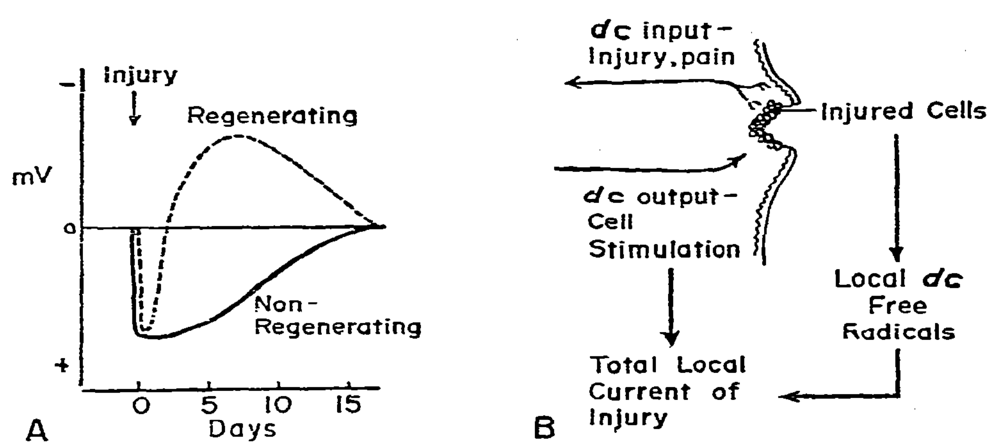

Fig. 3.

A. The current of injury as measured daily at limb amputation sites on a regenerating animal (salamander) and a non-regenerating but closely related animal (frog).

B. Diagramatic representation of events postulated to occur at a site of injury.

possible to relate regenerative healing in a causal fashion to the current of injury [11,12] Fig. 3 A and to consider it as a portion of a total control system with contributions from local damaged cells and from the *d.c.* activity of the nerves (Fig. 3 B). Since repair resulting from injury is a stimulus response system, it is possible to theorize that the input signal resulting from injury, which informs the total organism that an injury has been received, is what we perceive at the conscious level as pain. A number of observations on injured living systems [13,14] have led us to postulate a complete control system dealing with the entire injury–self repair complex utilizing the pre–existing *d.c.* electrical system (Fig. 4).

Previous analyses of the regenerative healing system by the same techniques enabled us to predict the portions of the control system which would be missing or inadequate in those animals lacking regenerative ability. [15] One of these was an inadequate local current of injury resulting from diminished peripheral nerve mass secondary to encephalization, particularly in mammals. Experiments at simply restoring this electrical environment in amputations in rats have resulted in the restoration of surprising amounts of complex regenerative healing. [16,17] We have concluded therefore that the neural function essential to regeneration is the *d.c.* electrical activity associated with the peripheral nerves.

An indication of the structures responsible for the generation and transmission of this *d.c.* signal was obtained from several studies on

