THE PHYSIOLOGICAL MECHANISMS OF ACTION OF MAGNETIC FIELDS ON NEURAL STRUCTURES.

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Introduction

The cyclic behavior patterns of lower animals (1) and the incidence of psychiatric disturbances in the human population (2) have both been related to changes in the earth's geomagnetic field. In the first instance, the normal biological cycle was significantly altered by exposing the animals to magnetic fields as low as 1 gauss intensity. In the latter case, significant statistical correlations were established between naturally occurring magnetic storms (which rarely exceed 1 gauss intensity)and the rate of admissions to psychiatric hospitals. Both of these observations imply an action of low strength magnetic fields upon the central nervous system in such a fashion as to produce an organized response.

The nature of the neural action potential theoretically precludes any effect upon it by externally generated fields and experimental evidence to date has uniformly substantiated this hypothesis. The conduction velocity, chronaxie and rheobase of extirpated axons are not altered by exposure to kilogauss strength fields (3). Therefore, it appears that any magnetic field effect must be mediated through some other physiological mechanism.

The differential action of the field upon molecules of different magnetic susceptibility has been proposed as the mechanism involved in general bio-magnetic effects (4). However, in order for such mechanical effects to exceed the thermal vibration of the molecules the field strength must be in the high kilogauss range. While this mechanism may be operating in the case of some growth inhibitory effects noted with high strength nonuniform fields(5), it is quite inadequate to explain the behavioral effects of low strength fields.

This paper proposes an alternative physiological mechanism for the effect of magnetic fields upon organized living systems. In this case the interaction between a direct electrical current and a magnetic field oriented at 90° to the axis of current flow results in the generation of an electrical potential at 90° to the axes of both the field and the current. If conducting paths are available in this direction, small currents will flow, and the total current along the original axis will be diminished. Pulsations in the magnetic field will be translated to variations in current flow. These effects are exceedingly minute in metallic conductors; however, they are as much as 10^6 times as great in semiconductors or other “electronic” conduction systems with charge carriers of high mobility. Evidence has been accumulated indicating the presence of semiconduction mechanisms in living material (6,7,8). While most work to date has been on highly purified proteins, etc., the theory has been advanced that these semi-conduction systems have important physiological functions (9). If this is so, then properly oriented magnetic fields, acting through the galvano-magnetic effect, would produce various physiological effects depending upon the function of the electronic conduction system involved.

Our investigations have indicated the presence of such an organized semiconduction system within the central nervous system (10,11,12,13,14).

Functionally, the level of irritability of any neural unit — as measured by its ability to generate action potentials — is apparently dependent upon this underlying electronic system being in a certain “normal” state as regards amplitude and direction of current flow. These observations appear to correlate well with those of Gerard and Libet (15), and of Goldring, et al. (16,17) on the direct current potentials of brain tissue, the measured d. c. potentials in this case may be interpreted as an indication of the state of the electronic system. These electrical potentials can also be measured on the intact body surface where they then indicate the functional state of the larger anatomical neural units, such as the brain and the brachial and lumbosacral nerve outflows (18). Direct current measurements across the cranial area are an index of the state of consciousness or irritability of the total organism and serve to demonstrate the physical nature of the electronic system. As viewed on the intact surface of the head, the cranial d. c. potentials are organized primarily as a single vector, extending fronto-occipitally in the midline with the frontal area negative in the fully awake organism. Loss of consciousness produced by any general anesthetic agent, by normal deep sleep, or by deep hypnosis (19) is accompanied by a decrease in the amplitude of this potential (i.e., the frontal negativity decreases). The magnitude of the change from the original level is proportional to the degree of loss of consciousness, may be correlated with the EEG changes noted in each state (Figure #1). This relationship between the magnitude of the “fronto-occipital” d.c. potential and the level of consciousness has been observed in all animal phyla demonstrating sufficient encephalization (annelida to mammalia) (20). The mechanism is therefore considered to be widespread in occurrence, and is postulated to be a basic parameter of neural tissue.

The basic thesis developed is that the semiconduction properties of the neural tissue are associated with minute electrical currents. The magnitude and direction of these currents are factors determining the functional state (i.e., irritability) of the neural units involved. In the cerebral area, the surface d.c. vector seems to indicate that the current flow resides in some midline structures arranged linearly in the fronto-occipital direction. Since we hypothesize that this system is basically a solid state electronic one, we should be able to alter its characteristics by two methods: first, by adding externally generated currents oriented along the same fronto-occipital vector with the direction of current flow either augmenting or decreasing the normal internal current; second, the exposure of the system to a magnetic field of sufficient strength oriented at 90° to the fronto-occipital axis should result in deviation of an appreciable amount of current from the original axis. It should be noted that this second method can only decrease the total internal current, in contradistinction to the external electrical current method which can either increase or decrease the internal current.

Since we postulate that the general level of consciousness is dependent upon the state of the internal current system, the experimental alteration of this system should result in corresponding alterations in the level of consciousness which may be reflected in the electroencephalographic pattern.

Methods

1. Techniques and instrumentation used in the measurement of the normally occurring direct current potentials of living organisms are described in full in the previous series of publications (10,11,12,13,14,18,19).

2. Experimental animals used in the present study were adult *Amblystoma tigrinum* (tiger salamanders). They averaged 8–10 inches in length, with head dimensions of 1”x0.75”. The direct current system of this vertebrate form had previously been intensively studied (8,9), and its characteristics were determined in detail. In all experiments (except those involving the deeply anesthetized state)the animals were lightly tranquilized by titration in tap water with Tricaine (Sandoz) until quiet and unresponsive to tactile stimulation. In this state the animals were sluggishly responsive to moderately painful stimuli, and they invariably recovered full consciousness within 15 to 20 minutes after removal from the solution. Their fronto-occipital d.c. potential is slightly decreased from the normal, and averages 5–18 mV, frontally-negative. In the deep anesthesia experiments the same agent was used in similar fashion, except that titration was carried to the point of complete unresponsiveness to painful stimuli. This state is accompanied by a fall in the fronto-occipital d.c. potential to zero, with an occasional minor polarity reversal. Generally all buccal respiratory movements cease during the major portion of this phase.

3. Electroencephalographic technique.

Electrodes used were silver-silver chloride in isotonic saline agar, with short terminal cotton wicks of 0.5 mm diameter. Potentials were amplified and recorded with a multi-channel Offner Type R Dynagraph. Time constants of 0.3 second were used, and input filters set the upper limit of frequency response to 50 c.p.s. Amplification levels used produced a pen deflection of 1 cm for an input signal of 50 microvolts (μV). Two channels of electrode placement were employed: fore-to-midbrain, and mid-to-hindbrain. The brain in this animal is not folded, and averages 0.75” in length. Previous dissection established surface landmarks which were used for constant positioning of the two pairs of electrodes. The general frequency pattern of the EEG in these animals is not unlike that of other vertebrates, including man. The fully awake, resting animal displays a rather fast alpha rhythm (10–14/sec) averaging 25 μV in amplitude. Respiratory artifacts are common due to the proximity of the buccal respiratory movements to the electrode positions. The deeply anesthetized animal displays a typical delta pattern of 1–3 per second, averaging 50 μV in amplitude. The same pattern was found in anesthesia produced by Tricaine, chloretone, ether, and cyclopropane. (The barbiturates produced a high-frequency pattern of 20–40/sec with slightly reduced amplitude. In deep barbiturate anesthesia the EEG is sparse, of low voltage, and does not demonstrate the large delta waves seen with the other agents). In general, therefore, conversion of an alpha pattern to a delta pattern may be taken as evidence of a decrease in the level of consciousness, and vice versa.

