

# SOME OBSERVATIONS INDICATING THE POSSIBILITY OF LONGITUDINAL CHARGE-CARRIER FLOW IN THE PERIPHERAL NERVES

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The direct-current potentials measurable on the surface of amphibians have been shown to be organized into a complex dc "field" pattern, with a remarkable relationship to the underlying neural structures (Fig. 1). Further observations

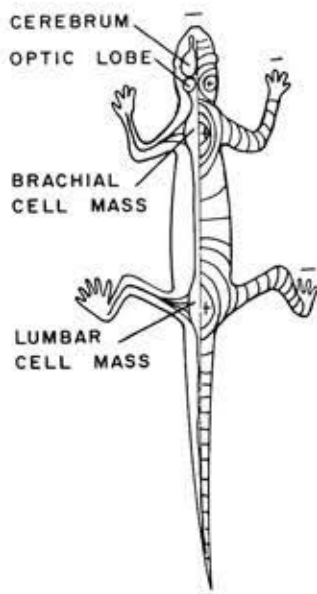


Fig. 1. Schematic view of salamander's central nervous system (left) and surface dc field (right). The lines of the dc field are equipotential and continue across the left side of the body. Note the congruity between the cellular enlargements of the CNS (cranial, brachial, and lumbar) with the positive sink areas. The nerve-outflow terminations are negative.

have led to the thesis that this dc field is generated within and distributed by elements of the central nervous system and that it constitutes a primitive type of data transmission and control system (Becker, 1960; Becker and Bachman, 1961a). The surface dc potentials of the human have been found to be similarly organized (Fig. 2) and to have similar control-system characteristics (Becker and Bachman, 1961b). Input parameters of the system have been found to be trauma and external electromagnetic force fields. System outputs are some measure of control over the propagated action potential activity of the neurons and some control over postembryonic growth processes.

The possibility of actual longitudinal charge-carrier flow as an element of this dc field was considered. To obviate the technical difficulties inherent in direct measurements of current flow, the Hall effect phenomenon was utilized in intact animals. Definite transverse or Hall voltages were obtained in the presence of a steady-state magnetic field indicating the existence of some type of charge-carrier flow in a longitudinal direction (Becker, 1961). This phenomenon was shown to be dependent upon an intact central nervous system, although the

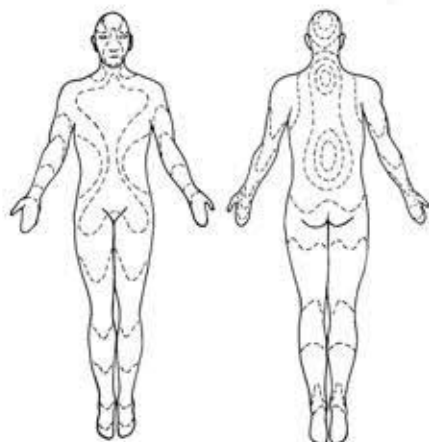


Fig. 2. Equipotential line plot of the surface dc field in the human. The central nervous system is not shown but the positive sinks again overlie areas of cellular aggregation in the neural axis. (The spinal cord becomes progressively shorter compared to body length as one ascends the evolutionary scale. This accounts for the apparent cephalad shift of the brachial and lumbar sink areas.)

relationship demonstrated was an indirect one. A consideration of the results obtained under the experimental circumstances strongly indicated that the charge carriers possessed a high mobility and were, therefore, probably electrons or similar units rather than ions.

The present report concerns observations made directly upon the sciatic nerves of the bullfrog (*Rana catesbeiana*), utilizing different techniques. Evidence has been obtained to substantiate the charge-carrier hypothesis and to further delineate the operating parameters of the dc field control system.

#### METHODS

Animals were anesthetized by titration with Tricaine<sup>®</sup> (Sandoz).

The sciatic nerves were atraumatically dissected free from their surrounding tissues in the thigh, lifted from their bed, and a 7-10 cm length was isolated by inserting a thin polyethylene plastic sheet beneath it. The nerves were not sectioned and were left attached to both the spinal cord and their peripheral terminations. Electrodes were Ag-AgCl, saline agar with flexible terminal wicks. Electrode potentials were under 100  $\mu$ v and remained stable. Nerve potentials were amplified by either a Hewlett Packard 425A microvoltmeter or a Kiethley 600A electrometer. Input impedances from  $10^6$  to  $10^{14}$  ohms were used and no system loading was noted above  $10^7$  ohms. The recorder was a Varian Type G 11A servo potentiometer.

