Reprinted from NEW YORK STATE JOURNAL OF MEDICINE, Vol. 62, No. 8, April 15, 1962

The Direct Current Control System

A Link Between Environment and Organism

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A STUDY WAS UNDERTAKEN *of the problem of the relationship between D.C. (direct current) potentials and regeneration. A complex electrical field was found rather than the expected simple dipole, and its spatial configuration was noted to bear a close relationship to the gross anatomic arrangement of the central nervous system. The D.C. potential gradient was measured on the exposed but otherwise undisturbed main sciatic nerve in the frog. The results were indicative not only of moving charges, but also indicated further that the charge carriers were nonionic and were probably units of the size of electrons. A definite relationship has been established between the time sequence of D.C. changes at the site of a limb amputation and the subsequent healing process. In the human being a similar neural-related pattern was found as in the amphibian. It appeared likely that the organized D.C. activity of the brain was in some way closely related to general behavior, possibly as a controlling mechanism of sorts and that, since the actual D.C. flow of charge carriers was an integral part of the system, then the operating parameters of the system could be influenced by external force fields (magnetic, electrostatic) and by such physical parameters as levels of air ionization.*

FOR MANY YEARS the relationship between D.C. (direct current) electricity and living organisms has been under investigation. Insofar as is known, all forms of life exhibit measurable D.C. potentials on their inner and exterior surfaces. Previous studies indicated that these surface potentials were arranged as a simple dipole with cephalocaudal polarity.[1] Studies of these potentials in a variety of animals, including man, indicated some obscure but definite relationship to such factors as embryonic growth,[2] initial responses to injury,[3] healing processes includeing regeneration,[4] tumor formation,[5] activity of cerebral cortex neurons,[6,7] local[8] and general anesthesia,[9] sleep,[10] hypnosis,[1]1 schizophrenia,[12] and ovulation.[13] A consideration of these factors reveals that they include the general areas of growth, neural irritability, and cyclic behavior.

The application of direct electrical currents to living organisms, in strengths below the cauterization level, has been reported to produce physiologic effects in the same general areas. Direct current applied fronto-occipitally in human beings is capable of producing sleep and surgical-plane anesthesia depending on the amount of current passed.[14,15] The application of direct current to plants increases the rate of regeneration in an approximate linear fashion with the current denaity.[16] The complete disappearance of implanted malignant tumors in mice baa also been reported following brief daily administrations of direct current for periods of a few weeks.[17] In the central nervous systems of various species the application of small-density direct current has been reported to modulate the spontaneous action potential activity of neurons.[18–30] In all these observations the effect was dependent either on the polarity (positive or negative) of the current or the direction of the imposed D.C. field.

In 1936 Burr,[21] a pioneer in this field of research, postulated that the naturally occurring D.C. potentials had an actual control function and he proposed the electrodynamic theory of life. According to this concept the potentials were quasi electrostatic in nature and were generated by the electrical activity of all of the cells of the organism with no relationship to any discrete internal structures or systems. This concept was at variance with the then-prevailing neurophysiologic concepts of an all-or-none action potential activity of the neuron as the mechanism of communication and control, and accordingly it never received wide support. The intervening years have seen rapid growth in the field of neurophysiology, with a resulting revision of many previously accepted theses and a recognition that many unsolved problems still remained.[22] The interest in D.C. phenomena was sporadic throughout most of this time and was directed primarily toward taxonomic experiments on the results of exposing living organisms to various D.C. densities. Two factors nevertheless remained evident: Living organisms do produce measurable D.C. potentials, and these potentials are to some extent concerned with growth and general behavior.

During the same period these two problems of growth and behavior were subjected to extensive study by the biochemical and neurophysiologic disciplines. Nevertheless, no effective control over growth or behavior has been forthcoming primarily because the basic natural control mechanisms for these parameters of life still remained obscure. However, rapid strides were made in the area of the application of physical sciences to biology. Medical electronics has assumed the stature of an almost independent discipline, biophysics has begun to apply solid state technics and quantum theory to life processes, and control systems analysis has been applied to the study of biologic control systems. These younger disciplines produced new technics, both in instrumentation and analysis, which heretofore had not been applied to the problem of the D.C. potentials in living systems.