4. Methods of administration of direct electrical currents.

Electrodes utilized were similar to those used for EEG signal pick-up, except the terminal wick diameter averaged 2 mm. The larger wick diameter prevented wick drying, which results in an increase in electrode resistance. The electrodes were applied directly to the moist skin surface of the animal in the midline, one over the most rostral portion of the head, the other at the level of the foramen magnum. Current was derived from a standard B battery (Burgess type 5308, used at 22.5 volts), and fed through a series of 3 voltage- dropping potentiometers totaling 1.11 megohms. Current was continuously monitored by a Hewlett Packard 425-A microvoltammeter in series with the circuit. The circuit resistance produced by the animal averaged 1000 ohms, and voltages necessary to pass all ranges of current used were under 1 volt. Increasing amounts of current were obtained by gradually decreasing the total amount of resistance in the potentiometer series. In this fashion, sudden surges of current were avoided when either increasing or decreasing current flow. In the experiments in which modulation was added to the basic direct current, a Hewlett Packard 202-A low-frequency generator was used. The sine wave output was capacity-coupled to the direct current circuit, the resultant modulated d.c. was monitored on one channel of the Offner recorder, and the generator output was adjusted for 25–50% modulation.

5. Methods of application of magnetic fields.

The magnetic field used was obtained by a Varian model V-4007-1, 6” electromagnet with ring shim pole caps fixed at a gap width of 2.58”. Power was furnished by a Varian model V-2200-A power supply. Field uniformity was excellent, deviation being less than 0.1 gauss for a 1 inch spherical volume located at the gap center. Field strengths were measured with a Varian-type F-8 magnetic resonance fluxmeter, using a proton probe. Field determinations were made with an accuracy of ±0.2%.

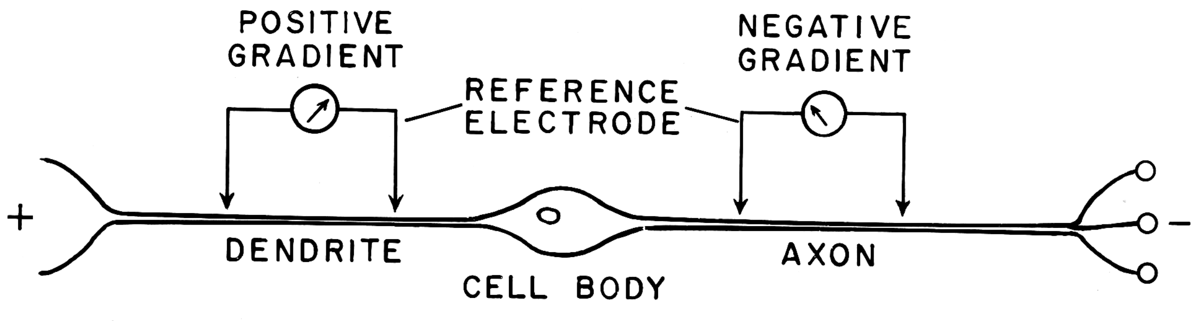
The lightly tranquilized animal was placed on a sheet of plexiglass, suspended in the magnet gap with its head occupying the area of maximum field uniformity in the gap center. The long axis (fronto-occipital)of the head was carefully positioned to be 90° to the flux lines of the field. EEG electrodes were positioned and held in place with non-magnetic clamps. Care was taken to prevent contact between any portion of the animal or recording electrodes and the magnet pole faces. Magnet gap diameter permitted positioning of only one pair of electrodes at a time. The field strength was continuously variable by means of the power supply control. The field strengths were increased and decreased in uniform fashion, and sudden changes in strength were avoided. No external modulation was added to the fields; the power supply delivered ripple-free current to the magnet coils. Particularly, the field was totally free of fluctuations in the 1 to 30 c.p.s. frequency ranges, which could have been confused with EEG patterns.

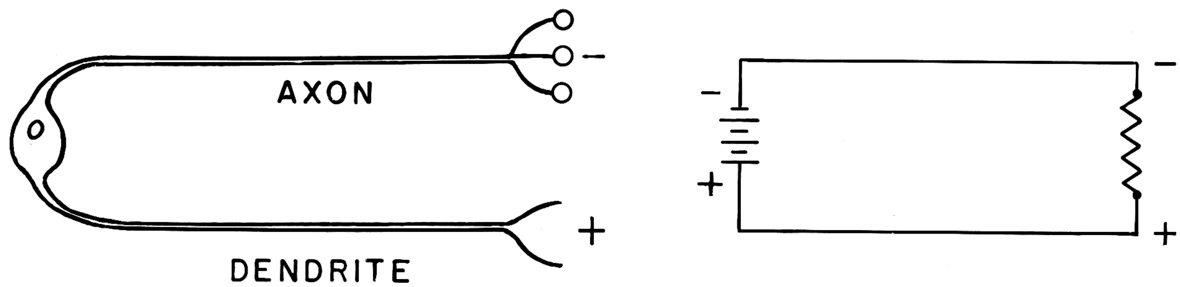
Presentation

Two decades ago standard concepts of the structure and function of living cells and organisms did not include any mechanism which could interact with physical force fields to produce detectable biological changes. Since then, however, electron microscopy has revealed precise anatomical organizations at the molecular level indicative of solid structures of a quasi-crystalline nature. Within the same period, largely under the impetus of Szent Gyorgyi's speculative theses, interest has grown in the possibility that semiconduction or other solid state mechanisms may play important functional roles in living systems. Experimentally, some semiconduction properties have been demonstrated, particularly in the linear proteins and the chloroplasts. Stable free radicals have been identified in biological materials and have been implicated as intermediates in many enzyme systems. My laboratory has studied organized biological solid state systems for several years, and has obtained data of some basic as well as clinical significance. We defined organized semiconduction systems as control systems, performing a specific function, with at least one part of the control system loop based upon semiconduction properties of a tissue. In seeking methods of experimental verification of these properties we began using the interactions between semiconducting materials and electromagnetic force fields as well as with small direct electrical currents. These interactions are well known in the case of inorganic semiconductors and lead to easily observable changes in the behavior of the semiconductor. Utilizing these principles and knowing the operating parameters of a biological semiconducting system, one may predict the results of its interaction with an applied magnetic field. If such predicted results are experimentally obtained then one has obtained some confirmation of the semiconduction system. Since the semiconduction systems studied are considered to be functionally important, one obviously will also observe a functional change in the organism or in one of its component systems as a result of the exposure to the physical force field. It is my contention that experimentation on the interaction between physical force fields and living organisms is best evaluated on such a basic plane rather than in a simple empirical or phenomenological fashion.

