

THE DIRECT CURRENT FIELD: A PRIMITIVE CONTROL AND COMMUNICATION SYSTEM RELATED TO GROWTH PROCESSES. Robert O. Becker, M.D.*

All living organisms possess to some degree the property of self-repair. A major characteristic of this process is its "releasability" to the total organism. In regenerative growth processes, for example, the part formed under normal circumstances is quite appropriate to replace the missing part, and, in fact, in those animals most highly endowed with this ability it is an exact duplicate. It would appear that the regenerating part is furnished with information from the remainder of the organism indicating the desired physical parameters to be fulfilled, and that some error-sensing process determines the overall organizational pattern of the regenerate to best fit the furnished instructions. This concept implies the existence of some communication system capable of passing appropriate and meaningful signals in both directions between the regenerating cell mass and the remainder of the organism. Certain characteristics of this control or communication system may be predicted. Since the process of self-repair may be considered to be a basic attribute of living things, the control system governing the process should be equally primitive. It should utilize physiological mechanisms of a nature that could have been operating in the earliest living organisms. Secondly, since the function of the system in regenerative growth is to relate the growth to the entire organism, the system must in some way be present throughout the entire organism. However, the parameters at any point in the organism must somehow be representative of that specific point. Knowledge of the system values (? coordinates) at any point should be an expression of the anatomical configuration of the organism at that point. Thirdly, in view of its primitive nature, one would further predict that the system possessed other control and communication functions of a basic nature in addition to control over regenerative growth. During the past several years we have made certain observations on the direct current electrical activity of the central nervous system indicating that this activity constitutes an organized control and communication system of a very primitive type possessing the previously mentioned characteristics. It appears to be related, among other things, to the sensing of trauma and to the control of repair processes following trauma. Presently available data indicates that this phenomena is based upon some solid state or semiconductor property of the neurone, and that the current flow is electronic rather than ionic in nature. The system parameters, as presently known, would seem to furnish a logical basis for study of the role of electrical and neural factors in many types of growth processes.

METHODS: Details of technique have been reported in previous publications, and the interested reader is referred thereto (1-5).

OBSERVATIONS: A. Surface Patterns of Direct Current Potentials. In 1932 Barr (8) published the first of a long series of papers dealing with the direct current potentials found on the intact surfaces of a variety of organisms. He related changes in these potentials to certain physiological functions in—* Department of Surgery, State University of New York, Upstate Medical Center at Syracuse, New York.

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cluding growth & development (10), tumor formation (12), sleep (13), and ovulation (11). At the same time, Burge (7), working with the surface cephalo-caudal d.c. potentials, demonstrated a reversal of this potential with anesthesia and predicted a causal relationship between the two. We have examined these cephalo-caudal potentials in a phylogenetic series, and observed a sequence of magnitude that appears to be related to either body size or complexity. Man appeared to occupy an anomalous position in this regard, showing the only reversal of the head-negative polarity. According to the standard concepts, these potentials represented a relatively simple dipole field generated in some fashion by the entire organism and unrelated to any specific tissue (9,14). If this is true, then moving the recording electrode along the dorsal midline from the cephalic portion toward the reference electrode at the caudal end should result in a relatively smooth decrease in field magnitude to zero. However, the potentials measured in this fashion showed a surprising complexity which was related to the general organizational pattern of the central nervous system in each organism. Wherever major masses of neurone cell bodies aggregated, there were evident relative "positive sinks" in the field pattern. These areas were single in planaria, annelids, and fish (Fig. 1), all of which have single cephalic, neuronal masses despite other neural differences of considerable magnitude. In the higher vertebrates the development of additional cord enlargements concomitant with the development of specialized limbs was associated with two more "positive sinks" located approximately over the cellular accumulations (Fig. 2). In man, with the relatively enormous development of the central nervous system compared to body size, particularly in the cranial area, the entire recording was positive, but again the three cellular accumulations were more positive than the intervening areas. Also in these vertebrates the limbs had well developed d.c. gradients of their own with the cord enlargements positive, and with an increasing negative gradient distally. This spatial relationship between the surface d.c. potentials and the general organization of the central nervous system in such a wide variety of life forms appeared to be of some significance, and the thesis was formulated that a causal relationship existed between the two.