Material and method

One of our preliminary studies was directed at the problem of regeneration, with the thought of the possible clinical application in bone-healing processes. The results have far exceeded expectations, and there has emerged a previously unsuspected function of the central nervous system which appears capable of explaining the heterogeneous observations relating direct currents and living organisms.

Our initial studies were directed toward the precision mapping of the surface D.C. field by determining the lines of equal electrical potential. A complex electrical field was found rather than the expected simple dipole, and its spatial configuration was noted to bear a close relationship to the gross anatomic arrangement of the central nervous system (Fig.1). Positive areas were located over the cellular aggregates of the neuraxis (cranial, brachial, and lumbar) with increasing negative potentials along the peripheral nerve outflows from each.[23] Analog technics indicated that models of the central nervous system containing D.C. generating sources could produce such a surface field, justifying the hypothesis that the naturally occurring D.C. surface field was generated within and distributed by elements of the central nervous system. This was strengthened by the observations that field potentials on the extremities could be reduced to zero by sectioning the nerve fibers to the extremities and that sectioning the spinal

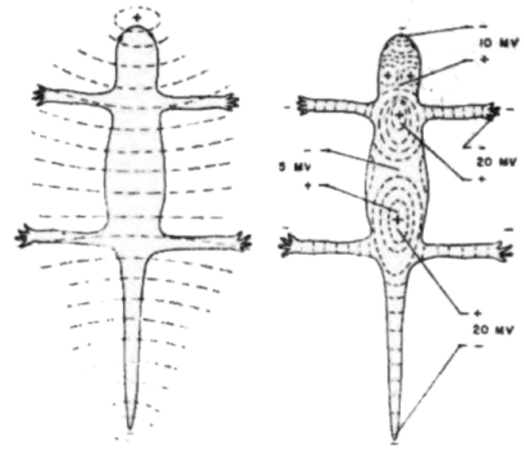

FIGURE 1. D.C. field configuration in amphibian. (Left) Theoretic equipotential lines on basis of dipole field. (Right) Equipotential lines actually found by measurement. Complexities of field, as well as relationship to central nervous system, apparent. Arrows indicate points of standard electrode placement and average values of potentials measured.

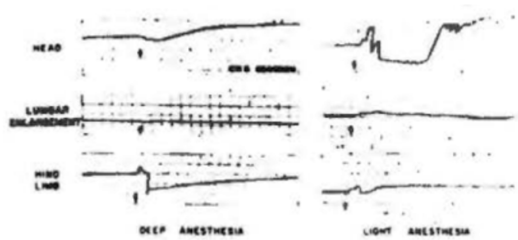

FIGURE 2. Response of D.C. field to hind limb trauma. Fracture of one of long bones in hind limb of a salamander produced at point marked with arrow. Simultaneous recordings made at areas indicated. Upward deflection indicates increasing negativity. Zero offset used to bring recording pens to chart center with amplification used. (Left) Deep anesthesia. Note prompt shift in D.C. potential in injured hind limb, very slight change in lumbar area, and small positive shift in head potential after time lag of two seconds. (Right) Light anesthesia. Head response much greater in magnitude and complexity although lag time remains the same. Head changes definitely not the passive transmission of injury potential but represent active response. (1 millivolt per 2 vertical lines)

cord at the level of the medulla produced severe changes in the field potentials distally, such changes correlating well with the time duration of spinal shock.