We have obtained several types of evidence for semiconduction activity within two tissues, nerve and bone. Although we have been able to produce the firmest scientific evidence in support of this hypothesis in bone we have evaluated much more thoroughly the force field interaction with the central nervous system and since the observed interactions are of considerable clinical significance this paper will be confined to this aspect.

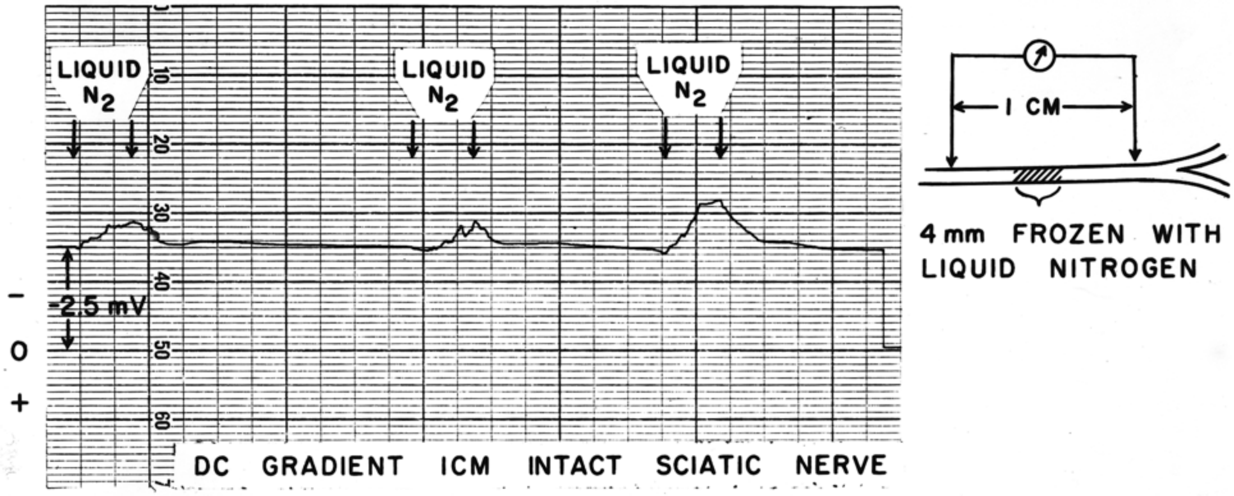
At the level of the single neuron we have determined that every such unit is electrically polarized in an axonodendritic or longitudinal direction and that this polarization is accompanied by the flow of a minute electrical current along the axis of the neuron. Under normal conditions this polarization is as pictured, however, since we do not know the sign of the charge carriers, we cannot indicate the direction of current flow with certainty. Assuming the carriers to be electrons the current direction is as indicated. The current has semiconduction characteristics and can not only traverse an area of nerve quickly frozen at 77°K, but the crystalline state produced by the freezing results in a slight enhancement of the effect.



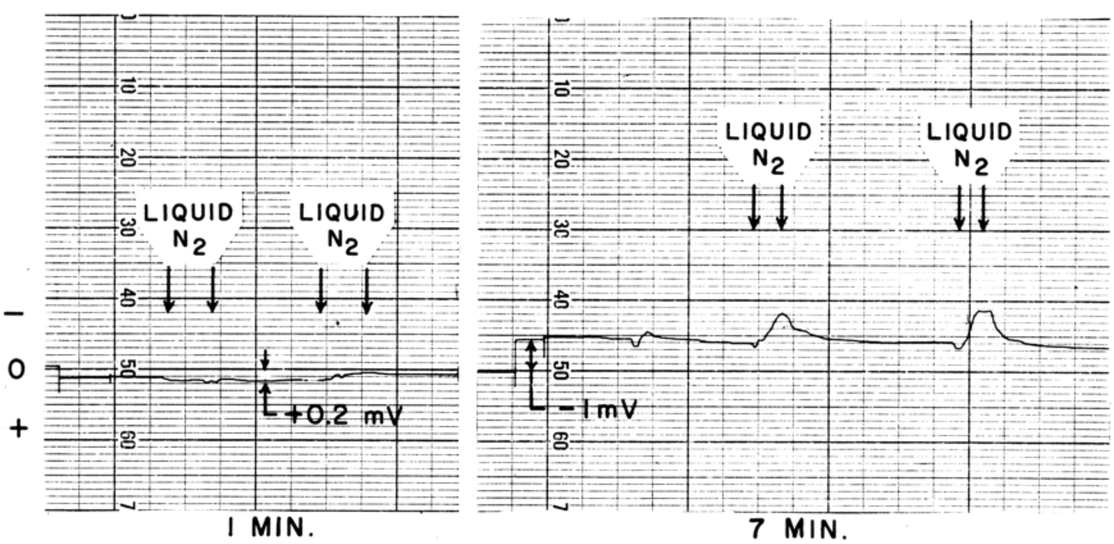


The voltage gradient over 1 cm of an intact frog sciatic nerve is about 2.5 mV. Freezing of a 3-mm segment in the center results in an increase of about 0.3 mV. If ionic currents were responsible for the voltage gradient, ionic movement could not occur across the frozen segment and the voltage would drop to zero as a result.

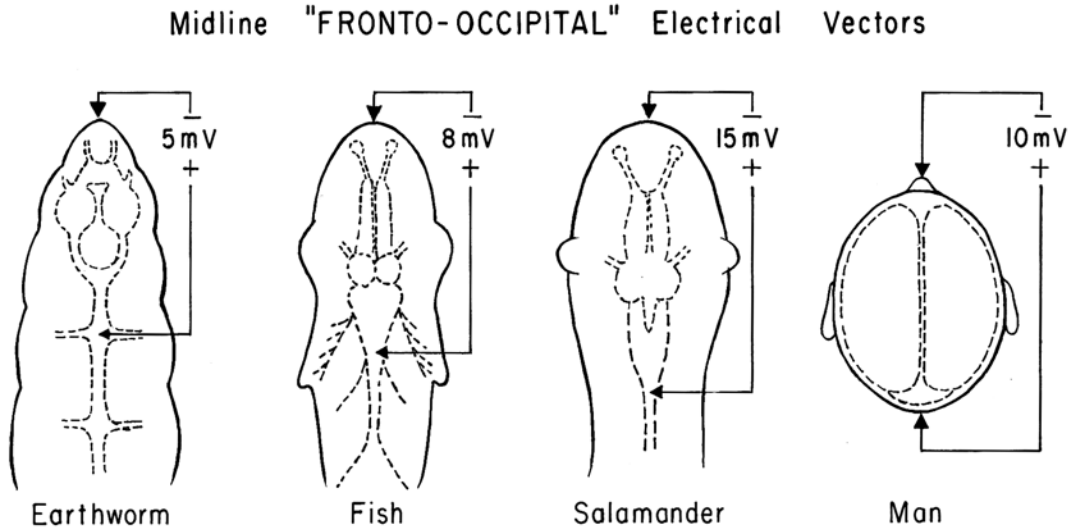
The current is directly related to the functional state of the neuron, considered as its ability to receive, generate and transmit action potentials. Alteration of the current flow by passing an externally generated current through such a neuron against the normal polarization gradient progressively decreases the ability of the neuron in this regard, until at the level of a zero resultant current or a reversal of normal polarity the neurons become incapable of such activities. Similar effects can be produced in the integrated CNS by internally generated command signals (or lack of same) from higher centers. For example, the state of spinal shock appears to be produced by such a mechanism. Measurements of the potential gradient on the sciatic nerve before cord section a the foramen magnum show a 2.5-mV gradient over a 1-cm length and freezing of the central 3 mm produced moderate increase in the voltage gradient.