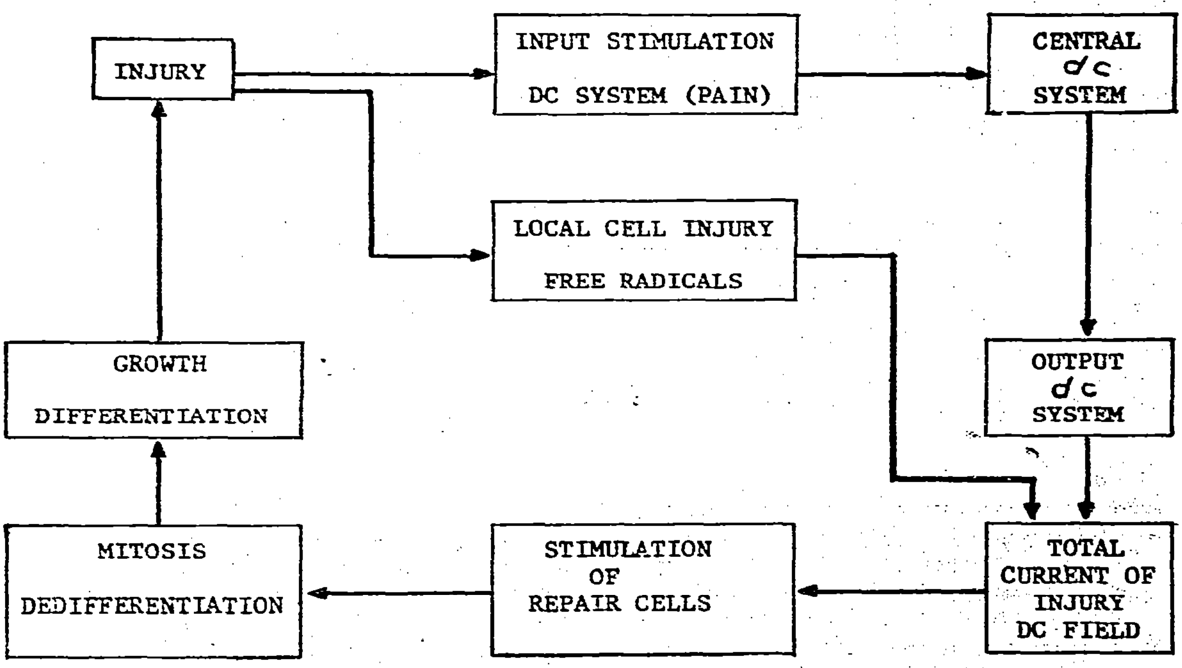

Fig. 4.
The theoretical *d.c.* control system involved with the response to injury.

fracture healing. In experiments on fracture healing in amphibians we were able to demonstrate a direct effect of the *d.c.* current of injury on the cells responsible for the healing.[13] In the mammal fracture healing is generally regarded as the only remaining vestige of true regenerative healing, demonstrating the formation of a blastema (mass of primitive type cells that gives rise to the regenerated tissue) early in its course. In view of SINGER's demonstration of the dependence of limb regeneration upon a quasi-mathematical relationship between nerve mass in the extremity and total extremity mass[10] it was decided to investigate the effect of denervation upon fracture healing in this animal. The laboratory white rat was the subject with fracture of the fibula in the hind limb the test system. It was found that, if fracture and denervation (by resection of a portion of the sciatic nerve) were performed simultaneously, the healing time of the fracture was markedly prolonged and the appearance of the blastema delayed. However, if denervation preceded the fracture, the delay of healing was progressively diminished until the situation in which denervation preceded fracture by 5 to 7

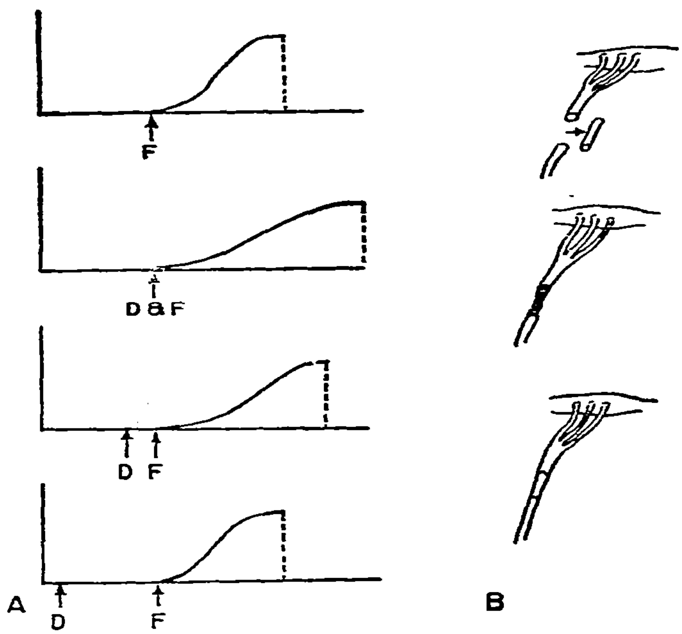

Fig. 5.
Effect of denervation on fracture healing.

A. Upper graph, normal rate of healing after fracture (F). Second graph, prolonged rate of healing following simultaneous fracture and denervation (D). Third graph, healing rate restored towards normal when denervation preceeds fracture by two days. Bottom graph, normal rate of healing when fracture preceeded by denervation by seven days.

