EVIDENCE FOR A PRIMITIVE DC ELECTRICAL ANALOG SYSTEM CONTROLLING BRAIN FUNCTION

Robert O. Becker, M.D.

ABSTRACT

Modern neurophysiology views the problem of integration of brain function as the result of massive interconnectivity of the neurons and almost all research in this area is based upon this concept. In the first article of this series I outlined some of the theoretical problems with this view. In this article I shall review the evidence gathered over the past 50 years indicating that a separate operational system exists, based upon extra-neuronal DC electrical currents, that serves this integrating function.

KEYWORDS: Mind, brain, electrophysiology, bioelectromagnetics, neuronal, glial

DC POTENTIALS AND CURRENTS IN BIOLOGICAL SYSTEMS

Brain DC Potentials

The existence of electrical oscillations from the human brain was first reported by Berger,[1] who described both the alpha and beta rhythms. Over the next decade advances in electronic instrumentation revealed the presence of other frequencies as well and loosely associated all of them with various functional states. Since the anatomical and functional unit of the brain was considered to be the neuron and its action potential, the much slower wave forms of the electroencephalogram (EEG) were ascribed to the relatively synchronous action potential discharges of large numbers of neurons. The factors producing this synchronization were the subject of much speculation but little firm evidence. In addition, the long term persistence of steady rhythms were assumed to be the result of some "pacemaker" neuron activity, again with little firm evidence. In 1936, Bishop[2] proposed that neuronal circuitry, acting via action potentials alone, could explain the synchronization of cerebral electrical activity. However, in the discussion of Bishop's paper, various theoretical alternate proposals were discussed including non-propagated potentials from groups of neurons producing steady state (DC) electrical fields.

Four years later, Gerard and Libet published the first report of DC and slow wave electrical potentials in the brain.[3] Using the olfactory lobe of the frog brain, they reported the existence of a steady electrical potential in the pia-ventricular direction. Since this structure is composed of a single layer of neurons all oriented in parallel with their axonal hillocks towards the pial surface, they attributed the steady DC potential to a persistent, longitudinal, axono-dendritic polarization of the neurons. However, their elegant series of experiments indicated the existence of an actual *extra-neuronal* electrical current flow. In addition to this steady DC potential they also observed a superimposed, spontaneous rhythm of 6 Hz sine waves. This spontaneous oscillation could be altered by depositing on a portion of the pial surface very small amounts of various chemicals such as caffeine or nicotine, following which the altered rhythm spread outward from the deposition area to involve the entire olfactory bulb. If such a deposition was made at one end of the olfactory bulb and the bulb then completely sectioned transversely and the two halves separated, the new rhythm was confined to the original section. However, if the two halves of the bulb

were simply approximated at the cut surface, the new rhythm was promptly transferred to the inactive portion. Obviously, the transection prevented the passage of action potentials but not the passage of electrical currents and Gerard and Libet[3] proposed that "a strictly electrical mechanism can regulate nerve cell beats and cause a spreading activation." This required the normal existence of directed polarization DC gradients, or vectors, in the brain and in addition to the pia-ventricular gradient they also described a longitudinal fronto-occipital DC gradient. By implication they postulated that the individual neuron possessed not only the ability to generate action potentials but also a continuous longitudinal DC current flow the return pathway of which was through the extra-neuronal space.

In a follow-up paper, Libet and Gerard[4] reported additional data and concluded that DC electrical currents flowing through the extra-neuronal fluids were possibly the basis for large scale neuron interaction and synchronization. In 1944, Leao[5] reported that, following mechanical or chemical injury to the outer cortex of the brain, a zone of depression of neuronal activity spread outwards from the point of injury. This was termed spreading depression and later Leao[6] reported that this depression of neural function was accompanied by simultaneous, long term DC potential changes in the same anatomical area.

In 1950, Goldring and colleagues[7] reported pia-ventricular DC potentials in humans similar to those reported by Gerard and Libet[3] in frogs. They also observed that these were mirrored by scalp recordings using surface electrodes and they reported major scalp DC potential shifts following electroconvulsive therapy and insulin shock therapy. In the latter case, the DC shifts *preceded* the convulsive state possibly indicating that the DC shift itself altered the sensitivity of the neurons which resulted in the convulsive state. At the same time, Bishop[2] who had previously "explained" the integration of brain activity on the neuronal system alone, confirmed the presence and functional significance of DC potentials.[8] Simultaneously, Goldring and O'Leary reported,[9] that small, externally generated DC currents applied to the brain altered the excitability level of the neurons. They concluded that "the experiments reported are consistent with the view that a relationship exists between steady potential change and cortical excitability." Most of this work was done on laboratory preparations and it was not until 1961 that Kaspers[10] reported data on non-anesthetized, free-moving rats. He noted that sensory stimulation and voluntary movements were associated with negative DC shifts which extended far beyond their primary projection fields while the onset of sleep was associated with a positive shift.