B. Direct Current Potentials of the Central Nervous System and Their Relationship to the Surface D.C. Pattern. It was initially observed that the surface d.c. gradient along an amphibian limb decreased to zero if the nerves entering that extremity were completely sectioned. More importantly, however, the gradient on the contralateral limb decreased by approximately 25%. Similar phenomena were noted in humans in chemical or pressure nerve block (6). In addition, section of the spinal cord or pressure neurone block at the level of the foramen magnum produced a depression in all limb d.c. gradients during the phase of spinal shock. As spinal shock was replaced by reflex hyperirritability, the limb gradients returned to normal or above-normal levels. The conclusion was reached that the surface d.c. potentials were a second-order phenomenon related to some activity of the central nervous system. On theoretical grounds, it seemed highly unlikely that summated action potential activity could be the generating source for the steady state potentials. It was also theoretically unlikely that polarization or electrostatic potentials could be long maintained within a conducting mass without some actual current flow taking

place. The electrical activity that could best fulfill the requirements was a longitudinal direct current potential along the long axis of the neurone accompanied by some small level of actual direct current flow. In 1940 Gerard & Libet (16) observed that a steady d.c. potential existed across the amphibian cerebral cortex in an axonodendritic direction. They noted changes in the magnitude and polarity of this potential with changes in cerebral irritability, and suggested that this axonodendritic polarization controlled, in part, the level of neural irritability. Subsequently, Goldring (17,18) extended and confirmed these observations both in animals and in humans. Our observations on the central nervous system proper have been confined to the spinal nerves. In this area several lines of endeavor have been explored to determine whether or not actual d.c. flow could be detected in the nerve fibers. The galvano-magnetic effect (Hall effect) was investigated in intact amphibian limbs, and some evidence was obtained for the existence of a neural-dependent, axial current flow (3). The observations indicated a current that was solid state or semiconductor in nature, rather than ionic. This was further evaluated by study on the injury currents in isolated nerve sections. It was observed that longitudinal steady current flow and potentials were maintained even though a segment of the nerve was frozen with liquid nitrogen at 77° K (4). The existence of a steady current flow requires the presence of a complete circuit loop, and a search was instituted for the in- and out-flow pathways. Our initial concepts were for a unidirectional flow in the peripheral nerves with a circuit completion pathway via some other tissue. Observations, however, indicated that the entire circuit path lay within the central nervous system (except perhaps at the peripheral terminals, where a short, higher resistance pathway exists through other tissues). We found that the axial d.c. potential gradients along spinal motor nerves were distally-negative, while those along spinal sensory nerves were distally-positive (5). The direction of the polarization, therefore, is related to the normal direction of message transmission, or, perhaps, more fundamentally, to the axonodendritic axis (6). (This requires that the peripheral fibers of the sensory nerves be viewed as dendritic in nature, despite their histological appearance.) We may therefore summarize our findings as follows: the surface d.c. potentials are a second-order phenomenon produced by the flow of small steady electrical currents within the underlying neural elements. The currents are polarized in an axonodendritic fashion, and are conducted by some element of the neurone possessing a solid state molecular lattice permitting electronic conduction. This property of the central nervous system is organized, therefore, into a complex electrical field which is related to the entire organism. Since electrical fields with associated currents have not only scalar (magnitude) but vector (directional) parameters, then any area of the body may be represented by a "set" of electrical coordinates. It is tentatively proposed, therefore, that one of the environmental parameters of each cell or group of cells may be a certain set of values of this electrical field in an organism.

C. Functions of the D.C. System. 1. Neural Irritability Level: The work of Gerard, Libet and Goldring on the relationship of the axonodendritic potential to the irritability of the cerebral neurones had been done on isolated cerebral tissue. In our measurements of the surface d.c. potential pattern, we had noted that a midline fronto-occipital vector of d.c. potential was

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present on the dorsal surface of the head, with the frontal area negative with respect to the occipital. All other measurement vectors across the head were lower in magnitude and, in fact, the transverse vector was generally zero. We noted further that the magnitude of the fronto-occipital vector was an expression of the state of consciousness of the animal. Anesthesia produced by any one of a variety of agents was associated with a fall in the magnitude of the potential to zero, and occasionally to a moderate reversal of the normal polarity. We postulated that this organization of the d.c. pattern was the resultant of d.c. activity within some midline structure of the brain (? reticular formation). In accord with the concept that the irritability level of the neural tissue was controlled by the d.c. potential, we postulated that the action of the anesthetic agents was to produce a decrease or reversal in this electrical vector by interfering with the electronic transducer. If this is the case, then variation in the level of consciousness should be produced by "overriding" the internal currents with externally administered electrical currents. Experimentation has proven the validity of this hypothesis: administration of low amplitude currents in a reversed direction (frontal-positive) produced EEG patterns (delta waves) and behavior typical of deep anesthesia in amphibia. The converse was also noted: animals deeply anesthetized with chemical agents could be made to demonstrate "awake" EEG patterns with the administration of "normally" oriented direct current (frontally-negative). Since we had previously determined that the internal currents were most probably semiconductor in nature, it was then postulated that a magnetic field of sufficient strength applied in a transverse direction to the normal midline current vector should produce a deviation of significant numbers of charge carriers from the vector resulting in a decrease in the total current flow, and a correspondingly decrease in cerebral irritability level. It was subsequently found that a 3.8 kilo gauss field applied at exactly 90° to the midline of the amphibian head produced a drop in the fronto-occipital d.c. potential, and the appearance of delta wave patterns in the EEG (Fig. 3). The evidence would indicate that, in the cerebrum at least, the organized d.c. field determined the level of neural irritability.