B. Diagramatic representation of denervation technique. Upper, resection of 5–8 mm. of sciatic nerve. Center, status at seven days, there is a thin delicate tissue connecting the nerve ends, but no neuronal growth. Lower, status at 45+ days, there is complete restoration of nerve continuity.

days in which case the time of appearance of the blastema, its extent and the time to full healing were identical to the normal (Fig. 5). We were forced to conclude that whatever the tissue was that transmitted the *d.c.* potentials and regulated the regenerative healing, it's continuity was restored in this short period of time. Restoration of the continuity of the nerve is not possible in such a short period and indeed all of the animals so treated continued to display complete paralysis of the limb until sacrifice. However, exploration of the sciatic nerve in these cases revealed that a thin delicate tissue had bridged the surgical gap in the sciatic nerve. While histological examinations are not fully conclusive at this time, this tissue appears to consist of the SCHWANN cell sheath structures associated with the peripheral nerves. This is consistent with the established fact that regrowth of peripheral neurones is preceeded by and in fact, dependent upon regrowth of the SCHWANN sheathes.[18] We are obliged to conclude therefore, that the control over local regenerative healing does not reside in the neurones themselves but in their accompanying " supportive " structures, the SCHWANN cells, and we propose that these cells are the tissue responsible, in part, for the generation and transmission of the *d.c.* electrical control signals. Since all peripheral nerves have SCHWANN cell sheaths, SINGER'S observations of the dependency of regeneration on the peripheral nerves, but not upon the action potential system of these nerves is understandable. Our findings lend themselves admirably, in conjunction with other well established anatomical facts, to a logical extension of our theories that appears to have great power for explaining the many seemingly diverse and unrelated observations of the effects of eletrical potentials (and magnetic fields) on living organisms.

The SCHWANN cells constitute only the peripheral representatives of a complex cellular system which completely pervades all neural tissues. The cells of the brain and spinal cord as well as their axons and dendrites are encased in a complex network of various types of glia cells, the cell bodies of the dorsal root ganglia and the autonomic nervous system ganglia are surrounded by satellite cells and the extensions of the neurons that constitute the peripheral nerves are completely encased in tubulations of SCHWANN cells (Fig. 6). The functions of these cells in general have been poorly defined, their extremely close associations with neural elements have suggested supportive or nutritive roles and these have been accepted without objective proof primarily in the absence of any other demonstrated function. Several aspects of this cellular system are particularly intriguing ; many of its components are organized into syncytia in which the cells have lost their cell walls at points of contact with each other, all of these cells are derived embryologically from the same tissue, the neuroectoderm, which gives rise to the neurones of the entire nervous system themselves and finally, it appears very likely that all components of this system are in intimate contact with each other. This system is so all pervading that if a method were devised to dissolve all neural elements and leave these " supportive " cells intact, the complete anatomy of the original nervous system would be preserved. If, as

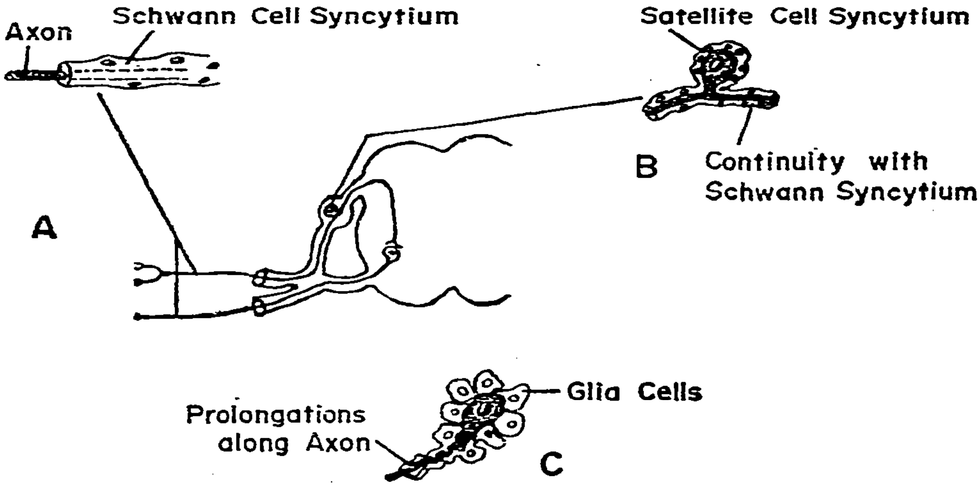

Fig. 6.

General anatomical considerations of the perineural cell system

A. SCHWANN cell sheaths. These are syncitia of cells derived from the neural crest which completely envelop all peripheral nerves. In those nerves that are myelinated the SCHWANN sheath produces the myelin by a complex folding process.

B. Satellite cell syncytia surround all cell bodies in the dorsal root ganglia, the autonomic ganglia and cranial ganglia. They are derived from the neural crest cells and have a direct syncytial contact with the SCHWANN sheaths of the peripheral sensory fibers.