The majority of workers involved in this research agreed with the initial postulates of Gerard and Libet[3,4] that the DC fields and slow waves served as an integrating or synchronizing agent for the unified operations of the brain. The exact origin of the these phenomena remained obscure and was simply assumed to be the result of longitudinal polarization gradients produced by the neurons themselves. This concept, however, neglected the fact that the DC potentials, or fields, could be measured for long periods of time. The persistence of an electrical potential over time in such a conducting medium requires the continuous production of an actual electrical current. Therefore, to account for the potentials, this concept required that neurons be able to produce *continuous* DC currents as well as generate action potentials, a thesis that appeared questionable.

Even though the concept of a DC electrical integrating system for brain function was attractive, most neurophysiological investigations in this area stopped in the early 1960's with the majority of the literature available at that time summarized by O'Leary and Goldring in their 1959 review.[11] This decline in interest was probably due to a number of factors. From a technical point of view the measurement of DC and slow wave potentials is much more difficult and fraught with artifact in comparison with measurements of action potentials. More importantly, the success of the neuronal action potential paradigm meant that any further work on DC potentials would be viewed as outside of the mainstream of science.

However, these reports clearly indicated that extra-neuronal, DC potentials naturally existed in the brain and demonstrated a polarity relationship with neuronal excitability levels and gross behavioral patterns. They also appeared to indicate a relationship between these potentials and various slow wave patterns. Most importantly, the DC potentials seemed to actually control, via their polarity and level of current flow, the level of excitability of cranial neurons. The origin of these potentials was assumed to be neuronal polarization gradients. However, from a physical point of view this appears unlikely and some alternate source should have been looked for.

Total Body DC Potentials and Fields and Their Functional Relationships

In the late 1950's, I became involved with DC potentials from an entirely different point of view. Being an orthopedic surgeon I was clinically interested in the process of bone and soft tissue healing for, if a patient failed to heal, even the most sophis-

ticated surgical procedure was ultimately useless, and there was little I could do to alter the healing process. At the time, most work on the factors stimulating and controlling healing was directed towards the biochemical events during the healing process, but this effort had produced little of practical use. Since bone healing was a regenerative process (actually it is the last vestige of regeneration available to mammals) I decided to simplify my experiments and look at limb regeneration in the salamander rather than fracture healing in the dog. The stimulus for my first experiment was derived from a 1957 report in the Russian literature on the current of injury in plants.[12]

The current of injury (CI) is an actual, continuously flowing, DC electrical current that is generated at the site of an injury in a living organism. It was responsible for Galvani's original observations on electrical activity of tissues, but was unrecognized as the CI by him. Siniukhin,[12] described the normal CI in plants and associated it with control of the subsequent regeneration of the missing part. In addition to measuring the natural CI, he reported that adding a small DC electrical current of the normal polarity significantly increased the rate of regeneration while a similar current of reverse polarity to the normal CI, retarded regeneration. At the time, the prevailing view of Western science on the CI was that it was a second order phenomenon due to leakage of transmembrane potentials from damaged cells and thus had no physiological action or significance. While this concept was purely theoretical and lacked experimental confirmation, it conformed with the accepted paradigm and was consequently accepted without question.

Based on Siniukhin's report,[12] I theorized that the DC electrical CI might be the active agent that stimulated regenerative healing in animals, and postulated that the CI might be different at the site of a limb amputation in an animal capable of regeneration, a salamander, compared with an animal lacking that ability, a frog. Fortunately, the result of the experiment on regenerating salamander forelimbs compared with frogs healing the same amputation by simple scarification was unequivocal: the CI in salamanders was negative in polarity while the frog's was positive, in both instances the CI persisted until all healing was completed, in excess of 30 days later.[13] These results clearly indicated that the CI was not simply leakage from damaged cell membranes since damaged cells would either die or repair themselves within a day or two while the CI persisted for several weeks in both salamanders and frogs. Furthermore, the polarity of the transmembrane potentials was identical in both animals and could not be used to explain the opposite polarities of the two CI's. Therefore, I concluded that the long term persistence of the CI and the

appearance of an opposite polarity during regeneration indicated the CI was an *active* process that might play a role in stimulating and/or controlling regeneration.