In addition, if the D.C. potentials were measured at multiple points on an animal, including the bead, a specific series of changes occurred following the application of a traumatic stimulus to the hind limb (Fig. 2). These changes progressed up the neuraxis, reaching the cranial area after a delay of two seconds, and producing an active response. This suggested that the sequence of D.C. field changes bad transmitted information regarding trauma. Very specific changes in the field polarity, particularly across the head, were noted with anesthesia. In deep chemical anesthesia, the polarity of the frontal area was found to be positive with respect to the occipital area. Spontaneous slow recovery from anesthesia was associated with a shift through zero to a negative polarity which tended to increase in amplitude until in the normal unanesthetized state the polarity of the frontal area was negative. It is significant that electronarcosis[14,15] is produced by applying a modulated direct current across the head along the fronto-occipital axis with a polarity tending to drive the frontal area positive.

Since the extremities revealed a D.C. potential gradient that was increasingly negative as one proceeded distally, the gradient was measured on the exposed but otherwise undisturbed main sciatic nerve in the frog. This proved also to be negative distally and was fairly linear, being the same along various 1-cm lengths. Since the potentials measured were direct current in nature and completely unrelated to the action potential activity of the nerves, it appeared that we might well be dealing with an entirely new phenomenon. Standing or electrostatic potentials could not be long maintained in a conducting medium such as a nerve fiber unless they were associated with a continuous flow of electrical charges in some manner analogous to the flow of electricity in a wire connected to a battery. The nerve impulse or action potential does not involve any such activity being basically a traveling wave of membrane depolarization. Present-day theories relate this to a radial movement of ions in and out of the fiber, with no longitudinal transmission of electrical charge. It seemed most probable that we were observing the continuous movement of charges longitudinally in the nerve fiber, and evidence was obtained to substantiate this by utilizing a physical phenomenon, the Hall effect (Fig. 3).

The results obtained were indicative not only of such moving charges, but also indicated further that the charge carriers were nonionic and were probably units of the size of electrons.[24] This would indicate that some phenomenon such as semiconduction- or conduction-band electron transfer was occurring within the nerve fiber. The application of cryogenic technics to exposed nerve fibers provided some confirmatory evidence for this and indicated further that the magnitude of the current flow varied with the state of activity or irritability of the fibers.[25] We had by this time concluded that the surface D.C. potentials are a second-order phenomenon, resulting from the charge transport system associated with the neural tissues. However, charges that move in a D.C. fashion in one direction must ultimately return to their source to complete the circuit.

Our concept of the system at first was that the nerve fibers conducted in one direction, presumably distally, and that the

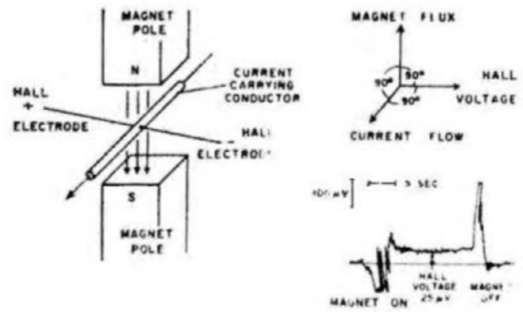

FIGURE 3. The Hall effect. (Left) Schematized basic arrangement necessary for Hall effect experiment. To generate a potential across Hall electrodes, charges must be moving within conductor. (Right) Mutual 90-degree axes necessary illustrated at top. Using nerve outflow in forelimb as analogous to current conductor, Hall effect experiment can be set up. Permanent magnet on movable support furnishes magnetic flux necessary. Representative Hall voltage obtained from one such experiment illustrated at bottom. Steady 25 microvolt change in D.C. voltage obtained during application of magnetic field. Transient wave forms associated with magnet on and magnet off are due to movement of magnet in and out of position. Moving lines of flux generate transient voltages which die out in one or two seconds and contribute nothing to steady Hall voltage.

return path was through the soft tissues or some component thereof. A search for this return path was initially unsuccessful until the routine measurements of the D.C. gradients along the peripheral nerves were extended to the branches of the sciatic nerves. The gradient of the posterior tibial branch was found to be of the same polarity as the main sciatic nerve (negative distally), although considerably higher in magnitude. The gradient along the peroneal branch was then noted to be reversed, that is, positive distally, and lower in magnitude than the posterior tibial branch. The arithmetic sum of the gradients along 1-cm. lengths of the two branches was approximately equal in polarity and magnitude to the D.C. gradient along 1 cm. of the main sciatic. A comparison of the fiber-size spectrum of the two branches revealed that the peroneal branch, which was positive distally, had a preponderance of small myelinated flibers compared with the posterior tibial branch.