#### RESULTS

The dc potential gradients along 1-cm segments of the main trunk and the two main branches of the sciatic nerve were measured in 24 specimens. In very deep anesthesia, the 1-cm gradients of all areas were either zero or slightly positive (in all cases the polarity is expressed as that of the distal electrode referred to the proximal electrode). This phase of very deep anesthesia was generally brief—less than 5 min—and was followed by a 30-min period of moderate anesthesia during which the animal did not respond to painful stimuli of any type and no other reflexes were elicitable. All measurements were taken during this phase to insure compatibility of results. The main sciatic trunk revealed 1-cm potential gradients ranging from 2 to 8 mv, roughly inversely proportional in amplitude to the depth of anesthesia. Invariably these potentials showed a negative distal polarity. One main branch (posterior tibial serving the calf area of the lower leg) was also negative distal in polarity but gradient ampli-

tudes were always higher than those of the main trunk, averaging 6 to 15 mv. The other main branch of the sciatic (the peroneal serving the anterior portion of the lower extremity) always displayed a positive distal polarity that was invariably less than that of the posterior tibial in amplitude (Fig. 3). In some instances the algebraic sum of the potentials of the two branches was equal in amplitude and polarity to that of the main trunk. Generally, however, the posterior tibial negativity was too high for such a manipulation and an excess negativity resulted.

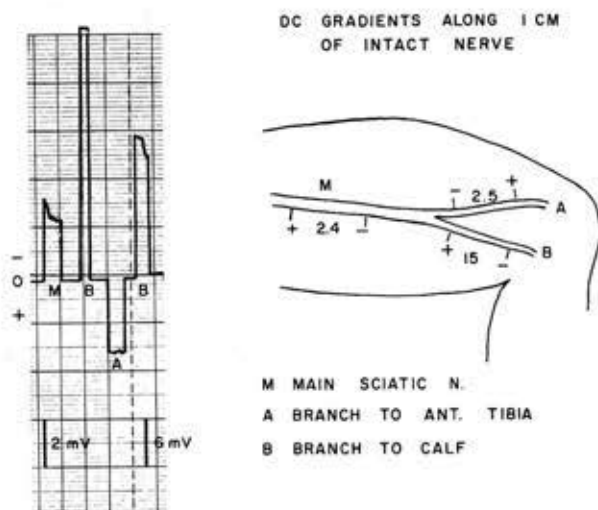


Fig. 3. One-centimeter dc gradients along the sciatic nerve and its main branches. On the left are actually recorded potentials in a representative experiment during moderate anesthesia. The main sciatic (M) and the posterior tibial branch (B) are negative in polarity while the peroneal branch (A) is positive. A recording from the posterior tibial at a lower level of amplification is shown in the right-hand portion of the chart record. The results are schematically represented on the right, showing the relationship of the main nerve and its two branches.

The effect of quick-freezing a 4-mm segment centered between two electrodes 1 cm apart on the main trunk was noted. Freezing was accomplished by liquid nitrogen which was enclosed in a 6-mm-diameter round-bottom test tube and was kept in a Dewar until used. The rounded tip of the tube was lightly approximated to that portion of the nerve equidistant between the two electrodes. Freezing the two electrodes in a similar manner produced no potential variation. Chemical and electrical contact was avoided; the temperature of the tube end was not measured but was assumed to be close to that of the liquid nitrogen ( $-320^{\circ}\text{F}$ ). Quick-freezing in this fashion produced a prompt increase in the distal negative potential of 1-2 mv with each application. Visual observations indicated thorough, quick-freezing of the 4-mm segment and correlated thawing of the area with a return to the original baseline potential (Fig. 4, upper). This phenomenon could be repeatedly obtained from a good preparation up to a maximum of ten times before potentials abruptly fell off and evidence of injury currents from the frozen area could be noticed.

It had been previously noted (Becker, 1960, 1961) that sectioning of the spinal cord at the level of the base of the brain produced a prompt drop in all surface dc potentials below the level of the section. Sorokhtin and Temper (1959) correlated this phase with that of "spinal shock," during which all neural activity distal to the area of section is completely depressed and no reflexes can be