At the time, it was known that a certain minimal amount of nerve supply to the injured area was an absolute requirement for regeneration,[14] although the mechanism involved was not known. In the light of my data on salamanders and frogs I postulated that the local CI was the result of some organized DC activity of the nerve supply. Measuring the DC potentials on the surface of intact salamanders, I found a total body pattern that was congruent with the anatomical arrangement of the nervous system, and which varied in a predictable fashion with variations in the level of consciousness as indicated by recovery from anesthesia.[15]

This work seemed to indicate that an active, total-body DC system existed which appeared to be regulated by DC potentials in the brain. Amputation produced changes in the overall pattern of this DC field, including the brain. The local CI appeared to be related to the overall field pattern. Only later did I become aware of the preceding work on the DC activity of the brain and realized that my work not only substantiated but extended it as well.

Evidence for an Actual Electrical Current Flow Associated with Intact Neurons

It is important to understand that the presence of continuous, long term, DC potentials in the brain as well as in the total body requires that an actual DC electrical current be continuously flowing through the relatively low resistance of the body. It seemed, therefore, that the demonstration of such a current was essential to both acceptance of the concept of the DC-current concept and further research. There are basically three known types of electrical conductors; metallic, ionic and semi-conducting. Since we could exclude metallic conduction in the body, I concluded that the DC current must be either ionic or semi-conducting in nature.

To test this concept, what was required was some method that would yield an unequivocal, non-artifactual demonstration of an actual electrical current flowing within the nervous system. The ideal technique would be totally non-invasive to avoid artifact produced by the CI attendant to any incision or electrode penetration. To accomplish this, a little known phenomenon appeared to be applicable, namely the Hall effect, which involves the interaction between a steady-state magnetic field

and a DC electrical current flowing in a conductor immersed in the magnetic field and oriented at 90 degrees to the field lines. The interaction of the field and current produces a measurable DC voltage (Hall voltage) at right angles to both the current direction and the magnetic field vector.

The Hall effect offered a number of advantages in that the voltage could be measured on the exterior of the conductor, thus eliminating injury-related artifacts and, further, it could distinguish between ionic and semi-conducting currents for the following reason. The magnitude of the Hall voltage depends upon both the strength of the applied magnetic field and the amount of current flow but, more importantly, upon the *mobility* of the charge carriers. Ions are large, relatively immobile entities and produce extremely small Hall voltages while electrons or "holes" in semiconducting materials have great mobility and produce Hall voltages many times greater. Considering the levels of voltages observed on the salamander (from 1 mv to 10 mv), the current flow had to be extremely small. Therefore, if a magnetic field was set up perpendicular to the axis of a salamander's limb and Hall voltages were observed, it could be concluded that an electrical current was flowing linearly in the limb. In the experiment, steady state Hall voltages were detected and observed to actually increase in amplitude with recovery from anesthesia.[16] This supported the hypothesis that a *semi-conducting, DC current, directly proportional to the level of consciousness*, was flowing in the peripheral nerves of the salamander's limb. I therefore concluded that the observed distribution of body potentials was real and was produced by the flow of a semi-conducting electrical current associated with the nervous system. I then postulated that this property constituted a primitive type of analog control system related to the nervous system.

DC System Control of Brain Activity

In the course of experiments with salamanders, I found that the major DC field vector across the head was a longitudinal gradient extending from the frontal to the occipital area with the frontal area negative in the intact, conscious animal. The polarity reflected the depth of anesthesia, with the frontal area demonstrating a shift to positive polarity with increasing anesthesia. On the theory that the neuron excitability level was a function of either the amount of current flow or its direction along this vector, I postulated that artificially reversing the fronto-occipital vector with a small amount of externally administered DC should produce loss of consciousness. Using the salamander EEG (which has the same frequency

patterns as the human) as the indicator, it was found that a few microamperes of frontally positive DC resulted in a shift from a beta to a delta frequency with the amplitude of the delta waves increasing with increasing applied current.[17] Simultaneously, the behavioral state appeared to be that of deep anesthesia with the animal being non-responsive to painful stimuli. The delta EEG pattern and depressed state of consciousness persisted for a period of approximately 20 minutes following the cessation of applied current indicating the possibility of some persistent, short-term structural change in the responsible tissues.

