NEUROPHYSIOLOGIC EFFECTS OF RADIOFREQUENCY AND MICROWAVE RADIATION*

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OVER the past five years awareness has been increasing among neurobiologists of ways in which information is processed in brain tissue.[1]

Three lines of recent evidence are sharply at variance with most of what we learned in medical school about information transaction in central nervous tissue. The first line of evidence indicates that cell-to-cell communication between brain cells probably involves only slow waves in much of these interactions. The second is that brain cells sense electric fields in their own environment and that these fields are far below those electric gradients associated with synaptic processes. Specifically, I shall address the apparent role of the oscillating electric fields in the fluid around cells as an element in transaction of information.

The third line of investigation is even more remote from classical biochemistry and physiology of brain tissue, in that it addresses the virtual certainty that at least some classes of information transaction at the surfaces of brain cells involve nonequilibrium processes. Under that impressive term is subsumed the simple concept that we no longer think of ions massively transferred from one side of a membrane to another in the initial steps of excitation, but rather that there are forms of resonant interaction between ions located at binding sites on membrane charge sites, surface macromolecules, and that they "see" one another at considerable atomic

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distances. Given these three lines of evidence that may help us understand some aspects of field interactions with brain tissue, what should we look for in central nervous interactions with an impressed electromagnetic field? First, we should seek a structural substrate in the anatomy of cerebral tissue. Second, we should search for physiological and biochemical effects, and, third, we should seek behavioral correlates.

Possible Anatomical Substrates for Field Interactions with Brain Tissue

In simple nervous systems, such as those that characterize the simplest animals like *Hydra,* there are no "interneurons." A sensory cell is connected directly to a motor cell. There is no opportunity for the plasticity of a changing response that might result from a continuing pattern of stimuli. A typical brain is really a great overgrowth of interneurons interposed between the sensing cell and the motor apparatus. In *Hydra,* for example, there are neuroepithelial cells at intervals in the epidermis. Typically, they connect directly to a muscular apparatus between the external epidermis and the endoderm. By contrast, the brain is constituted of an enormous number of interneuronal cells, and in all vertebrates, particularly in mammals, brain neurons differ from neurons in the rest of the nervous system in that the cortical neuron has a very small cell body and a huge series of branches that we call dendrites, extending out for a vast distance. Dendrites make contact with dendrites in a functional sense and "dendrites speak unto dendrites."[2] It is in this structural substrate that there appears to be at least one elemental aspect of a possible interaction with environmental fields.

The ontogeny of cortical development provides further evidence of the importance of dendrites in cortical tissue. In the human infant brain at birth, cell bodies are widely separated. There is very little dendritic growth. At four months, cell "packing density" is no higher, but dendrites start to grow out. By 15 months there has been a vast proliferation of dendrites, though still incomplete, and those from one neuron make contact with dendrites of other neurons. The older classical concept envisaged a "through" neuronal circuit with a nerve fiber terminal in contact with a cell body (or soma), then carrying a traffic of impulses, and ending in a synaptic terminal on another neuron. That concept is being replaced by one in which there are interactions through dendrites contacting dendrites of an adjacent neuron. In the retina, for example, the activated receptor transmits activity to bipolar cells and horizontal cells and on down to amacrine cells. No impulses occur until activity reaches some of the large amacrine cells and cells in the ganglionic layer that give rise to the optic fibers. Neurophysiologists now speak of a "silent retina," to exemplify that its essential initial transactions do not involve impulses, but only slow, wavelike activity. Similarly, there is slow, wavelike activity in the olfactory bulb. If we look at the way in which dendrites "speak unto dendrites," the synapses are often reciprocal, placed one alongside of each other, with activity passing in opposite directions through adjacent synaptic connections. Evidence of this type is exemplified by the finding that about 60% of cells in cerebral cortex have no long nerve fiber (or axon). They communicate through dendrite-to-dendrite contact. These cells are the majority of neurons in the cortex and are known as Golgi type II cells.

Possible Physiological Substrates of Electromagnetic Field Interactions with Cerebral Tissue

What are the physiological mechanisms on which the environmental field might impinge? As noted above, the electric process between dendrites is one of slow waves, not impulses. The integral of the slow wave activity between dendrites constitutes the electroencephalogram. This can be recorded in the fluid surrounding brain cells, as well as outside the skull.