One minute after cord section the gradient is zero and freezing has no effect. Seven minutes later as spinal shock disappears the gradient returns (along with a return of reflex activity) and again freezing produces an increase in the voltage gradient. The fact that freezing during the phase of spinal shock produced no voltage change indicates that the changes otherwise noted were not artifacts due solely to the change in state.



DC GRADIENT AFTER SPINAL CORD SECTION



Slide 4. In all animals studied, which had some degree of encephalization, a specific steady-state electrical potential or D.C. vector was measurable across the cephalic portion which reflected in a linear fashion the level of consciousness (or the overall functional level of neural activity), regardless of the fact that a wide variety of neural types was represented.

This vector is located in the midline in the fronto-occipital direction with the frontal area negative relative to the occiput in a normally awake organism; the polarity was the same in all phyla studied. All other vector directions were lower in amplitude, and the vector at right angles to the fronto-occipital one was invariably the lowest in magnitude, and frequently was zero voltage.

In all cases, anesthesia was accompanied by a decrease in the magnitude of this vector, regardless of the anesthetic agent employed. The decrease was roughly proportional to the level of anesthesia induced and deep general anesthesia was accompanied by a decline to zero voltage.

Similar vectors can be measured in man, however here the folding and overlay of the cortex has to be taken into account (Fig. 1). The vector appears to be more related to the brain stem with little cortical contribution. Note that the levels of consciousness are determined not only clinically but also by EEG patterns and that in deep surgical plane anesthesia the drop of the fronto-occipital vector to zero is accompanied by the appearance of typical delta waves in the EEG.

On the basis of the specificity of the vector direction in all animals and its obvious functional relationship to the level of consciousness it was postulated that it resulted from some organized semiconduction activity in mid-line unpaired brain stem structures. In view of the known relationship between the brain stem reticular formation and consciousness we presently feel that this is the location of this activity. It was theorized that if this in truth represented an organized electronic system, and that if this system did control the level of cerebral activity, then the passage of an externally generated current through it should produce alterations in consciousness evidenced both clinically and electroencephalographically. In addition two diametrically opposite results should be obtained depending upon the direction of the applied current. For example, the application of current to null out the normal frontal negativity should result in a a decrease of the consciousness level, while the addition of current to the system in a normal direction (frontal negative) should increase the functional level of activity.

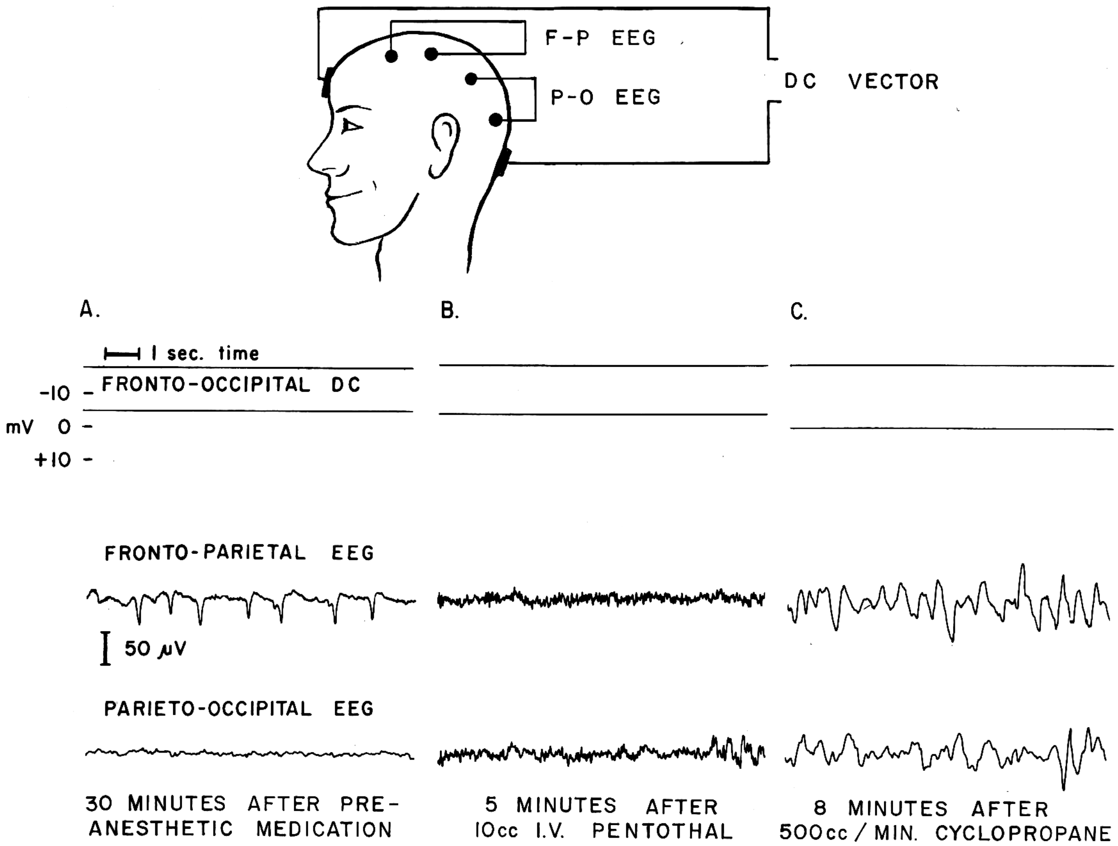


Figure 1. Changes in the human fronto-occipital d.c. potential and electroencephalogram with general anesthesia. Section A demonstrates the pattern present at the start of anesthesia, the d.c. level is 5 mV frontally-negative. Section B was taken ten minutes after 10cc of 2.5% pentothal were administered intravenously. It demonstrates a 1 mV decrease in the d.c. potential and a fast EEG pattern typical of barbiturate effect. Section C was taken fifteen minutes after 500 cc/min of cyclopropane was started in a semi-closed system. Clinically, the patient was in deep general anesthesia. The fronto-occipital d.c. has dropped to zero, and both channels of EEG demonstrate a marked delta pattern.