C. Neuroglia cells. The cells surround all nerve cell bodies in the brain and envelop all axonal outgrowths in fiber tracts within the brain and spinal cord. They are derived from the neural tube.

All of these cells are derived from parts of the same embryological neuroectoderm that gives rise to all units of the central nervous system. It is postulated that they all function in an integrated fashion to produce a single data transmission and control system.

we indicate, the SCHWANN cells generate and transmit the peripheral *d.c.* potentials that are responsible for growth control, it is entirely reasonable to suggest that the central elements of the system, the glia and satellite cells also generate and transmit *d.c.* potentials. There are many evidences that support this view. *d.c.* potentials are measurable in the brain and correlate well with general neuronal activity. [8,19] The entire area of cerebral *d.c.* potentials has been reviewed by O'LEARY and GOLDRING who reached similar conclusions. [20] TASAKI has obtained considerable evidence that the glia cells themselves are the primary sources of the cerebral *d.c.* potentials. [21,22] It would appear that the functional level of cerebral neurones is controlled by the *d.c.* potentials generated by their investing glia cells.

Since it is generally agreed that *d.c.* graded responses must have antedated the action potential, [23,24] it is now possible to theorize the evolutionary development of the data transmission and control system in living organisms from its earliest inception as a simple unicellular semiconducting, possibly piezoelectric matrix, through the stage of a complex syncytical network handling basic type data on an analog (*d.c.*) basis to the present hybrid system containing the original basic, analog system transmitting data as a *d.c.* signal (glia, SCHWANN) which surrounds and controls the newer digital system capable of large data capacity as action potentials (nerve cells) (Fig. 7). The primitive basic tissues (glia, satellite and SCHWANN cells) are supportive to the neurones, not in a mechanical but in an electrical sense. The close association of their membranes, with remarkably narrow dimension gaps between these " supportive " cells and the nerve cells suggest an electrochemical function of

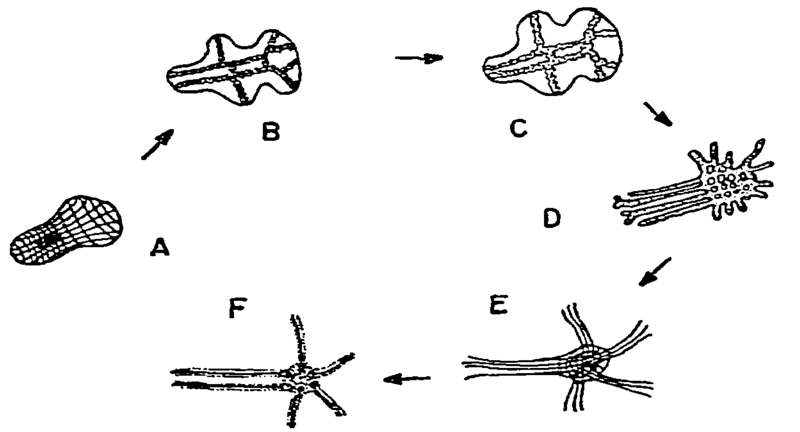

Fig. 7.

Theoretical development of the nervous system as a hybrid type.

A. Primordial organism, pseudo-cellular in type, transmitting data in a self-organizing semiconduction based network, as *d.c.*

B. Early metazoan (multicellular organism) transmitting data by a network of cells similar to those in A. Presumably after some development, these cells would become specialized for this data transmitting function.

C. Later metazoan in which the data carrying cell network has become syncytial in nature. This facilitates the transmission of *d.c.* information by avoiding the high resistance intercellular junction.

D. Still later metazoan with more complex organization of the data network and early establishment of a central locus.

E. Highest development of the *d.c.* data transmitting system with establishment of a complex central locus and input and output tracts. The central locus and its peripheral portions would be analogous to the present day glia and satellite cell network, while the peripheral tracts would be composed of SCHWANN cell syncytia. This theoretical organism would be capable of all basic inputs such as the receipt of injury stimuli, biological cycles and controlled outputs regulating cellular growth and repair and body organization.

F. Development of high speed digital data channels within the pre-existing *d.c.* network. The characteristic data transmission unit of this system would be the action potential. These fast data channels are completely surrounded by elements of the *d.c.* system and dependent upon them for the determination of their basic operational level (bias). This system corresponds to that present in the majority of organisms living at this time. For simplicity many aspects of the system are not included in this figure. However, several of the complexities of the present day system, such as the generator potentials of peripheral receptors are quite compatible with this thesis.

the former as necessary for maintenance of the neuron's transmembrane potential and subsequent action potential generating ability.