The converse experiment, reversal of the state of chemically induced anesthesia, was attempted with only modest success. Administration of normally polarized (frontally negative) DC current required levels approximately 5 times greater to produce the appearance of beta frequencies which were, however, superimposed on the persistent delta pattern of the chemical anesthesia and there was no associated behavioral alteration. Nevertheless, the results of both experiments were in accord with Gerard & Libet's concept[3,4] that *the general level of cranial neuronal excitability is governed by changes in extra-neural, DC current flow in some mid-line, fronto-occipital vector.* Further, this cranial DC appeared to be part of a total body DC system that controlled the excitability levels of the neurons in the remainder of the body.

If this midline vector of cranial DC electrical current was part of the total body DC system that I had previously investigated, then it should also be semiconducting in nature. In the semiconducting Hall effect, voltages are produced by magnetic deviation of the charge carriers. This results in the decrease of the total amount of current in the *original vector* of current flow. This suggested an experiment in which the current-carrying conductor was the DC fronto-occipital vector of the brain. If this vector was exposed to a strong enough DC magnetic field at right angles, a drop in the total amount of current flow along that vector should result, possibly producing a detectable decline in the level of consciousness. In testing this idea, a 3000 *gauss*, DC magnetic field oriented at 90° to the fronto-occipital vector of a salamander resulted in the appearance of large delta waves in the EEG and a behavioral state of deep anesthesia similar to that noted with administration of frontally positive DC electrical current.[18] In contrast to the external-current administration experiment, a normal EEG and complete recovery of consciousness occurred within a few seconds of turning off the magnetic field. This is in accord with the postulated physics of the two experiments. The introduction of an externally-generated electrical current

produces residual polarizational changes in the structures involved, while the magnetic field simply deviates the charge carriers without altering the matrix within which they flow.

After developing appropriate electrodes for use on dry-skin animals, similar DC experiments were carried out with human volunteers.[19] We observed the same type of total-body DC potential pattern in humans as in salamanders. Significantly, this reflected the different anatomical distribution of the nervous system in the human, The cranial DC potentials demonstrated the same midline fronto-occipital vector and the same type of alterations with anesthesia. A similar, but not identical, relationship of the cranial potentials also was observed in the deep hypnotic state.[20] Most interestingly, the induction of hypnoanalgesia in an extremity produced the same DC potential changes in the extremity as local chemical nerve block.[21]

The DC Electrical Activity of the Human Acupuncture System

On the strength of the above observations, I *postulated* that the system of acupuncture points and meridians described in the literature were real entities that served as input channels for the total DC system, serving to convey information concerning peripheral injury. We began investigating this in the early 1970's and were able to demonstrate that approximately half of the acupuncture points that were measured had an objective basis in reality, in the sense that they demonstrated measurable electrical parameters significantly different from the surrounding, non-acupuncture skin.[22] Conversely, all of the meridians examined demonstrated significant electrical parameters suggestive of the cable constants of electrical transmission lines.[23] Due to lack of continued funding, it was not possible to investigate the functional properties of this system or to search for postulated anatomical relationships. However, sufficient evidence was obtained to indicate the reality of this system and relate it to some DC electrical function. Since one of the major clinical effects of acupuncture is relief of pain, it appears possible to postulate that the acupuncture system provides input to the DC system, with correlated sensory effects.

DC Electrical Control of Somatic Growth Process

Shortly after the demonstration of a unique CI associated with limb regeneration we reported that microampere levels of negative potential DC current produced new

bone growth in dogs while positive potential DC current appeared to retard this growth[24]. This observation led to many other studies which have resulted in a number of electrical and electromagnetic therapeutic techniques presently in major clinical use to stimulate the healing of non-united fractures in humans.