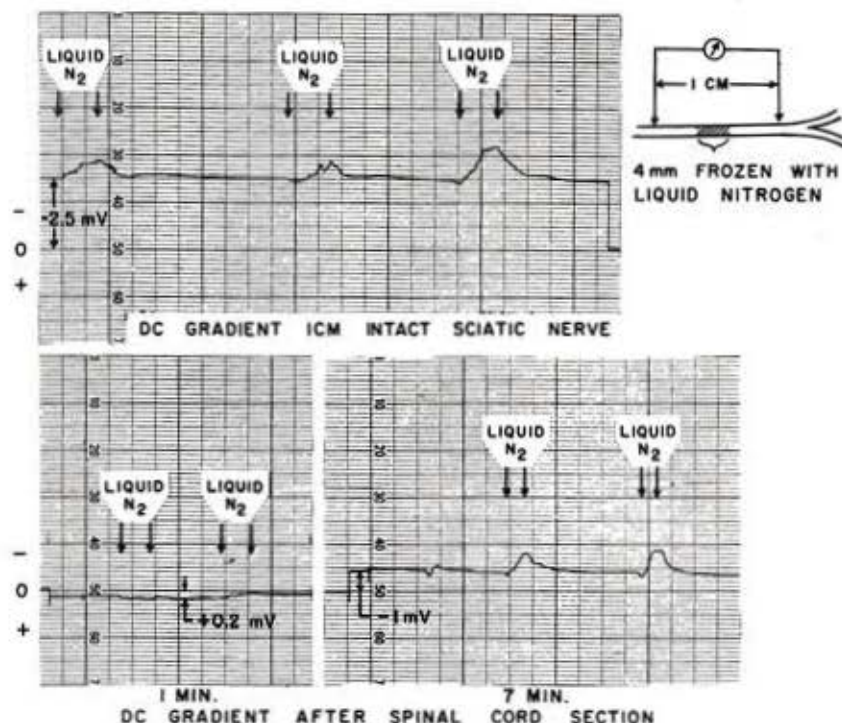


Fig. 4. Effect of quick-freezing on the 1-cm dc gradient of the main sciatic nerve. Upper trace: The 1-cm dc gradient of the main sciatic of the moderately anesthetized frog—in this case 2.5 mv. Application of the liquid nitrogen as indicated for 7-8 sec produced increase in the dc gradient of from 0.5 mv to 1.25 mv. Lower left trace: The dc gradient and effect of liquid nitrogen during the phase of spinal shock. There was a slight distal-positive potential noted but negligible potential variation from the freezing process. Lower right trace: The dc gradient and effect of liquid nitrogen during the phase of recovery from spinal shock. There is a return to a distal-negative gradient and freezing again produces an increase in the amplitude of the gradient. The same nerve was used for all three traces. The chart speed was 5 sec between vertical lines. The experimental setup is shown schematically at the right top.

obtained. Recovery from spinal shock is characterized by hyperreflexia and a return of the dc potentials to original levels. In the frog, the phase of spinal shock lasts approximately 5 min and during this time the 1-cm gradient along the sciatic nerve was found to be essentially zero. Additionally, during this phase the application of liquid nitrogen did not alter the dc gradient in any manner (Fig. 4, lower left). With recovery from the depressed spinal-shock state, the dc gradient returned, again negative distal in polarity. The application of the liquid nitrogen at this time produced an increase in the negative gradient similar to that noted prior to the spinal cord sectioning.

Observations were made upon the dc injury potentials generated by a 2-cm length of previously undamaged main sciatic nerve. The nerve segment was placed on a thin glass microscope cover slip and was kept slightly moistened with isotonic saline. Injury potentials, negative in polarity and equal in amplitude, could be measured at each cut surface with reference to the undamaged center of the 2-cm segment. These potentials generally averaged 8-12 mv in amplitude. Quick-freezing the entire fiber (by immersing it in a beaker into liquid nitrogen in a Dewar) invariably produced a polarity reversal of the injury potential with an amplitude less than that of the original prefreezing potential. Thawing produced a return to a normal negative gradient which was less in amplitude than either the prefreezing-negative or the frozen-positive potentials. It was found

that a good preparation could be cycled in this fashion, up to a maximum of 8 cycles, with little change in either the unfrozen-negative or the frozen-positive potentials (Fig. 5).