With sophisticated microelectrode recording, it is possible to place an electrode inside the body of a cortical neuron. It was a surprising finding that in many neurons the baseline of the intracellular membrane potential is not steady. It oscillates in a wavelike fashion, due to waves produced in the dendrites. Only at intervals do we see the production of impulses. When the animal is asleep, the electroencephalogram is slow, as are the waves inside the cell. When the brain is awake, the electroencephalogram is fast, as are the waves inside the cell. One can carry out very complex mathematical analyses showing these relations. The electroencephalogram is produced by the leakage of these big waves inside dendrites into the fluid around the cell. The difference in size is about 200 to 1. The electroencephalogram recorded over the dimensions of the cell is a few microvolts. The neuronal wave inside the cell is of the order of 5 to 15 millivolts. Thus, the difference in amplitudes is about 200 to 1. Firing of the cell is a high order transform of these waves inside the cell. Firing of the cell to produce an impulse is always on the positive going peak of the intracellular wave, but often there are very large waves inside the cell and no impulse is produced.

Given this background, we may conclude that the cerebral neuron has a large dendritic apparatus; its transactional processes involve waves; it transmits waves to other cells; it leaks waves into its own environment.[3] Thus we come down to a critical question. Does the electroencephalogram in the fluid around the cell have an informational content? Do brain cells sense the electroencephalogram around them? Or, as many have said, is the electroencephalogram "the noise of the brain's motor"? If it is only the noise of the brain's motor, then the fields around the head entering the electroencephalogram's domain would be expected to be as ineffective as the electroencephalogram in changing the animal's behavior. If the electroencephalogram does have informational significance, can one induce subtle behavioral changes if one imposes environmental fields that look like the electroencephalogram?

I do not propose to discuss studies that have shown that the electroencephalogram is very finely correlated with behavior. By computer analysis, one can show that there are patterns in individuals that characterize them when they are lying or when they are emotionally disturbed.[4,5] These signatures for the individual are as unique to them as their fingerprints, and they share those signatures with a group of subjects. One can also develop group signatures for the same psychological correlates. However, I shall discuss the electroencephalogram as a phenomenon in tissue and consider how it might relate to fields in the environment impressed on the head.

Let us first consider the levels of typical environmental fields. If we sleep under an electric blanket, the field is of the order of 200 volts per meter. If we walk under a high voltage 60 cycle power line or a DC power line, the field is on the order of 10,000 volts per meter. A hair dryer against the head produces a magnetic field of about 30 gauss, or roughly 100 times the background field. A microwave oven may leak as much as 5 $mW/cm.^2$ at the door. This translates into an electric field of 130 volts per meter. A powerful handy-talkie will produce 130 volts per meter at the head. As Mr. Janes has pointed out, a high background of radiofrequency fields in suburbia is 1 to 4 $\mu W/cm.^2$, 2 to 4 V/m. I shall stress volts per meter as the parameter in the environment because this translates to tissue gradients in volts per centimeter, which gives a measure of potential ability to excite brain tissue.

Some tissue sensitivities to environmental electric fields are extremely high. Sharks and rays navigate and exhibit predation in fields of one hundred millionth of a volt per centimeter. Nevertheless, this sensitivity is not anomalous in terms of normal tissue thermal noise produced by molecular collisions, and appears to relate to properties of cell membrane surface electric fields. These fields limit the speed of ion movements along the membrane surface, and thus may diminish interfering effects from thermal agitation. Moreover, this electric field sensitivity of sharks and rays lies in an intensity "window." The upper limit of the window is about 100 times the threshold strength. Above this, the phenomenon disappears. It is limited in the frequency window DC to 10 Hz.[6]

Migrating birds cut diagonally across the horizontal component of the earth's magnetic field. It has been suggested that nodding of their heads has something to do with this sensitivity. It is of the same order as in sharks and rays, 10^{-7} V/cm. Circadian rhythms in birds, subjective time estimates in monkeys, and circadian rhythms in man appear similarly sensitive.[7,8] These are extremely weak gradients by comparison with the size of natural electric phenomena in nerve tissue. The membrane potential is 100,000 V/cm. A synaptic potential changes the membrane potential by 1,000 V/cm. The electroencephalogram is 0.1 V/cm., measured over the dimensions of a single cell. One would assume that this gradient is so small at 0.1 V/cm. that there was no way for it to modify directly the excitability of the cell through its effect on the membrane potential. It certainly could not unless there were certain amplifying mechanisms. I shall address some relevant physiological models.

Sharks and rays have tubular electroreceptors, the ampullae of Lorenzini, on their heads. These tubes have a high wall resistance. This rapidly attenuates responses at increasing frequencies of field oscillation. The mechanism is known to be used in orienting, navigating, and searching for prey.

Wever in Germany has done interesting experiments in human subjects in underground chambers. Shielded from weak environmental electric fields, the free-running 24-hour cycle has a period as long as 26.6 hours in some subjects. Imposition of a 10 Hz., 2.5 V/m. field, which produces about 10^{-7}/V/cm. in the tissue, caused the rhythm to change back toward 24 hours. Turning the field off again after eight days was then followed by cycles lasting 36.7 hours, as measured by sleep and wakefulness.