By 1970, we had investigated the entire process involved in fracture healing in amphibians.[25] We reported the same sequence of electrical changes in the CI during this process as were present in salamander limb regeneration. In addition we were able to demonstrate that the negative electrical potentials acted by producing de-differentiation of the nucleated erythrocytes in the fracture hematoma, resulted in a blastemal mass of primitive cells, which are required for regenerative growth and subsequent differentiation. By 1972, I was able to produce a limited amount of organized multi-tissue limb regeneration in mammals (rats) by the application of small amounts of negative DC to the bone marrow cells at the site of forelimb amputations.[26]

While this appeared to indicate a general growth-stimulating property for negative potential DC currents, clinical experimentation aimed at stimulation of soft tissues, rather than bone, was unsuccessful. It was not until the early 1980's that the scope and complexity of the cellular responses to such minute electrical currents became apparent. In brief, we now know that only certain cells respond to these currents by de-differentiating. In the salamander, apparently *all* cells (including neurons) have this ability while, in the human, only some cells of the active hematopoietic bone marrow have this capability.[27,28] This explained the ability of the salamander to, at least in part, regenerate all tissues and organs while the process in the mammal is limited to the bone regeneration required for fracture healing. The modest limb regeneration I obtained with negative DC in the rat,[26] indicated the recruitment of too small a number of such cells from the hematopoietic marrow to accomplish total limb regeneration. Nevertheless, the formation of organized , multi-tissue structures appropriate to the area indicated that the deficit of regeneration in mammals is due to a *cellular* deficiency and not to a loss of the growth control system that regulated the regenerative process. Therefore, if a suitable source of de-differentiated cells can be found or produced in the human, true, multi-tissue, organized regeneration would be possible.

During this same time considerable interest was directed towards the possibility of positive polarity DC having a growth-retarding effect upon cancer cells. Unfortu-

nately, few investigators took into consideration the toxic products produced at an anode when voltage levels productive of electrolysis were used. As a result of this oversight, they incorrectly ascribed tumor necrosis to the positive electrical polarity alone. *When voltages and currents well below electrolysis levels are used, the growth of tumor cells is markedly enhanced equally by both positive or negative polarity.*[29] It is now evident that the responses of mammalian cells to naturally occurring levels of DC current are complex. Nevertheless, evidence indicates that the organized DC system that regulates growth processes is still present in the human.

In summary, there is excellent evidence for DC electrical currents flowing within some elements of the nervous system, both in the brain and through-out the entire body. These DC currents are organized into an apparent system within which certain vectors of potential appear to exert major regulatory functions. The polarity of the DC vectors of current flow in the brain appear to regulate the excitability level of the neurons by both the amounts of current flowing and the polarity, or direction, of current flow. This large-scale control of cranial neuronal excitability provides a basis for integrating the activities of these units as well as raising the possibility that this DC system itself may represent the initial, primitive "brain" antedating the neurons proper. The interaction of these DC vectors with an external magnetic field produces an objective demonstration of the current flow being semiconducting in nature (Hall voltages) as well as suggesting a possible link between living organisms and the geomagnetic field. In addition to controlling the excitability level of the neurons proper, the DC potentials appear to play a role in the sensing of injury as well as the initiation and control of the tissue reparative processes in the remainder of the body. The responses of somatic cells to naturally occurring DC electrical parameters are complex but real. We have arrived at the outlines for the primitive analog-type data transmission and control system which was discussed in the first paper of this series.[30] The tissue of origin of these DC currents remains unknown. The data, however, strongly suggest an extra neuronal origin.

THE ROLE OF THE PERINEURAL CELL SYSTEM IN DC PHENOMENA

As previously noted, some type of perineural cell is an inevitable companion of *every* neuron, central or peripheral, myelinated or non-myelinated. All types of perineural cells are derivatives of the embryonic neural crest area, the same embryological area

that gives rise to the neurons proper. Morphologically, the perineural cells can be divided into two large groups; several different types of glial cells in the brain and spinal cord, and Schwann cells that enclose each peripheral axon and penetrate into the spinal cord. All perineural cells are in intimate contact with each other via tight junctions and may be viewed as a total system extending from the glial cells in the brain to the Schwann cells at the terminations of the peripheral nerves. In contradistinction to the neurons, the perineural cells have retained their ability for cell division in the adult organism and are involved in the healing of injuries to the CNS.

Originally the perineural cells were considered to serve only a supporting and nutritive role for the neurons proper. Over the past few decades, however, advances in microscopy and physiological techniques have revealed the possibility that the perineural cells have more active functions. Galambos [31] reviewed the data available in 1971 and noted evidences for intimate morphological contacts between glia and neurons in the brain and between Schwann cells and axons in the peripheral nerves. He also reported: (1) increased growth of cerebral glia in animals raised in enriched environments compared with animals kept in the usual laboratory conditions, (2) evidence for the conduction of electrical potentials and currents via gap junctions between glial cells, and (3) functional interactions between both types of perineural cells and neurons. Galambos proposed that central nervous system activity be viewed as a cooperative process between neurons and perineural cells.