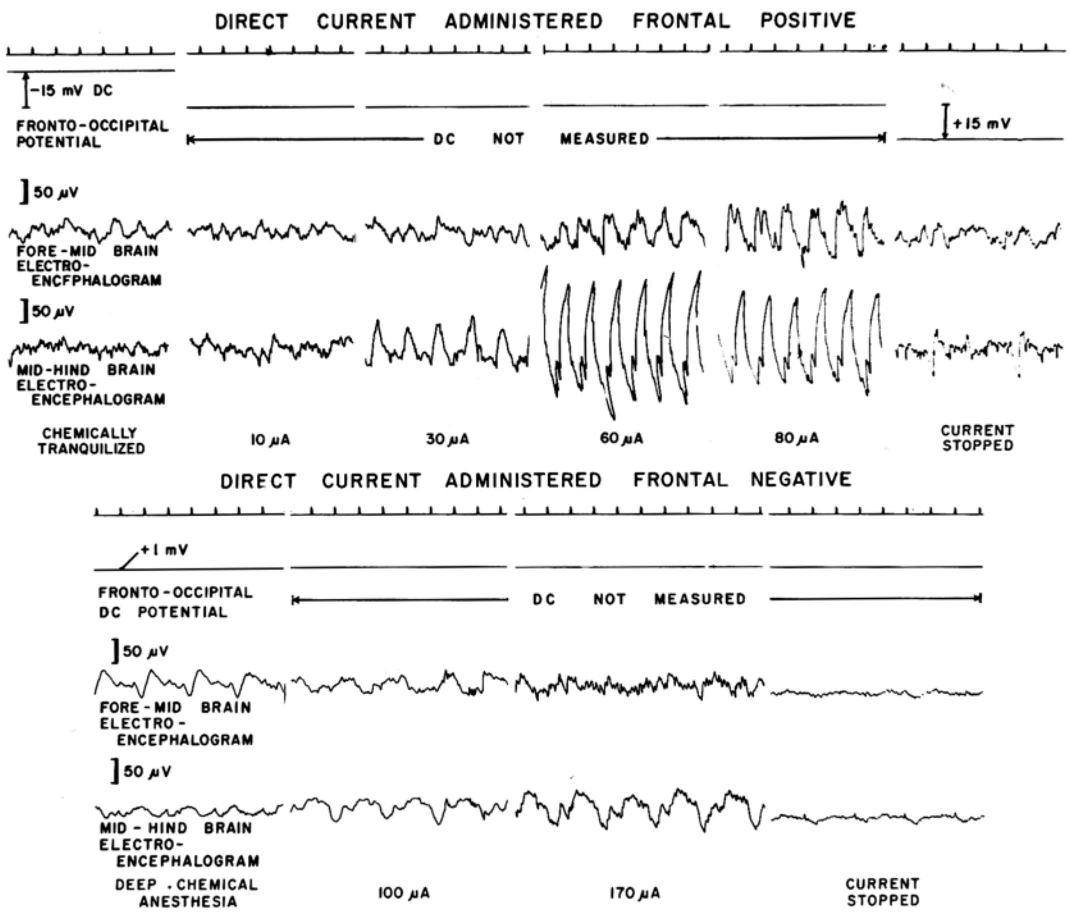


Figure 2. The effect of administration of direct current (midline, cephalo-caudally) to amphibian. The upper series illustrates the changes produced by various amounts of frontally-positive current administered to a lightly tranquilized animal. The first section demonstrates the naturally occurring fronto-occipital d.c. potential and EEG before current administration was begun. Both (EEG) channels demonstrate increasing amplitude delta wave patterns with increasing amounts of current as noted. The last section was taken three minutes following cessation of current flow and demonstrates the residual polarization of the d.c. potential and some persistence of delta activity.

The lower series of recordings similarly demonstrates the effects of administering current in a frontally-negative fashion to a deeply anesthetized animal exhibiting zero d.c. potential, delta wave EEG patterns, and depression of respiratory movements. The fore-to-midbrain EEG channel demonstrates a relatively normal alpha pattenr during the administration of 170 µA of current. At the same tie regular respiratory movements were resumed by the animal, persisting only as long as this current was maintained. The EEGs, after cessation of current flow, no longer demonstrate the delta patterns present before current administration.

In both series of recordings the upper time marker has a one/second frequency, and amplification levels of the three channels are as noted.

In monitoring experiments on both animals and humans during induction and recovery from chemical anesthesia, it was noted that the fronto-occipital electrical vector showed modulation frequencies in the 0.1–1 cps range during times of changes in consciousness levels. It appeared therefore that to properly simulate the changes in the internal electronic system seen during chemical anesthesia, similar modulation frequencies should be added to the externally generated current.

Fig. 3 illustrates the results of such an experiment. The upper left section shows the fronto-occipital vector to be about 15 mV frontally negative and the EEG patterns are typical of light tranquilization. The next section shows the delta pattern EEG produced by the passage of 20 μA of direct current oriented frontally positive. This current was unmodulated and one should note that while delta frequencies are present they are superimposed on the preexisting alpha frequencies which remain unchanged. The basic direct current was then modulated at 0.1, 1.0, 10 and 100 cps and EEG recordings taken at each modulation frequency. The addition of 0.1 cps modulation resulted in the complete disappearance of the alpha pattern. While increasing frequencies of modulation were correspondingly less effective in this regard, in the ranges studied, all modulated direct currents were more efficient than unmodulated current.

At this point it is interesting to note that the most frequently utilized method of electrical anesthesia is a direct current modulated at 100 cps and passed through the head in a fronto-occipital direction with the frontal area positive. It is believed that the phenomenon of electronarcosis is best explained on the basis of the neural semiconduction system hypothesis and furthermore it would appear that much more efficient anesthesia may be obtained if the modulation frequencies is changed from 100 cps to 0.1 cps.

The results obtained so far seemed to support the thesis that some midline unpaired structure in the brain was the site of organized electronic activity of a steady state nature and that this activity governed the functioning level of the entire brain. If this electrical current vector is semiconducting in nature then it should be possible to influence it by external magnetic fields of sufficient strength by means of the well-known Hall effect. For maximum effect the magnetic field vector must be at 90° to the electrical current vector. Under these circumstances the influence upon the charge carriers is to deviate a percentage of them into alternate pathways, at 90° to both the original current axis and the magnetic field axis. This results in a decrease in the total current carried by the vector in the original fronto-occipital direction and if the field strength were high enough, the drop in the total current should be reflected in a decrease in the level of consciousness evidenced by a conversion of the EEG from an alpha to a delta pattern.