It may be argued that perhaps there were cues for man in those chambers. The experiment was therefore repeated with birds and, again, in the presence of the 10 Hz., 2.5 V/m. field, the bird's daily activity was locked around 24 hours. When, after 10 to 15 days, the field in the shielded chamber was turned off, the diurnal rhythm became substantially longer. The effect reversed when the field was restored. It is clear that the environmental field in the shielded chamber provided some essential stimulus for maintenance of normal circadian rhythms.

Experiments in our own laboratory have shown an influence of similar weak fields when they are imposed across the chamber in which a monkey is sitting. They affect its ability to estimate the passage of time in the absence of external cues. A 5.0 second estimate brings an apple juice reward. The estimate of 5.0 seconds is reduced by about 0.5 seconds by a 7.0 Hz. field of 56 V/m. At 10 Hz. the effect is less. A 10 V/m. field has less effect and a 1.0 V/m. field produces virtually nothing. The Illinois Institute of Technology Research Institute has measured total current induced by a 10 V/m., 7 Hz. field in a phantom monkey head at 0.9 nA. From this we conclude that the tissue gradient is of the order of 10^{-7} V/cm.

We have done much work with 147 MHz. VHF radio fields and with 450 MHz. microwave fields. We have an anechoic microwave chamber set up for 450 MHz. First, I shall discuss some electroencephalographic experiments with metal electrodes implanted in the brains of cats. This is not now considered to be good engineering practice, but from spectral analysis of electroencephalographic trainings we conclude that the presence of the metal wires in the brain did not significantly contribute an artifact to the records. From the spectral analysis it is clear that the radio signal at the electrodes was less than 0.1 μV, or 200 times less than the electroencephalographic signal.

In animals and man EEG records tracings from deep brain structures normally exhibit spontaneous rhythm patterns. These appear as bursts of waves in different brain structures that last for two to three seconds. Animals can be trained to make these bursts by reward or punishment. For example, if one presents a flash of light, the animal must make that response within two seconds or be "punished." In this punishment the eyes are involuntarily deviated to the opposite side by stimulation of the brain itself. This is unpleasant but not painful. After training for two or three days, presentation of the flash of light is followed by these bursts of waves in about 80% of the tests.[9]

After training in this way, punishment may be omitted. Without punishment, in what are called "extinction trials," performance drops very rapidly in a day or so to the level before training. On the other hand, if the animal is trained in the presence of a radiofrequency signal modulated at the frequency of the particular brain signature, the number of correct responses goes much higher, to over 90%. In the ensuing extinction trials, where no punishment is given, the animal keeps on performing at a level significantly above chance for almost two months in the absence of any punishment. Thus, the presence of the field appears to delay the "forgetting" of the learned habit as well as enhancing correct responding in training trials.

Incident energy of these fields was about 0.8 mW/cm.[2] Tissue dosimetry indicates that the field included an electroencephalographic level gradient in brain tissue, about 0.1 V/cm. No significant heating of tissue was involved.

In the context of these experiments, it should be mentioned that there is a medical therapeutic device, known as the LIDA, developed in the Soviet Union and patented in this country. It is designed for the treatment of psychoneurotic illness and emotional disorders. It emits pulsed radio signals up to one tenth of a second long at rates up to two per second, with a maximum generator output of 40 to 80 watts. The instrument can also generate pulsed light, sound, and heat, and the four stimulus modalities can be delivered separately or in any desired combination. Reports of clinical tests in the U.S.S.R. in juveniles and adults suffering from emotional disorders are said to have been favorable.

Role of Cell Membrane Surfaces in Detection of Weak Electromagnetic Fields

How does the brain sense these fields? The process appears to relate to effects at the surface of the cell where there is a highly organized glycoprotein glue-like material, specialized in places where there are synapses at the surface of the cell and interposed also between the surface of the neuron and the neuroglia. This concept has been developed in detail in the Singer-Nicolson fluid mosaic model.[10] In this model, attention is directed to lipid and protein molecules inserted into the lipid bilayer of the plasma membrane or classic cell membrane. Many of these intramembranous particles have stranded external protrusions negatively charged at their terminations, which are sialic acid molecules. These charged terminals constitute a polyanionic sheet. Thus, the surface of virtually all normal cells is a sheet of negatively charged glycoprotein material that attracts cations, specifically, calcium and hydrogen ions that compete for most of these binding sites. Those two ions are the subject of an elaborate model of excitability and transductive coupling developed by Bass and Moore[11] more than 10 years ago. This interaction of hydrogen and calcium ions on cell-surface glycoprotein strands suggests that this is the site of the first and most sensitive transductive couplings in brain tissue.