Since the smaller fibers are considered to be associated generally with sensory function, a survey of known sensory (dermal) and known motor (muscular) nerves was done. In all cases the sensory nerves had a distal positive gradient, while the motor nerves were distal negative. It is evident that the gradient of a mixed nerve will therefore be the arithmetic sum of the negative and positive gradients of the motor and sensory fibers respectively. Since the normal direction of impulse conduction in a sensory nerve is toward the nerve cell body, the sensory nerve fibers may be viewed as anatomically dendritic in nature. Obviously the motor fibers in a peripheral nerve are anatomically axons. Since all of the sensory nerves (dendrites) were observed to have a D.C. gradient distally positive in polarity and all of the motor nerves (axons) were found to exhibit the opposite polarity, might we be dealing with a D.C. gradient extending longitudinally throughout the entire neural unit: dendrite to cell body to axon? In this regard, the previously mentioned works of Gerard and Libet7,26 are particularly pertinent. They observed such an axodendritic polarization in the cranial neurons of the frog and, most important, related this potential to the activity, as determined by the electroencephalogram, of the same neurons. Goldring and O'Leary[27] have reported that by artificially reversing the potential results in convulsive-type electroencephalograms while artificially augmenting the potential with the same amount of current, an increase in the voltage of the normal electroencephalogram is produced. In another study, Goldring et al.28 demonstrated the existence of a similar pia ventricular D.C. gradient in human being and successfully related changes in the neuronal D.C. pattern to changes in the D.C. potentials measured by skin electrodes.

Comment

As a result of all these investigations, we propose that a property common to all neural tissue is an axodendritic electrical polarization (Fig. 4) accompanied by a longitudinal D.C. flow. It is possible to draw a "circuit diagram" for this system as it functions for spinal neurons (Fig. 4B). It is evident that circuit resistance between peripheral terminals (AB) is higher than the resistance be-