2. Sensing of Trauma: The perception of pain is a complex phenomena; the phenomenon of delayed pain (20) is still somewhat difficult to explain on physiological grounds. In amphibians multiple-point recordings of changes in the d.c. field attendant to hindlimb trauma have shown that the time delay before cerebral d.c. changes approximated that of delayed pain. It would seem possible that the d.c. field transmits information of a basic nature related to body damage, i.e., that it informs the organism of the event and possibly of the extent of the injury via a relationship to currents of injury.

3. Control over Regenerative Growth Processes: Preliminary experiments have been done on the d.c. field changes occurring during regenerative and non-regenerative healing processes following limb amputation in two species of amphibians (2). Regenerative growth was noted to be accompanied by a complex series of changes in the d.c. field along the axis of the amputated extremity. The sequence of changes in the field appeared to be related to the two phases of the regenerative healing process. The non-regenerative healing process, on the other hand, demonstrated an initial injury current which was gradually reduced to a value appropriate for the normal d.c. field at the point of amputation.

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The administration of very small amounts of electrical energy polarized to augment the naturally-occurring potentials appeared to accelerate the two phases of the regeneration process individually. However, for technical reasons we failed to induce regeneration in the non-regenerating form by duplicating "regeneration sequence" of d.c. field changes. Other authors have reported the production of major alterations in growth patterns by the administration of low values of direct current (15,21,19). These observations would seem to be in keeping with Singer's observation on the essential role of the central nervous system in limb regeneration. We would postulate that the responsible activity of the central nervous system in this regard is the direct current system.

SUMMARY AND CONCLUSION: The central nervous system of a variety of organisms has been shown to possess the ability to generate and transmit small, steady electrical currents. This direct current activity is organized into a complex field pattern dependent on the organization of the central nervous system itself. Some evidence has been accumulated which indicates that this direct current system functions as a primitive analog-type control and communication system. It is sensitive to the presence of electromagnetic force fields in the organisms environment, and appears to respond to traumatic stimuli administered to the organism. The system in turn appears to have a controlling influence over the basic level of neural irritability and self-reparative processes following trauma. Perhaps most importantly it appears to be a representation of the entire organism as a functional unit. In this respect it is an objective, measurable expression of the field concept and furnishes a logical basis for further theorization and experimentation.

REFERENCES

(1) Becker, R.O. IRE Trans. Med. Elect. ME-7: 202-207, 1960.
(2) Becker, R.O. J. Bone & Joint Surg. 43-A: 643-656, 1961.
(3) Becker, R.O. Science 134: 101-102, 1961. (4) Becker, R.O. Biological Prototypes and Synthetic Systems. Vol. I, pp. 31-37. New York: Plenum Press (1962). (5) Becker, R.O. Nature 196: 675-676, 1962. (6) Becker, R.O., Friedman, H., Bachman, C.H. N.Y.S. J. Med. 62: 1169-1176, 1962. (7) Burge, W.E. Am. J. Physiol. 126: 451, 1939. (8) Barr, H.S. J. Comp. Neurol. 56: 347-371, 1932. (9) Barr, H.S. & Northrup, F.S.C. Q. Rev. Biol. 10: 322-333, 1935. (10) Barr, H.S. & Hovland, C.I. Yale J. Biol. Med. 9: 541-549, 1937. (11) Barr, H.S., et al. Science 88: 312, 1937. (12) Barr, H.S., et al. J. Biol. Med. 10: 535-544, 1938. (13) Barr, H.S. & Burton, D.S. Yale J. Biol. Med. 10: 271-278, 1938. (14) Barr, H.S. & Northrup, F.S.C. Proc. Nat. Acad. Sci. (US) 25: 284-288, 1939. (15) Frazee, O.E. J. Exp. Zool. 7: 457-476, 1909. (16) Gerard, B.W. & Libet, B. Am. J. Psychiat. 96: 1125-1152, 1940. (17) Goldring, S., et al. EEG Clin. Neurophysiol. 2: 297-308, 1950. (18) Goldring, S. & O'Leary, J.L. J. Neurophysiol. 14: 275-288, 1951. (19) Humphrey, C.E. & Seal, E.H. Science 130: 388-390, 1959. (20) Libet, B. Science 126: 256-257, 1957. (21) Simukhin, A.M. Biofizika (USSR) 2: 52, 1957.