The concentration of calcium is high on the outside of the cell (about 2 mM), and low inside in general cytoplasm (10^{-7}M). Calcium ions have been implicated in essentially every step of the transductive coupling of neurotransmitter substances in effects of every step of immunologic reactions and every step of the coupling of hormonal binding at membrane surfaces to cellular mechanisms. Calcium ions appear to hold the key to an understanding of every aspect of cell-surface transduction.

SENSITIVITY OF CALCIUM BINDING IN BRAIN TISSUE TO IMPRESSED ELECTRICAL FIELDS

Field interactions with brain tissue have been assessed by effects on calcium ion fluxes. In our laboratory the effects of electric fields on brain chemistry was first studied in the awake cat. With this method one can stimulate the cortex directly with very large electrodes that produce a relatively uniform electric gradient through the whole cerebral substance. This field can resemble the electroencephalogram in frequency. At the same time, a central well formed by a plastic cylinder over the exposed cerebral cortex can be used to place radioactive tracer substances in contact with the brain. After a period of equilibration, we can examine their efflux back into the well.[12] An electroencephalogram-level gradient imposed on that cerebral hemisphere causes a 20% increase in calcium efflux and a similar increase in the efflux increase in the efflux of the amino acid neurotransmitter gammaaminobutyric acid.

We have estimated the level of that gradient as only 1.0 μV across a synaptic terminal 0.5 μm. in diameter. This field would be less than one ten thousandth of the 50 mV membrane potential of the synaptic terminal. An amplification mechanism would appear necessary for such a weak extracellular field to influence transmitter release from within the synaptic terminal. This led us to examine the effects of weak imposed fields rather than direct stimulation. We tested the effects of sinusoidal extra low frequency (ELF) fields on the isolated chick cerebral hemisphere at a