Since the early 1970's an increasing amount of research interest has been directed towards the perineural cells. A recent article by Cornell-Bell *et. al.*,[32] reviews the more recent literature and illustrates the level of present knowledge. This includes the presence of gap junctions between glial cells and between glial cells and neurons and the passage of long range signals through networks of astrocytes (a type of glial cell), possibly via electrical conduction across these gap junctions. While this may appear to represent only a modest advance over the status of knowledge in 1971, it does indicate that modern methods confirm Galambos' observations and suggest that interest in perineural cell function is continuing to increase. At the present time the supportive/nutritive role for perineural cells has been superseded by a recognition that they are *functionally active, possess the ability for long range signalling among themselves and are intimately related to the overall function of the brain.*

This data raises the possibility that all perineural cells, peripheral as well as central, may be intimately interconnected in such a fashion as to make possible the transmission of DC electrical signals over long distances. If this is so, then the DC

potentials that appear to constitute an organized analog type data transmission system are generated and transmitted by the perineural cells, and not by the neurons proper.

THE ROLE OF THE PERINEURAL CELLS IN HEALING PROCESSES

Earlier in this paper I discussed the relationship between DC electrical factors and growth, particularly healing processes. It has been a long accepted clinical observation that denervated wounds are exceedingly difficult to care for and this, coupled with Singer's observations that a nerve supply to the injured area was a requirement for regeneration,[14] led to my original concept that the nerves themselves were responsible for the DC potentials. However, if the DC potentials are produced by the perineural cells then these cells *alone* should be responsible for stimulating and controlling the healing process. Madden[33] investigated, in the salamander, the phenomenon known as "paradoxical regeneration" in which various portions of an extremity are irradiated with X-rays and subsequently denervated and amputated. Under certain of these conditions regeneration occurs while other conditions are associated with failure to regrow or heal. Madden found that even though neural regrowth occurred and the extremity was innervated, if the experimental circumstance was such that the neurons *were not* accompanied by the Schwann cells, regeneration did not occur. Conversely, if the circumstances were such that only the Schwann sheaths regrew and neural innervation did not occur, regeneration still occurred. He concluded that the tissue responsible for initiating and controlling limb regeneration in this animal was the *Schwann cell sheath and not the nerve fibers themselves.*

In the course of an investigation of denervation and fracture healing in the rat, we observed that fracture healing (a regenerative process) occurred as soon as the Schwann cell sheaths regrew into the area, long before innervation with neurons occurred,[27] thus confirming Madden's observations in the salamander and supporting his conclusion that the Schwann cells, rather than the neurons stimulate and control healing process.

As noted previously, regeneration is a complex process. One of the complexities involves the role played by the neuro-epidermal junction. This is a structure formed by the growth of the severed nerve fibers into the newly formed epidermal covering

of the amputation site where intimate contact is made between nerve terminations and epidermal cells. The studies done thus far have indicated that the Schwann cell sheath terminates at the basement membrane of the neuro-epidermal junction although the Schwann cells' involvement in this structure remains unknown.[34] However, as noted, our studies indicated that this structure was responsible for the unique electrical polarity of the CI in regenerating animals.

We made use of this observation in an experiment on limb amputation in rats in which the nerve and its accompanying Schwann cells were brought through the skin covering the amputation site and sutured in place.[35] We found that typical neuro-epidermal junctions were spontaneously formed and were accompanied by the regeneration-type electrical polarity in the CI. That this CI was generated by the nerve and/or accompanying Schwann cells and not by the injured local tissue was shown by transplanting the nerve/Schwann cell complex to an uninjured site (on the outer aspect of the leg for example). *This uninjured site then displayed the negative polarity CI typical of regeneration while the amputation site itself displayed the standard non-regenerating positive polarity CI.*

In summary, while the present data are incomplete, the evidence appears conclusive that as far as regenerative growth is concerned, the peripheral perineural cells, and not the neurons, are the responsible agent for initiating and controlling this function by their production of the negative, regeneration-type electrical polarity of the CI at the site of injury.