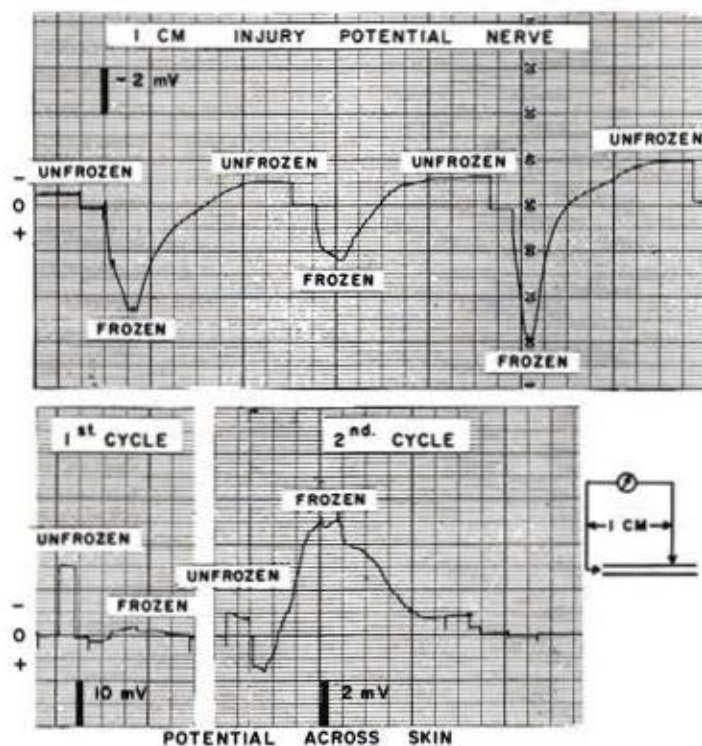


Fig. 5. Upper trace: The effect of quick-freezing on the dc injury potentials of nerve. The tracing shows 3 cycles of alternate freezing and thawing with unfrozen injury potentials running between 1 and 2 mv negative. (The original injury potential—before any freezing—was 6 mv negative.) The frozen potentials are reversed in polarity and average 2 to 6 mv in amplitude. Lower trace: The first and second cycle of freezing-thawing in skin potentials. The pre-frozen potential was 15 mv negative-exterior. The first frozen potential was approximately 2 mv of the same polarity as the unfrozen. Thawing produced a very low 1-mv negative-exterior potential which could be increased to 5 mv at the same polarity. However, following the second freezing, potentials fell to zero and remained at this level.

The effect of quick-freezing on the transverse (inside to outside) potentials of frog skin was determined. The normal potential was found to average 15 to 20 mv across the unfrozen skin with the exterior surface negative. Freezing (by the same technique as above) produced a potential of the same polarity but of only a few millivolts amplitude. This potential declined with thawing to about 1 mv with still the same polarity. Refreezing then would produce an increase in amplitude of approximately 4-5 mv but thawing at this time was accompanied by a fall to zero potential. In all instances two cycles of freezing-thawing resulted in an inert preparation with zero potentials under both circumstances.

#### COMMENTS

One of the difficulties encountered in elaborating the control system thesis for the dc field system was the return path of the current. Early analog devices (Becker, 1960) had assumed a return path through the tissue fluid but this was



disproved by the observation that the muscles making up the bulk of the extremity were polarized in a distal-negative fashion also. The observation that the two branches of the sciatic nerve are oppositely polarized appeared to furnish a solution to this return-path problem. Libet and Gerard (1941), working with the isolated cerebral hemisphere of the frog, postulated that these neurons were polarized in an axonic-dendritic fashion and suggested the possibility of current flow within the neuron. If this concept is extended to include the peripheral spinal neurons as well, then there should be a differential polarization between motor and sensory fibers in the peripheral nerves (the motor fibers are axons while the sensory fibers are, anatomically, dendrites). While definite identification of the proportions of motor to sensory fibers in a nerve can be made only by degeneration experiments, some indication of the composition can be made on the basis of the fiber-size spectrum. Preliminary determinations made by this method show that the positive peroneal branch is composed of a much greater proportion of small fibers compared to the negative posterior tibial branch. The latter branch also contains a group of very large myelinated fibers which are not seen in the peroneal branch. In accordance with these observations, we now propose the extension of axonic-dendritic polarization to include all neurons of the central nervous system. Since the peroneal branch appears to have a higher percentage of sensory fibers, we postulate that the dendrites in the peripheral nerves display a distal-positive dc gradient. The posterior tibial branch would therefore indicate that the axons have a distal-negative dc gradient. The circuit completion would therefore be via opposite polarization and current flow in the motor fibers, contrasted to the sensory fibers.

The increase in the 1-cm dc gradient along the intact sciatic nerve when a central segment was frozen appears to be a genuine phenomenon, dependent upon some active mechanism in the central nervous system. This is illustrated by the lack of response to the freezing process during the neural-depressed phase of spinal shock. Such an increase in potential could be produced by increasing either the resistance or the current flow and preliminary measurements have shown that the freezing process does produce an increase in the dc resistance. However, if one allows the assumption that the current of injury is based on a similar charge-carrier system, the polarity reversal with freezing cannot be explained on the basis of a resistance increase alone. In any event, the observations are best explained on the basis of some charge-carrier flow in the neural structures. It seems highly unlikely that the charge carriers could be ions since ionic mobility at  $-320^{\circ}\text{F}$  would be negligible. However, electron-transfer mechanisms have been found to be operative at this temperature (Chance and Nishimura, 1960) and the suggestion has been made that such circumstances might actually favor such a mechanism (Szent-Gyorgyi, 1960).

#### SUMMARY

Observations are reported indicating that the thesis of axonic-dendritic polarization of cerebral neurons can be extended to include mixed spinal nerves as well. This permits the return path necessary to complete the circuit of the dc fields. Potential changes at low temperatures in both dc gradients of intact nerves and nerve-injury potentials further indicate the possibility of charge-carrier flow involving units of high mobility.

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