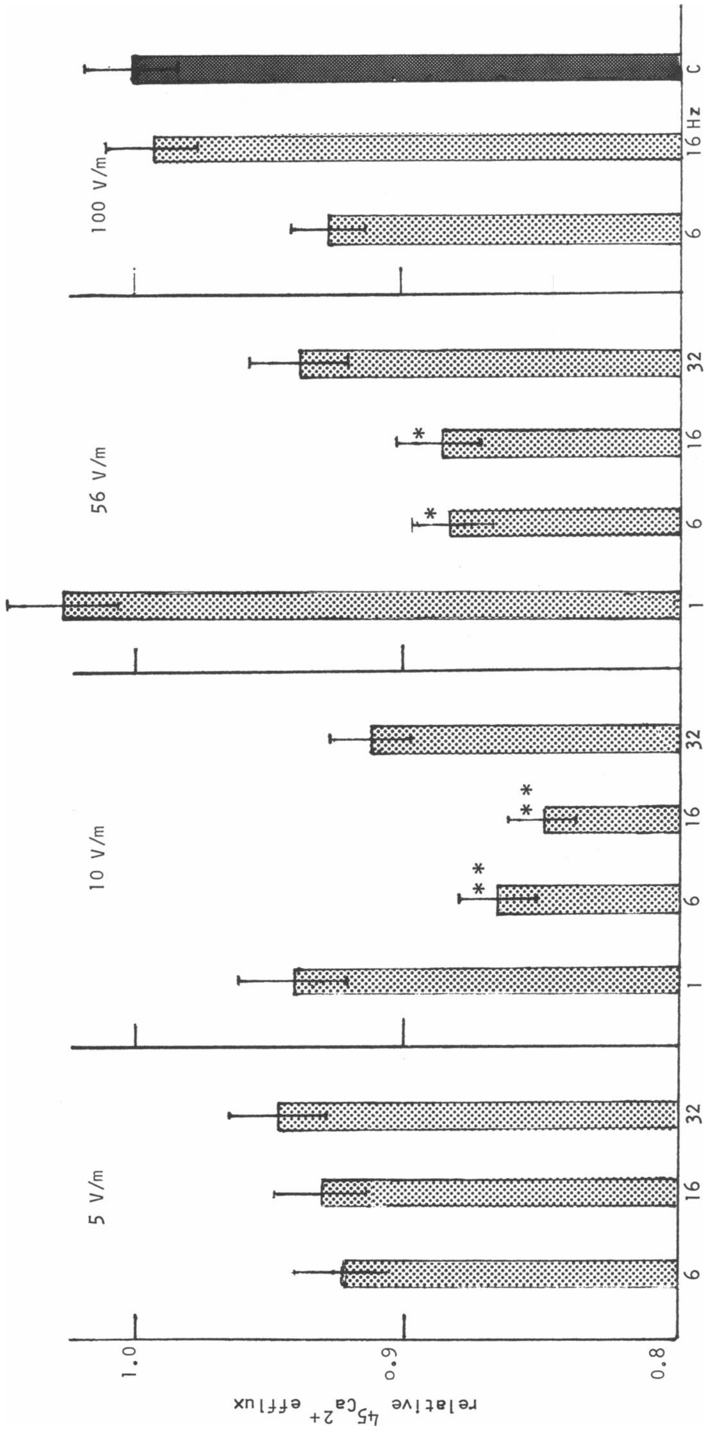

Fig. 1. Effects of extremely low frequency fields on $^{45}Ca^{2+}$ efflux from chick forebrain. The relative $^{45}Ca^{2+}$ effluxes, given ± SEM, are referred to the mean value of control condition (C). *, $p<0.01$ that the mean is the same as that of the control. Reproduced by permission from Bawin, S. M. and Adey, W. R.: Sensitivity of calcium binding in cerebral tissue to weak environmental electric fields oscillating at low frequency. *Proc. Nat. Acad. Sci. U.S.A.* 73:1999-2003, 1976.

number of frequencies from 1 to 32 Hz. and at a number of intensities from 5 to 100 V/m. (Figure 1). At 5 V/m., as compared with the means of control values in all experiments, occurred a nonsignificant reduction in calcium efflux. At 10 V/m. there was a significant reduction in calcium efflux for fields at 6 and 16 Hz. At 56 V/m. a similar reduction was significant at 6 and 16 Hz.[13]

In summary, these studies have disclosed a frequency window between 6 and 16 Hz. and an amplitude window, with significant effects for fields of 10 and 56 V/m., but not for 5 or 100 V/m. This is very suggestive of some form of quantum amplification. An amplifying process is involved. The findings are not consistent with such ionic equilibrium phenomena as those described in the Hodgkin-Huxley model of excitation. Moreover, electric gradients in these cerebral hemispheres were of the order of 10^{-7} V/m., based on measurements of total current induced by similar fields in tissue phantoms.

We repeated these experiments with radiofrequency signals using sinusoidal amplitude modulation from 0.5 to 35 Hz. These radiofrequency fields coupled much more strongly into the tissue. Thus, a 147 MHz., 0.8 mW/cm.^{2} field produces about 50 mV/cm. electric gradient in tissue, or about the same gradient as the EEG. Chick cerebral hemispheres exposed to this field showed a "tuning curve" in relation to modulation frequencies between 0.5 and 35 Hz., but were unresponsive to the unmodulated carrier wave (Figure 2). When modulated between 6 and 20 Hz., there was a highly significant increase in the calcium efflux, but not at higher or lower modulation frequencies. Thus, the modulation frequency becomes a very significant aspect of these interactions.[14]

Next, we searched for and found an amplitude window. The effects were only present when the incident energy of a 450 MHz. field, amplitude modulated at 16 Hz., was between 0.1 and 1.0 mW/cm.^{2} (Figure 3).[15] Using Bassen's tripole probe described at this conference by Mr. David E. Janes, we measured electroencephalogram-level gradients, 50 to 100 mV/cm. Higher and lower intensities were without effect. This amplitude window for radiofrequency fields was first noted by Blackman and his colleagues, who have also confirmed the modulation frequency sensitivity.[16]

Questions have been raised concerning the relevance of these findings in isolated chick cerebral hemispheres to possible sensitivity of intact mammalian brain tissue. In continuing studies we have exposed awake cats