Philosophically, this concept would appear to be logical. The earliest living organisms could not have had access to such sophisticated mechanisms as the action potential. Furthermore, they would have had no need for such an ability not having developed the sophisticated inputs (vision, hearing, etc.) or outputs (muscular movement and coordination) that would have demanded such a system. They would however, have had need for a system capable of the receipt of injury stimuli (? pain) and subsequently capable of controlling the self-repairing processes occasioned by the injury. The solid state physical basis for the conduction of the simple analog *d.c.* signals would have rendered the system sensitive to electrical and magnetic environmental fields and it is not unreasonable to predict that such forces would have been nontrivial environmental factors at that time.

This concept is capable of explaining, or at least furnishing a testable frame of reference for the observations of : electrical anesthesia, [25] growth stimulation [12,16,17] and retardation [26] by applied electrical currents ; biomagnetic effects in general [27] and the apparent coupling between the magnetic field and complex behavior. [28,29]

Analysis of the empirical technique of acupuncture by this concept has lent additional weight to its substantiation. The transmission of *d.c.* signals over a resistive net involves decline in signal strength to noise ratio with distances due to resistive and inductive losses. If it is necessary to effectively transmit such a signal over any distance this " line loss " must be compensated for by the installation of operational amplifier or generator units at appropriate points along the lines (Fig. 8). Such generator or amplifier points would have a greater sensitivity to perturbations produced by local electrical fields than the transmisson lines proper and such perturbations would be propagated throughout

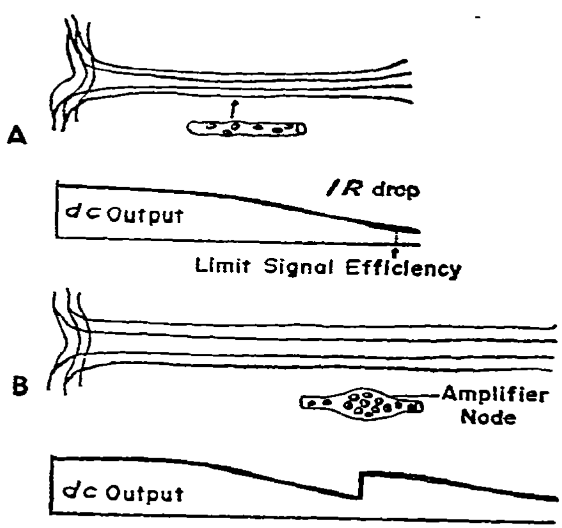

Fig. 8.
Influence of organism size on the *d.c.* system.

A. Theoretical limit of transmission of *d.c.* along a syncytial cell channel. Factors such as resistance and impedance would reduce signal level proportionally to the length of the channel.

B. Data channel length that exceeds limit of signal intelligibility requires additional generating sources (operational amplifiers) at or before theoretical limit. If one postulates that the *d.c.* data channel is along the SCHWANN cell sheath, then the local generating source should be anatomically distinct.

the net as a result. Can the meridiens of acupuncture be considered as SCHWANN Cell transmission lines with the acupuncture points being the spaced generating sources? Initial observations would appear to indicate that this is so. The technique of locating the acupuncture points by impedance or resistance measurements is well known. However, one must consider that if these points are sources of *d.c.* rather than points of diminished resistance, the bridge measurements would be the same. We have determined by *d.c.* measurements using Ag–AgCl electrodes and high input impedance electrometers that the acupuncture points are in truth point sources of *d.c.* fully as discrete as when measured by impedance or resistance bridges (Fig. 9). Obviously, much more

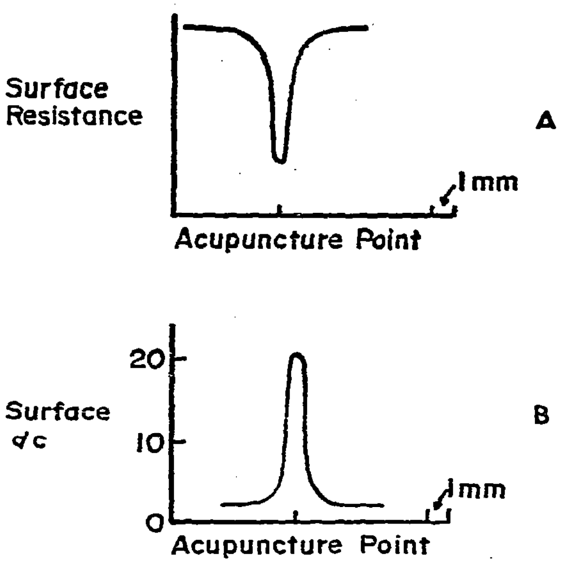

Fig. 9.
Electrical measurements over acupuncture "points".
A. Resistance bridge measurement.
B. *d.c.* measurement with Ag–AgCl electrodes and 10^{14} ohm input electrometer.