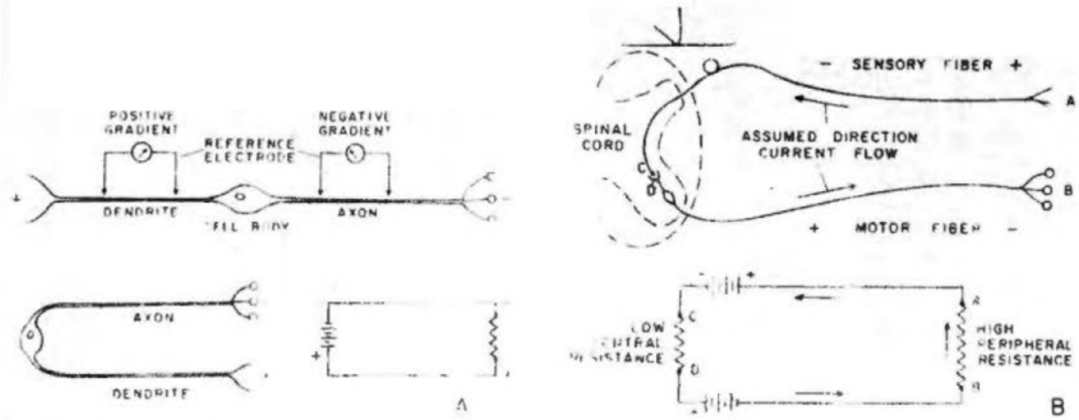

FIGURE 4. (A) Basic axodendritic D.C. polarization of spinal neurons. (Top) Over-all polarization of neuron with illustration of different polarities obtained on dendrite versus axon resulting from position of reference electrode. In studies on peripheral spinal nerves the reference elecdtrode was proximal or nearest to cell body. This is equivalent to reversing voltmeter connections on sensory fibers compared to motor fibers. Therefore, if over-all longitudinal D.C. gradient existed it would be recorded with opposite polarities on each type of fiber. (Lower left) Single neuron bent into loop producing completed circuit. (Lower right) Electronic analog of circuit assuming current source is located solely in cell body. (B) Functioning D.C. circuit composed of two basic neurons. Orientation of each neuron determines its direction of direct current flow. A sensory and motor neuron therefore constitute not only a simple reflex arc but also a complete D.C. circuit. Electrical circuit analog illustrated, again the assumption made that current source is concentrated in cell body. Very narrow gap at central synapse (CD) considered lower in resistance than peripheral path through tissue (AB).

tween central terminals (CD) and that a higher potential therefore will be observed peripherally. The use of such skin-resistance measurements as galvanic skin response as an index of the psychologic state can be interpreted as variations of D.C. flow in such cases. It has been shown that the state of functional activity of cranial neurons, as measured by action potentials, is related directly to the presence of a normal D.C. potential gradient and current flow.[6,7,26] It therefore appears that each neuron is capable of two types of activity: the first being the generation of a D.C. potential accompanied by longitudinal D.C. flow and the second being the generation of rapidly propagating action potentials as disturbances in membrane polarization. The second activity depends on the first being in a normal state. By influencing the rate of message-flow action potentials, the D.C. system qualifies as a data-transmitting control system. In addition it appears to transmit certain types of data such as pain and injury, by variations in its own state: an analog type of data transmission. It also seems to exert controls over certain peripheral as well as central or cranial functions. The reaction times of such an analog system are low but the versatility high; therefore it is thought that possibly this was the original functioning system in the first primitive nerve nets.

It became desirable to evaluate the control functions of this unified D.C. system in regard to the parameters of growth and behavior. Concerning the first, a definite relationship has been established between the time sequence of D.C. changes at the site of a limb amputation and the subsequent type of healing process. Animals demonstrating regenerative abilities followed an entirely different sequence of D.C. changes from that of closely related by nonregenerative forms. Furthermore, the rate of regeneration could be accelerated as well as retarded by artificially implementing or decreasing the magnitude of the measured D.C. field change.[29]

Conclusion

At this time it became technically possible to make long-term D.C. recordings from

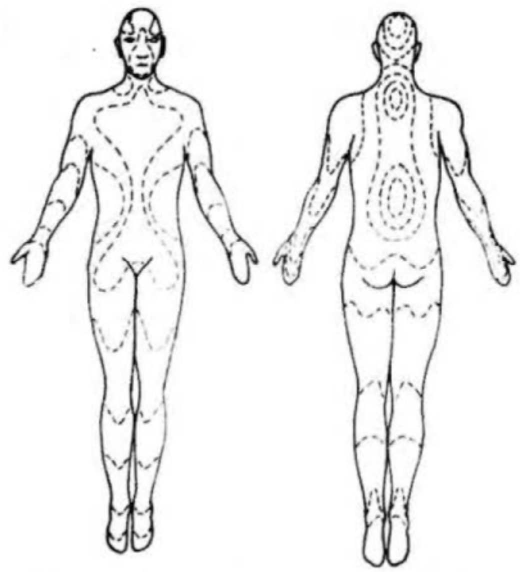

FIGURE 5. Pattern of equipotential D.C. field lines in human being. Similarity in this pattern to that shown by amphibian evident; same relationship to central nervous system.