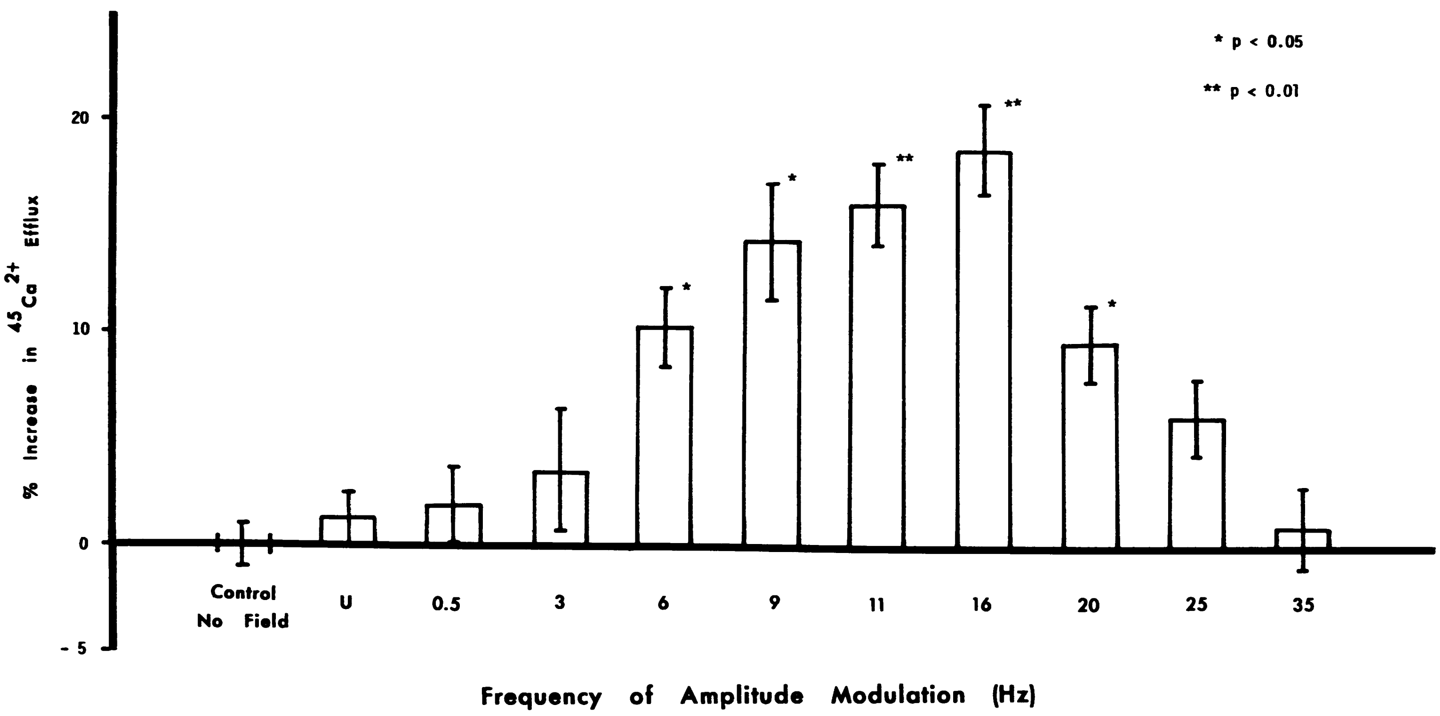

Fig. 2. Effects of amplitude-modulated 147 MHz. fields on the $^{45}Ca^{2+}$ efflux from the isolated forebrain of the neonatal chick. The results, given ± SEM, are expressed as percentage of increase of the calcium efflux, by comparison with control condition, in the absence of fields. *,$p < 0.05$; **,$p < 0.01$. Reproduced by permission from Bawin, S. M., Kazcmarek, L. K., and Adey, W. R.: Effects of modulated VHF fields on the central nervous system. *Ann. N.Y. Acad. Sci.* *247*:74-81, 1975.

under local anesthesia to a 450 MHz. 0.375 mW/cm.^{2} field, amplitude modulated at 16 Hz. In eight of the 12 experiments there was a sharp rise in $^{45}Ca^{2+}$ efflux, with a response curve identical to that obtained by direct electrical stimulation of brain tissue at the same intensity.

Chemical and Physical Models of Interactive Processes

These phenomena appear to belong to a class of events called "cooperative processes," and are characterized by weak triggers at one point in a system producing a major effect at another point. That major effect may occur in immunological reactions, where antibodies on the surface of the cell are bridged back to the surface of the cell with lysis of the membrane. In that example the bridging occurs along elements of complement protein that enclose calcium and magnesium ions. In cooperative processes the system has already spent energy in preparing for this type of event. It is true also for endocrinological reactions, where the arrival of a hormone molecule at the surface of a cell produces a ripple effect that may involve large segments of the cell membrane. For the red cell, ripple effects of this kind can be produced by a very few hormone-mediating molecules, such as prostaglandin. Schwarz[17] has pointed out that energy levels of charge sites on a biopolymer sheet may become identical over considerable distances for periods in the millisecond range. In this condition of identical energy levels, adjacent charge sites are described as coherent. On the cell surface they are sustained in this condition by "pumping" to that energy level from within the cell. We may suggest that the membrane surface would be a functional patchwork of coherent zones separated by a "sea" of incoherent charge states. Calcium ions bound at charge sites within a coherent zone may be released or modified in their binding by very weak triggers from outside the coherent zone. A cooperative process may be initiated which spreads widely across adjacent coherent zones, a process millions of times stronger than the initial triggering event.

Emergent Concerns on Central Nervous Sensitivities to Nonionizing Radiofrequency Radiation.