work remains to be done to establish the details of the system including anatomical determination of the generator or amplifier nodes, and determination of the imput–output characteristics of the system including cerebral *d.c.* shifts in response to peripheral stimulation. Nevertheless, this analysis would appear to indicate that the general concept the *d.c.* data transmission system based upon the SCHWANN–glia cell tissue is a powerful tool (Fig. 10).

In summary, it is proposed that all organisms presently exitant have hybrid data transmission and control systems. That the basic system consisting of the glia, satellite, SCHWANN continuum is an analog type handling data as a slowly varying *d.c.* potential generated and transmitted by an integral semiconducting or other solid state property. This system is involved in the receipt of damage or injury stimuli which we perceive as pain and in the control of the various growth processes of repair, including regeneration. Its nature renders it susceptible to

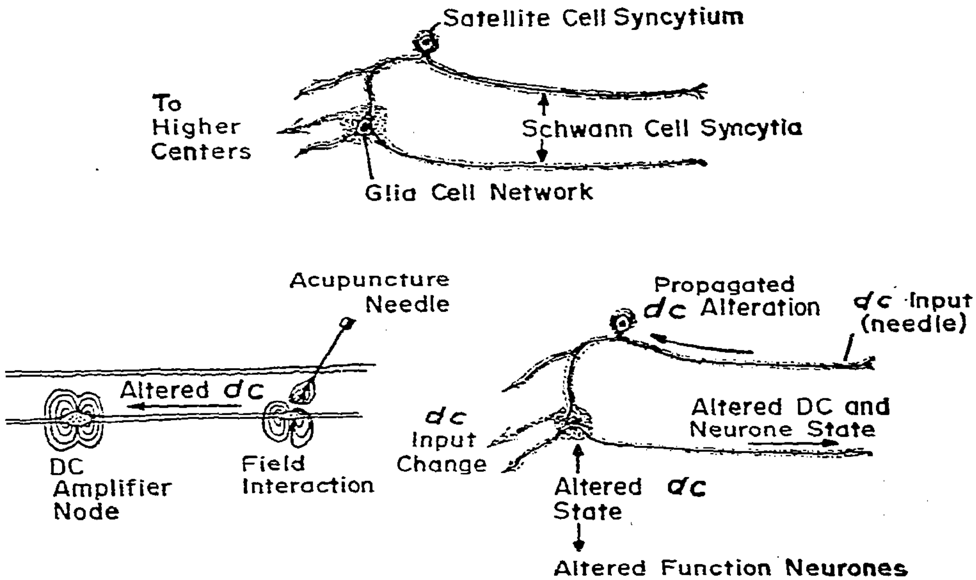

Fig. 10.
General aspects of the present hybrid type data transmission systems.
A. Schematic of the general system.
B. Diagram of a postulated *d.c.* input channel along an acupuncture meridien with field interaction between needle and point generator.
C. Postulated circuit influenced by acupunture technique.

perturbation by electrical and magnetic fields and it is proposed that it furnishes the linkage mechanism between biological cycles and geomagnetic cycles. Since it is the basic system and the parent of the more sophisticated neural digital action potential system, the functions of the latter are dependent upon the state of the former. It is particularly interesting that during the period of the maximum growth of computer technology and the development of cybernetics that one of the foremost scientists in this field, JOHN VON NEUMANN, predicted on logical and mathematical grounds that such a hybridization of data transmission and control functions must exist in the biological world. [30] A similar concept with respect to *d.c.* potentials was developed by the present author in 1960. [1] The analog system has two interfaces, one with the digital system which it encompasses and incorporates and the other, with the somatic cells, whose basic functions it controls. Each of these interfaces is perforce across a fluid milieu and the actions must be transmitted by a combination of electrical field gradients and electrochemical mechanisms.

If the concepts developed in this paper prove to be correct, biomedical science will be provided with much clearer insight into how living organisms function and the resultant changes in clinical therapeutics will be far reaching.

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