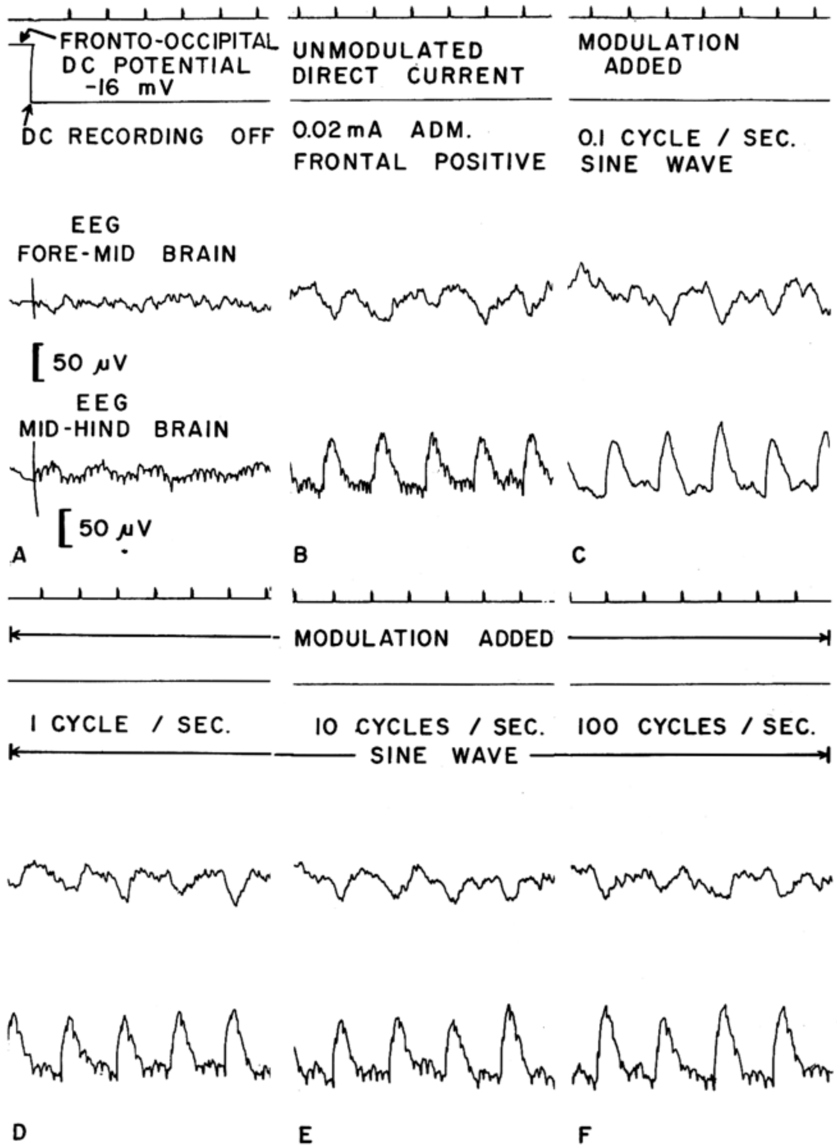


Figure 3. The effect of adding modulation at various frequencies to a frontally-posiitve direct current of 20 μA magnitude. Section A demonstratres the d.c. potential and EEG patterns existing before starting the direct current. Seciton B shows the delta pattenr produced by the direct current passage alone. Note that the pre-existing EEG frequencies are still present despite the large delta waves. In Section C the addition of 0.1 c.p.s. sine wave modulation to the basic d.c. level results in almost complete obliteration of all fast activity in the EEG and some slight augmentation of the delta activity. The other frequencies of modulation as noted have less effect; however, all seem to potentiate the action of the direct current to some extent.

The recordings of the amphibian EEG (Fig. 4) were made sequentially; the numbers indicate the strength of the applied magnetic field in kilogauss. The EEG at the start of the experiment was a normal alpha pattern and as the magnetic field strength is increased, a low amplitude delta pattern becomes evidenced at about 3000 gauss while 3400 gauss resulted in a constant delta pattern for as long as it was applied. As the magnetic field is decreased in intensity the normal alpha pattern promptly reappears. It has been found that animals may be kept in a quiescent state if properly oriented in a 3400 gauss field, for as long as several hours. Alteration of the 90° angle between the current vector and the magnetic field vector markedly reduces the effect. It would therefore appear that properly oriented magnetic fields of sufficient strength can produce functional states similar to electrical anesthesia but without the persistent polarization and with prompt recovery from the anesthetic state. In view of the previous experiment one would predict that modulation of the magnetic field at a 0.1 cps rate would result in a marked potentiation of the effect.

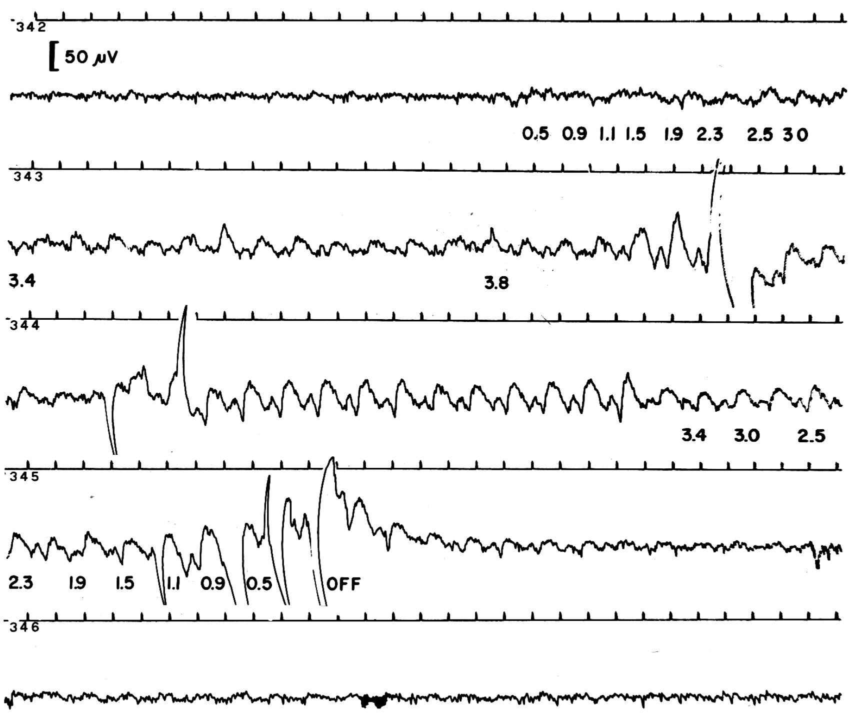


Figure 4. alteration in electroencephalogram pattern of a lightly tranquilized amphibian produced by exposure to a uniform steady-state transverse magnetic field. The five recordings, arranged vertically, were taken sequentially, the time markers in all being one/second and the EEG being recorded from the fore-to-midbrain area. In the uppermost recording, the EEG before the magnetic field was applied is shown demonstrating an alpha frequency of 10–12 c.p.s. The numbers to the right in this record are the field strengths of the magnetic field in kilogauss as it is turned on and increased. The 3.8 kilogauss figure in the center of the second record marks the end of the increasing field strengths and the start of the steady-state magnetic field period. This field strength was maintained until one–two seconds before the 3.4 kilogauss figure in the third recording. The appearance of a delta pattern of approximately one/second during the steady field application is evident in the third recording. The fourth and fifth recordings demonstrate the decrease in field magnitude and the return to a normal pattern as the field is turned off.