What concerns should emerge from these studies of central nervous sensitivities to nonionizing radiofrequency radiation? First, that their cooperative character, as revealed by the windows in power and frequency, appears to set certain bounds on the optimal field characteristics for

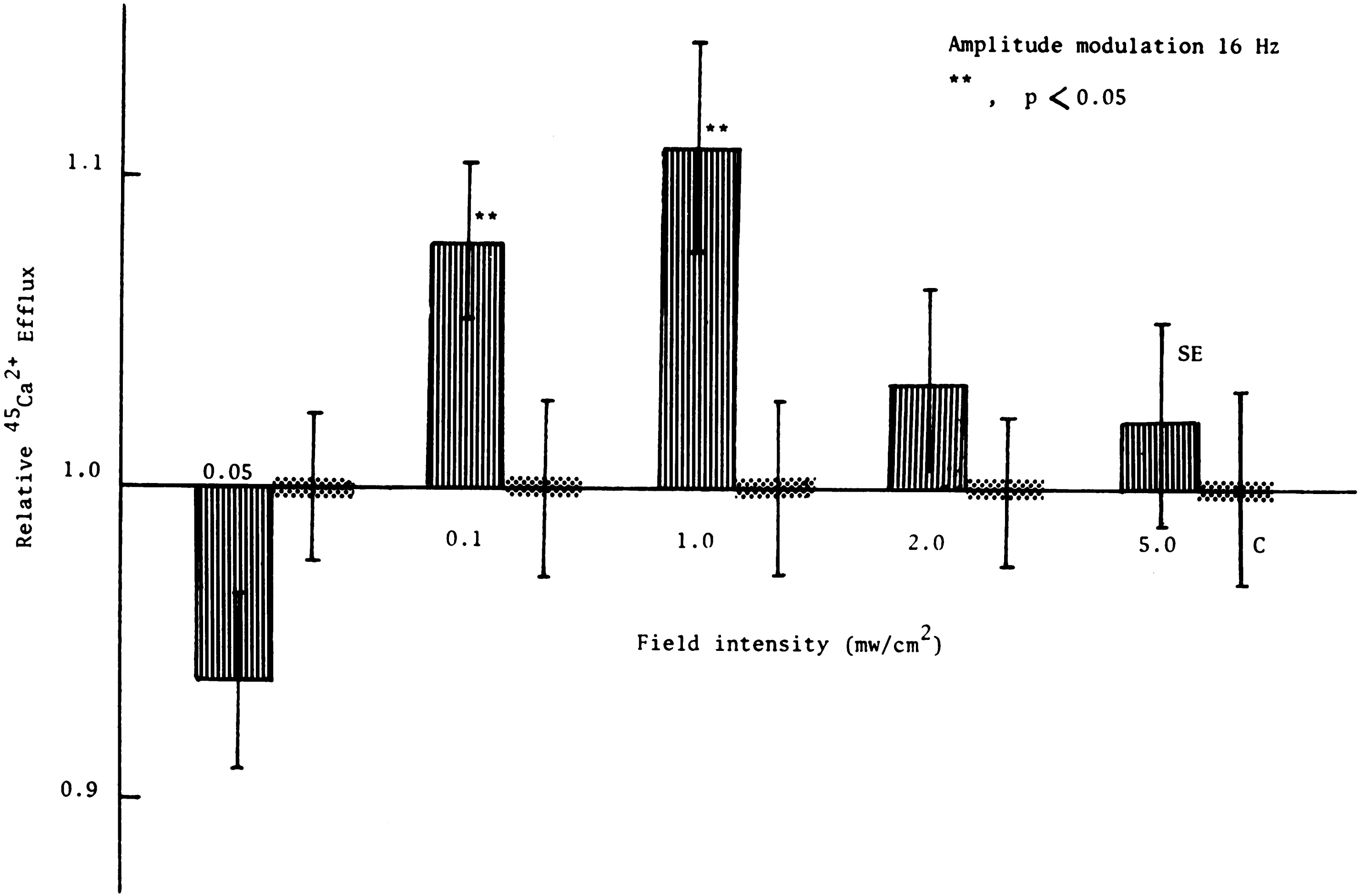

Fig. 3. Effects of changing intensity of 450 MHz. field amplitude modulated at 16 Hz. on efflux of $^{45}Ca^{2+}$ from chick cerebral hemispheres. Cross-hatched bars show levels of efflux from control specimens tested simultaneously in same series of exposures. Variance shows as SEMs. Reproduced by permission from Bawin, S. M., Sheppard, A. R., and Adey, W. R.: Possible mechanisms of weak electromagnetic field coupling in brain tissue. *Bioelectrochem. Bioenerg.* 5:67-76, 1978.

physiological interaction with the brain. Fortunately, communication and power distribution systems have not generally utilized oscillating generators in this range between 1 and 30 Hz., either as low frequency fields or as an amplitude modulation on a radiofrequency or microwave carrier. Some notable exceptions are now appearing and will merit close scrutiny and further research. In any event, groundwork has been laid that strongly emphasizes the potential impact of these specific signals at very low tissue levels, far below levels associated with a nominal thermal threshold around 0.1 C. Future research may indicate that long-term human exposure to signals with these particular low-frequency characteristics should be avoided or carefully controlled.