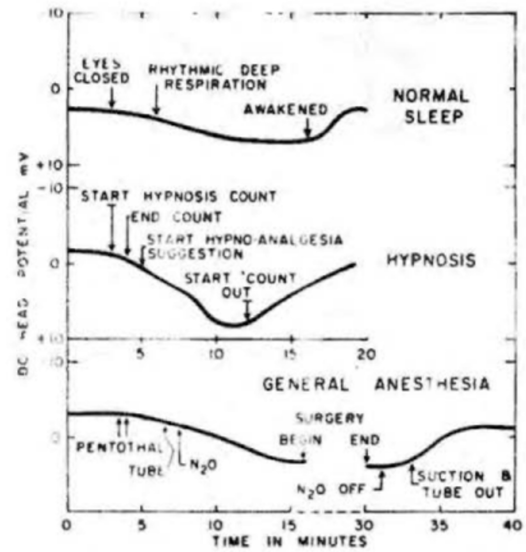

FIGURE 6. Representative changes in transcranial (measured from occiput to frontal region) D.C. potentials of human being during various changes in state of consciousness (sleep, hypnosis, anesthesia). (Top to bottom) All of these associated with shift in positive direction of frontal area.

human beings because of the development of a new type of electrode.[30] Since many papers had dealt with D.C. phenomena in human beings based on the dipole field theory, there appeared little doubt that such D.C. potentials did exist in man. However, because of the generally unsatisfactory nature of the electrodes previously used and the fact that measurements were taken from essentially random points, both the pattern of the field and the significance of the reported changes were in doubt. The first step was to measure the field in the same manner as was done previously with the amphibian. In general the same neural-related pattern was found with differences ascribable to the relative shortening of the spinal cord and the capacitive effects associated with dry skin (Fig. 5).

It was further noted that voltage-regulation curves typical of D.C. sources with internal resistance could be determined along nerve pathways, a fact indicating that the source of the potential could and does supply a current. As with the amphibian, specific changes in the transcortical D.C. potentials were noted with general anesthesia (Fig. 6). It is interesting that the changes noted were of the same polarity as the currents used to produce electronarcosis. In addition, similar polarity shifts were noted in sleep and hypnosis.[41] In all of these states the physiologic level was related to the magnitude of the polarity change. A procaine block of the peripheral nerves produced a drop in the surface potential measured from the brachial area to the palm of the hand (Fig. 7). Two cases with brachial plexus injuries were evaluated. One case with clinical avulsion of the brachial roots demonstrated a zero potential. The other case in which the block was caused by pressure demonstrated complete motor and sensory paralysis immediately postoperatively with zero D.C. gradients. Within forty-eight to seventy-two hours deep pain sensation alone had returned, and this was accompanied by a nearly normal D.C. gradient level. Since deep pain is generally related to C fibers[32] and these C fibers to the phenomenon of "second" or "delayed" pain with a delay time of 0.5 second,[33] the time lag of two seconds noted in the animal's cranial D.C. response to trauma is highly suggestive. A significant relationship was noted between extremity

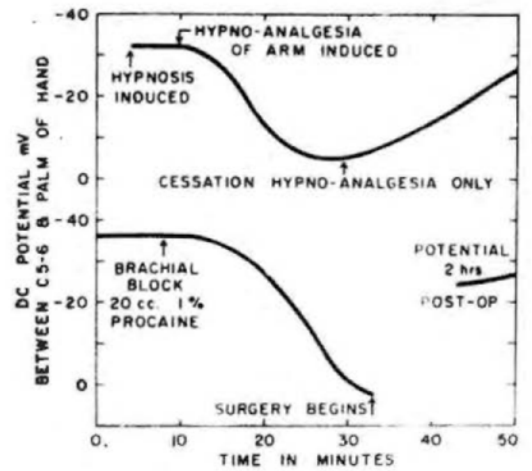

FIGURE 7. Changes in D.C. potential along limb neural gradient (upper arm to palm of hand) associated with chemical nerve block and hypno-analgesia. In each case local anesthesia associated with drop in normal negative potential.