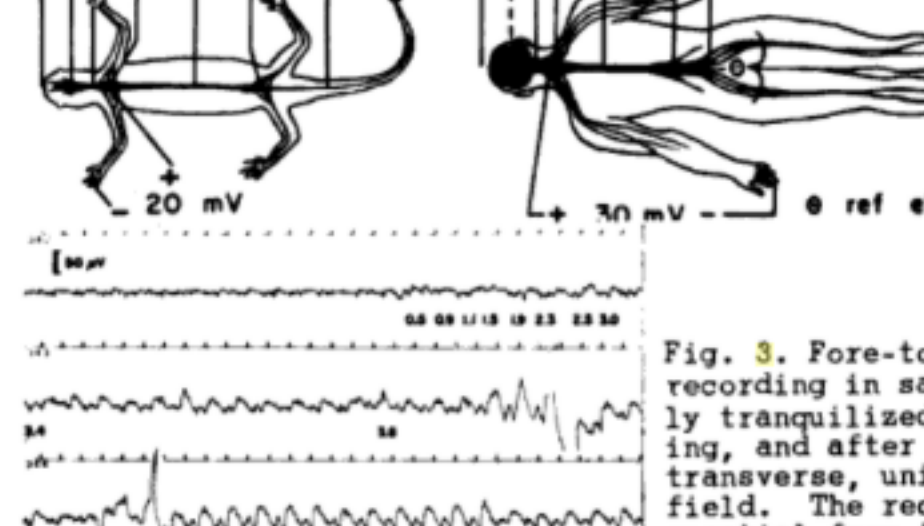


Fig. 1. Midline cephalo-caudal d.c. potentials in planaria, earth worms and fish. Arrows indicate potentials over the single main nerve cell mass. Reference electrode at tail in all cases.

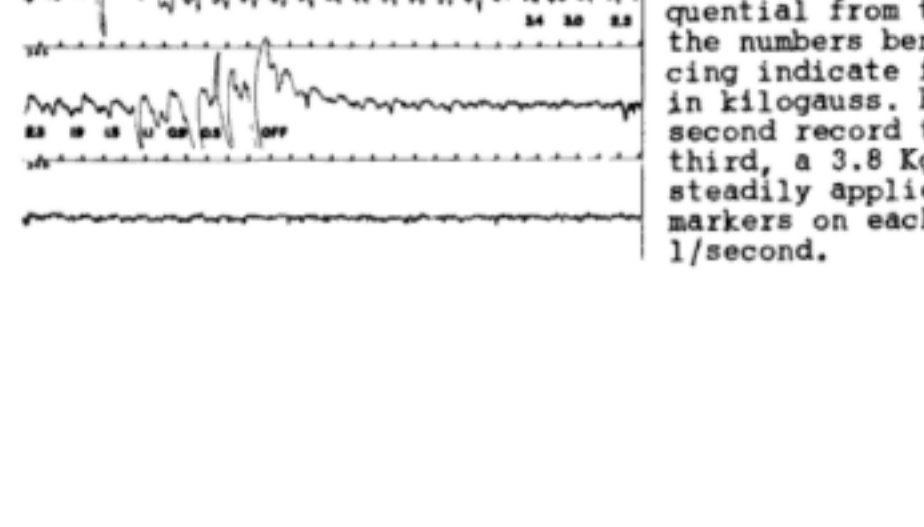


Fig. 2. Same as Fig. 1 except in salamander *A. tigrinum* and man. Arrows indicate potentials over each of two major nerve cell masses.

Fig. 3. Fore-to-hind brain EEG recording in salamander (lightly tranquilized) before, during, and after application of transverse, uniform magnetic field. The recordings are sequential from top to bottom; the numbers beneath the tracing indicate field strength in kilogauss. From 3.8 on the second record to 3.4 on the third, a 3.8 Kg. field was steadily applied. The time markers on each record are 1/second.