Obviously rather high magnetic field strengths are required to produce this effect, however one must keep in mind that the effect is a very gross one, namely the production of a state of general anesthesia. Might it not be possible that much smaller fields properly modulated could produce physiological or functional effects of a much more subtle nature? Some of our previous experiments had indicated a relationship between biological cycles and the cerebral semiconducting system. The possibility was therefore entertained that alterations in the earth's normal magnetic field could be productive of functional changes in humans who might be more susceptible to such effects due to some defect in the organization of their electronic system. Since it is known that the occurrence of schizophrenia is not a random process, but that admissions to hospitals for acute schizophrenia seem to occur in groups and since some physiological abnormalities had been noted in these patients, this population group was statistically correlated with changes in the earth's magnetic fields. The relationship between admission rates for schizophrenia and major magnetic storms was evaluated over a four-year period on a day-to-day basis utilizing over 26,000 patient admissions. A direct linear relationship was found between the total number of admissions for schizophrenia per month and the total number of days of magnetic storms during the same period. The coefficient of correlation was shown to vary from 0.22 to 0.35, indicating a very high degree of relationship between the two variables.

In summary then, based on our previous work indicating the existence of organized functional semiconduction activity within neural elements, we predicted certain interactions with applied electrical currents and magnetic fields. These interactions have been looked for and found, and in general indicate that such external forces can profoundly influence the basic functional level of the central nervous system. A not unexpected finding was the relationship established between disturbances in the earth's normal magnetic field and the central nervous systems of individuals with schizophrenia. The clinical implications are obvious and range from electrical and/or magnetic anesthesia to a better understanding and possibly some measure of control over certain types of mental disease.

Results

A. Administration of direct current to oppose the normal fronto-occipital d.c. potential in lightly tranquilized animals (Figure #2, upper section).

As the direct current is increased in magnitude, a delta wave pattern becomes evident on the EEG at 30 μA. Further increases in the current produce increasing amplitude in the delta waves. This effect is visible in both channels of EEG recording, but is more prominent in the fore-to-midbrain channel. Both channels, however, demonstrate a marked change from the predominantly alpha pattern seen before current administration. Accompanying these EEG signs indicative of deepening loss of consciousness is a depression of the respiratory center, respiration ceasing generally between 80 and 100 μA. After completion of the experiment, measurements of the fronto-occipital d.c. potential show a reversal of the pattern seen prior to the current administration with what appears to be a residual polarization induced by the current flow. This persists some 15 to 20 minutes, gradually decreasing to zero, and then returning to the normal frontal-negative pattern. The time to full recovery from the effects of the tranquilizing dose of Tricaine is greatly lengthened. Normal recovery is 20 minutes following removal from solution. If current is administered with a frontal-positive polarity for 10 to 20 minutes after removal from solution, recovery is delayed until 30 to 40 minutes following cessation of current administration.

B. Administration of direct current oriented to produce a normal d.c. potential in deeply anesthetized animals (Figure #2, lower section).

This experiment was done for two reasons: first, if the previously described EEG changes were due to side effects of the current administered (pain, heating at electrode junctions), similar EEG patterns should be seen with the same amount of current with reversed polarity; second, if the theory that anesthetic action is mediated primarily by the agent's producing a depression of the normal d.c. potential and current flow is true, then some signs of lightening of the anesthetic state should be produced by artificially restoring the normal current flow. The conditions prior to current administration were a fronto-occipital d.c. potential of almost zero, delta patterns in both channels of the EEG, and absence of respiratory movements. The administration of 170 μA of frontally-negative direct current results in the appearance of a fairly typical alpha pattern in the fore-to-midbrain channel, this, however, being accompanied by an increase in the mid-to-hindbrain delta activity. However, respiratory movements return with normal rate and rhythm during the time that this amount of current is administered; with cessation of current flow, the respiratory movements cease. We have not been successful in restoring responses to painful stimuli, and it is evident that much higher levels of current must be administered to produce even the minimal changes seen in the figure. The general effect of frontally-negative current administered to a deeply anesthetized animal, however, is some apparent lightening of the depth of anesthesia. The differential nature of the results obtained in experiments A and B, depending only upon the polarity of the administered currents, indicates that the results are not due to secondary effects, but are dependent upon the direction of current passage. Other experiments using similar levels of direct current administered transversely across the head have failed to demonstrate any such specificity of action, although delta frequencies are occasionally produced in the EEG of lightly tranquilized animals with 50–60 μA of current so oriented.

C. Administration of modulated direct currents to lightly tranquilized animals (Figure #3).

The production of EEG patterns typical of deep anesthesia by passing frontally-positive direct current appeared to substantiate claims for the production of clinical anesthesia by similarly oriented, but modulated, direct current (21). The modulation utilized is generally a sine wave of 100 c.p.s. superimposed upon the direct current, although the choice of this frequency is strictly empirical. Our observations on the changes in the natural direct current system during changes in consciousness induced by chemical agents had previously indicated certain frequency components, but in the 0.1 to 1 c.p.s. range. It was, therefore, postulated that the internal direct current system was, to some extent, frequency-dependent, and that appropriate modulation frequencies for electronarcosis would be in the 1 c.p.s. -or- lower range. Since it is impossible to record EEG patterns during the passage of the modulated current, electroencephalographic confirmation of the anesthetic state has not been obtained by workers in electronarcosis. In our experiments, a sufficient amount of direct current was passed in a frontally-positive direction to produce delta patterns in the EEG but not obliteration of the higher frequencies. Various modulation frequencies were then added to this basic level, and EEG recordings made within five seconds of the cessation of each modulation frequency, the basic d.c. level being maintained throughout. All frequencies produced potentiation of the direct current effect, as judged by a decrease in the higher EEG frequency. However, this was most evident at the 0.1 c.p.s. range with decreasing effect as the modulation frequency was increased. The neural electronic current system, therefore, does appear to be frequency-sensitive, particularly in the ultra-low frequency range.

It is interesting to note that recent observations of the geomagnetic field have demonstrated the presence of frequency components in the same range. It has even been suggested that these "micropulsations" are somehow connected with the widespread occurrence of similar EEG frequencies in the animal kingdom (22).