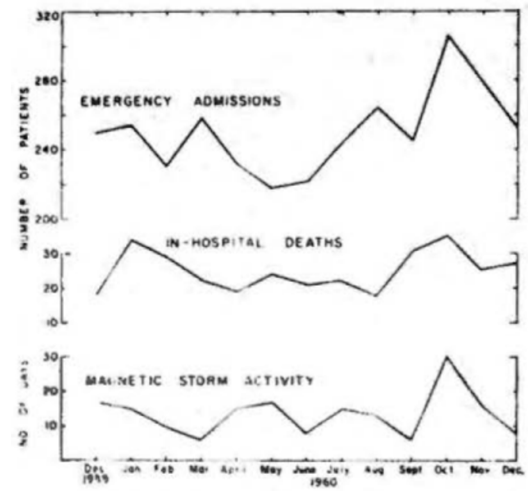

FIGURE 8. Monthly records of numbers of emergency admissions and deaths compared with number of days in which magnetic storms occurred. Magnetic storms global in occurrence and the admission and death rates determined for the Veterans Administration Hospital in Syracuse, New York, only. Rates of hospital admissions and deaths commonly do not follow a real random distribution. Graph indicates there may be relationship between this nonrandom distribution and some geophysical parameter.

D.C. gradients and the production of extremity analgesia by hypnosis. Analgesia in this case was accompanied by a drop in the D.C. potential similar to that noted with a chemical block (Fig. 7). Apparently there is some relationship between cranial areas and the peripheral D.C. gradients which is susceptible to control during the hypnotic state.

Since the cranial D.C. potential appeared to be a particularly important parameter in the state of consciousness or level of irritability in the human being, the possibility that it was the controlling mechanism for biologic cyclic behavior was considered. In a very preliminary study the transcranial D.C. potentials of 2 normal subjects and 2 schizophrenic patients were determined daily for a period of two months. A definite cyclic pattern was evident in all 4 subjects, with a periodicity of approximately twenty-eight days and with all 4 following similar cycles. However, definite differences appeared between the normal and the schizophrenbic persons, the significance of which must await further study.

Two considerations of very basic importance were now entertained. First, it appeared quite likely that the organized D.C. activity of the brain was in some way closely related to general behavior, possibly as a controlling mechanism of sorts. Second, since the actual D.C. flow of charge carriers was an integral part of the system. operating parameters of the system could be influenced by external force fields (magnetic, electrostatic) and by such physical parameters as levels of air ionization. It is interesting to note in this regard that the suggestion has been made frequently that there is some relationship between psychiatric disturbances and geophysical parameters of the environment. If one compares the incidence of magnetic storms with the incidence of emergency hospital admissions and death for a year, some relationship is apparent (Fig. 8).

We have recently reported on a more rigorous statistical evaluation of this possibility.[34] The daily magnetic field intensity measured at Fredricksburg, Virginia, has been correlated with the daily psychiatric admission rate to two Syracuse, New York, hospitals during the past four years. The coefficient of correlation obtained, although low, was highly significant. Because of the crudity of the data used, this result is to be considered as indicating only some possible but promising relationship between psychiatric disturbances and some geophysical parameter, not necessarily a magnetic field. Nevertheless, it is considered highly significant that even with such crude data the result predicted by theoretical analysis was found.

Summary

The D.C. potentials measured on the surface of living organisms appear to be the result of D.C. flow within the central nervous system. This direct current appears to be a phenomenon of nerve fibers in general and is organized into a complex system which is capable of transmitting information and effecting control. Sensory inputs to the system are identified as trauma and external electromagnetic force fields. The system influences and may exert control over growth processes. It determines the basic level of irritability of the neurons themselves and may possibly be related to various aspects of psychologic functioning. This has indicated to us that any comprehensive formulation of psychiatric disorders should take into account these new parameters involving direct current neural mechanisms and their interaction with environmental physical factors.

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