THE PERINEURAL CELLS AS PRECURSORS OF THE NEURONS

The concept proposed in the first article of this series requires that whatever the nature of the original analog "nervous" system, it must have later given rise to the excitable cells, the neurons. While it is manifestly impossible to examine any current life forms resembling the earliest in this respect, it is possible to examine the behavior of living perineural cells. Both glial cells and Schwann cells demonstrate electrical activity similar to neurons, however, the time course of excitation is much slower than that of the neuron's.[36-39] These insights have all been recently confirmed and extended by work such as that reported by Cornell-Bell.[32] Collectively this research

suggests, to the author, that only minor modifications would be required to transform many of the perineural cells (or their precursors) into physiological neurons.

In my laboratory, for instance, we were able to grow mammalian Schwann cells alone and devoid of any neural cells in tissue culture. After several weeks of unrestricted growth, the Schwann cells formed semi-organized structures consisting of parallel cords and arrays of spindle-shaped cells, in swirling patterns. When appropriately stained and examined microscopically this pseudo-tissue consisted of primarily spindle shaped Schwann cells in intimate arrangements. However, scattered throughout these structures were numerous morphologically typical neurons, complete with cell body, dendrites, axonal hillocks and axons. They formed no obvious connections with the Schwann cells and we lacked the capability of examining their electrical characteristics. While this work was preliminary in nature, and has not been replicated or extended, it would appear to indicate the possibility that neurons were derived from the original precursors of the perineural cells.

SUMMARY

It appears possible that the perineural cells, the various types of glia in the brain and the Schwann cells in the periphery, constitute a complete, interconnected system capable of transmitting information and control signals via semiconducting DC or slowly varying electrical currents. In the brain, this system regulates the level of excitability of the cerebral neurons and probably also serves to integrate the function of these cells. The peripheral Schwann cells directly initiate and control growth and repair process by the stimulatory effect of their electrical currents on somatic cell activity. Elements of the Schwann cell portion of the system may be involved in input signalling, and the acupuncture system of points and meridians may be an expression of this function.

Further, it is feasible to consider the cranial perineural cells as a primitive type of "brain" within which information is processed by DC electrical parameters, and primitive functions of the total body are regulated via information flow in Schwann cells of the periphery. These cranial perineural cells also appear to regulate and control the activity of the cerebral neurons. Sensory inputs into this system include information on bodily injury via the Schwann cells and information on magnetic fields received by the central glial cells. Peripheral output functions, at least those now known, are limited to the control of growth processes such as regenerative repair.

Postulating that this system functions via a semiconducting DC electrical current as the information carrier, one can make a number of interesting hypotheses. First, even though the current flows involved would be extremely small, a magnetic field would be generated that could be detected *outside* of the body if a sensitive enough detector were available. These magnetic fields might indicate the operational state of the internal DC system. Second, this internal system would be sensitive to external magnetic fields such as the geomagnetic field and perturbations in any such external field would produce perturbations in the operations of the internal DC system. Finally, one can postulate a system of inter-organism communication based upon the magnetic fields generated by the internal DC system of one organism being detected by the same system of another organism. The implications for parapsychological phenomena are obvious.

With evolutionary advances these primitive organisms would acquire the capability for additional sensory inputs such as light, and controlled outputs such as movement. When the capability for digital information processing was acquired, that is, normal neuronal depolarization, this was used as a tool that extended the capabilities of the dual system by increasing the data input and output capacity. Nevertheless, it appears that the overall control of the digital system still resides in the DC phenomena of the perineural system. In this view, the neurons properly serve as a second order information processing and control system whose function is to receive high data rate sensory inputs such as vision and to control integrated motor responses. Basic information processing involving biocycles, levels of central irritability, bodily injury and growth processes such as healing are all the responsibility of this perineural analog system and not the neuronal system.

It also appears possible to propose the heretical concept that it is the analog perineural cell system within which the integration of all nervous activity occurs, and which contains the foundation for such higher nervous functions as consciousness, creativity and paranormal experiences. Whether this concept is correct or not, it is apparent that present day neurophysiology is looking at only half a brain.

In the final article of this series I will review the latest data obtained from a variety of technical advances as well as the newly established scientific discipline of bioelectromagnetics that supports and extends this thesis of a dual nervous system.

CORRESPONDENCE: Robert O. Becker, M.D. • Star Route • Lowville, NY 13367

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