D. Exposure of lightly tranquilized animals to transverse magnetic fields (Figure #4).

In the lightly tranquilized animal, the alpha pattern EEG persists during exposure to low values of magnetic field (below 3 kilogauss), regardless of the length of time of exposure. If the field strength is increased over 3 kilogauss, delta patterns become evident in the EEG, and at 3.8 kilogauss they become persistent. Increase in field strength over this value (to a maximum of 5 kilogauss) does not result in an increase in magnitude of the delta pattern, or any other alterations in the EEG. Decrease of the field to values below 3 kilogauss (or to zero) results in a prompt return of the EEG to the pre- existing alpha pattern. There is thus no residual polarization effect as is present after administration of frontally-positive electrical current. Recordings of fronto-occipital d.c. potentials during the same type of experiment show a gradual decrease in the pre-existing negative polarity roughly dependent upon the field strength utilized. Deviation of the long axis of the head from its position transverse (90°)to the flux lines of the magnetic field decreases the effect. While only rough estimates have been made, it appears that positions greater than 20° from the transverse are ineffective in producing the phenomenon. These three observations tend to substantiate the thesis that some type of electronic conduction system is involved. It must be emphasized that the only reasonable explanation for this phenomenon is the interaction between the applied magnetic field and a naturally occurring direct current oriented fairly precisely in a fronto-occipital direction. In theory, a deeply anesthetized animal has had maximal depression of its electronic conduction system, and exposure to a magnetic field should produce no further alterations in its EEG or activity. Experimentation has substantiated this fully, no alteration in EEG being evident, regardless of the field strength used. Technical difficulties prevented the evaluation of magnetic fields modulated at the same frequencies as in the applied current experiments. Theoretically, at least, a potentiation of the effect should be produced. The relationship of this possibility to the aforementioned normal modulation frequencies of the geomagnetic field can only be speculated upon at present.

Conclusions

In the salamander the exposure of the cerebral area to either longitudinal electrical current or a transverse magnetic field resulted in changes in the electroencephalographic pattern. These observations appear to be best explained on the basis of an interaction between the physical force and a pre-existing electronic conducting system within the neural tissue. The neural electronic conduction system in the brain is postulated to be located within midline structures and appears to be causally related to the level of consciousness of the brain as a whole. Decrease in the normal amount of current flowing in the fronto-occipital vector results in a decrease in the level of consciousness as determined by encephalographic patterns and respiratory center functioning. Such decreases are produced by most chemical anesthetics, by the administration of direct current along the same vector with frontally-positive polarity, and by exposure of the animal to a magnetic field of sufficient strength oriented transversely to the current vector. Some reversal of the signs of deep chemical anesthesia can be produced by the administration of current oriented to restore normal polarity (i.e., frontally-negative). The general phenomenon appears to be related to electronarcosis in that the same physiological system is involved. In this case, greater depths of anesthesia were obtained with modulation frequencies in the 0.1 c.p.s. range, rather than with the 100 c.p.s. range presently in clinical usage.

The strengths of the magnetic fields used in these experiments were greatly in excess of the usual strength of the geomagnetic field. However, it must be emphasized that the “end point” used for determining the effects produced in the experiments was the appearance of EEG patterns indicative of major alterations in consciousness. Changes in cyclic patterns in animals or behavioral patterns in humans must be considered to be of an entirely different order of magnitude. The major point of the experiments discussed is that a properly oriented magnetic field of sufficient strength can produce objective changes in the EEG patterns of test animals, and that phenomenon is explainable on the basis of the thesis that has been developed concerning the presence of semiconduction phenomena in neural tissues.

REFERENCES

1. Brown, F. A. Jr., Webb, H. M. & Brett, W. J. Magnetic response of an organism and its lunar relationship. Biol.Bull.118:382-392,1960.
2. Friedman, H., Becker, R. O. & Bachman, C. H. Geomagnetic parameters and psychiatric hospital admissions. Nature, 200(#4907):626-628, Nov. 16, 1963.
3. Liberman, E. A., Vaintsvaig, M. N. & Taofina, L. M. The effect of a constant magnetic field on the excitation threshold of isolated frog nerve. Biofizika, 4:505-506, 1959.
4. Mulay, I. L.& Mulay, L. Effects of a magnetic field on sarcoma 37 ascites tumor cells. Nature, 190:1019, 1961.
5. Becker, R.O. The biological effects of magnetic fields - A survey. Med. Electron. Biol. Engng.1:293:-303, Pergamon Press, 1963.
6. Cardew, M. H.& Eley, D. D. The semiconductivity of organic substances. Disc. Faraday Society, #27, 115-128, 1959.
7. Rosenberg, B., Orlando, R. A.& Orlando, J.M. Photoconduction and semi-conduction in dried receptors of sheep eyes. Arch. Biochem. Biophy., 93:395-396, 1961.
8. Rosenberg, B. Electrical conductivity of proteins. Nature, 193:364-365, 1962.
9. Szent-Gyorgyi, A. Introduction to a submolecular biology. Academic Press, New York, 1960.
10. Becker, R. O. The bioelectric field pattern in the salamander and its simulation by an electronic analog. I.R.E. Trans. Med. Electronics. ME7:202-207, 1960.
11. Becker, R. O. Search for evidence of axial current flow in peripheral nerves of salamander. Science, 134: 101-102, 1961.
12. Becker, R. O. The bioelectric factors in amphibian limb regeneration. J. Bone & Joint Surg. 43-A:643-656, 1961.
13. Becker, R. O. Some observations indicating the possibility of longitudinal charge-carrier flow in the peripheral nerves. Biological Prototypes & Synthetic Systems. Vol. 1, E. E. Bernard & M. R. Kare, Editors. Plenum Press, New York, 1962.
14. Becker, R. O., Bachman, c. H.& Slaughter, W. The longitudinal direct current gradients of spinal nerves. Nature, 196:675, 1962.
15. Gerard, B. W. & Libet, B. Control of normal and "convulsive" brain potentials. Am.J. Psychiat. 96:1125-1152, 1940.
16. Goldring, S. & O'Leary, J. L. Correlation between steady transcortical potential and evoked response. EEG Clin. Neurophysiol. 6: 189-200, 1954.
17. Goldring, S. & O'Leary, J. L. Experimentally derived correlates between ECG and steady cortical potential. J. Neurophysiol. 14:275-288,1951.
18. Becker, R.O., Bachman, C. H. & Friedman, H. The direct current control

system. N. Y. State J. Med.62:1169-1176, 1962.

19. Friedman, H., Becker, R. O. & Bachman, C. H. Direct current potentials in hypno-analgesia. Arch. Gen. Psychiat. 7: 193-197, 1962.

20. Becker, R.O. The direct current field: A primitive control and communication system related to growth processes. Proceedings of the XVI International Congress of Zoology, Washington, D. C,, Aug. 20-27, 1963.

21. Smith, R. H., Goodwin, C., Fowler, E., Smith, G. W. & Volpitto, P. P. Electronarcosis produced by a combination of direct and alternating currents. Preliminary study. Anesthesiology. 22: 163-168, 1961.

22. Stewart, R. M. Structure of conditioned logic nets. Symposium on Bio-Medical Engineering. San Diego, Cal., 1961.