Our second concern should be to evaluate possible therapeutic applications that may be attributed to these very same modulation characteristics by direct enhancement or modification of intrinsic electrical rhythms that characterize the particular regions of cerebral cortex and vitally important deep brain nuclei. Their correlations with a variety of biological rhythms and behavioral states have become much clearer. Our ability to manipulate them for medical benefit has received little attention and the option is mentioned here in the context that nonionizing electromagnetic fields are not without considerable prospect in the pursuit of human health and relief of suffering from disordered brain funciton.

I suggest that our third concern is much broader. Faced with the overwhelming complexity of the brain as a tissue and as the organ of the mind, physical scientists and medical researchers alike have all too often retreated shamelessly into the classicisms and the argots of their respective trades. Too many physicists and engineers cling desperately to thermal models as the alpha and omega of bioeffects from nonionizing radiofrequency fields, shunning the exquisite beauty of long-range molecular interactions and resonant processes in biological macromolecules. In like fashion, medical physiologists, challenged by phenomena that I have discussed here, have turned away and fixed their eyes with a glassy stare on the comparative crudity of ionic equilibria as the be-all and end-all of excitatory processes as described in the massive ionic exchanges of Hodgkin-Huxley models.

True science can never be a popularity contest. The time has surely come when we should place these scholasticisms of another age in a proper context, counting ourselves thrice blessed at the prospect that through the use of nonionizing radiofrequency radiation as a research tool, the intrinsic organization of brain tissue, the subtleties of neuroendocrine phenomena, and the broad sweep of immunologic interactions may at last be understood in terms of transductive coupling at the molecular level.

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REFERENCES

1. Adey, W. R.: Models of membranes of cerebral cells as substrates for information storage. *BioSystems* 8:163-78, 1977.
2. Schmitt, F. O., Dev. P., and Smith, B. H.: Electronic processing of information by brain cells. *Science 193:*114-20, 1976.
3. Elul, R.: The genesis of the EEG. *Int. Rev. Neurobiol.* 15:227-72, 1972.
4. Walter, D. O., Kado, R. T., Rhodes, J. J., and Adey, W. R.: Electroencephalographic baselines in astronaut candidates estimated by computation and pattern-recognition techniques. *Aerospace Med. 38:*371-79, 1969.
5. Berkhout, J., Walter, D. O., and Adey, W. R.: Alterations of the human electroencephalogram induced by stressful verbal activity. *Electroenceph. Clin. Neurophysiol. 27:*457-69, 1969.
6. Kalmijn, A. J.: Electroperception in sharks and rays. *Nature 212:* 1232-33, 1966.
7. Wever, R.: Human circadian rhythms under the influence of weak electric fields and the different aspects of these studies. *Int. J. Biometeorol. 17:*227-32, 1973.
8. Gavalas-Medici, R. and Day-Magdaleno, S. R.: Extremely low frequency, weak electric fields affect schedule-controlled behaviour of monkeys. *Nature 261:*256-58, 1976.
9. Bawin, S. M., Gavalas-Medici, R., and Adey, W. R.: Effects of modulated very high frequency fields on specific brain rhythms in cats. *Brain Res. 58:*365-84, 1970.
10. Singer, S. J. and Nicolson, G. L.: The fluid mosaic model of the structure of cell membranes. *Science 175:*720-31, 1972.
11. Bass, L. and Moore, W. J.: A Model of Nervous Excitation Based on the Wien Dissociation Effect. In: *Structural Chemistry and Molecular Biology*, Rich, A. and Davidson, C. M., editors. San Francisco, Freeman, 1968, pp. 356-68.
12. Kaczmarek, L. K. and Adey, W. R.: Weak electric gradients change ionic and transmitter fluxes in cortex. *Brain Res. 66:*537-40, 1974.
13. Bawin, S. M. and Adey, W. R.: Sensitivity of calcium binding in cerebral tissue to weak environmental electric fields oscillating at low frequency. *Proc. Nat. Acad. Sci. U.S.A. 73:*1999-2003, 1976.
14. Bawin, S. M., Kazcmarek, L. K., and Adey, W. R.: Effects of modulated VHF fields on the central nervous system. *Ann. N.Y. Acad. Sci. 247:*74-81, 1975.
15. Bawin, S. M., Sheppard, A. R., and Adey, W. R.: Possible mechanisms of weak electromagnetic field coupling in brain tissue. *Bioelectrochem. Bioenergetics. 5:*67-76, 1978.
16. Blackman, C. S., Elder, J. A., Bennane, S. G., Weil, C. M., and Eichinger, D. C.: Two factors affecting the radiation-induced calcium efflux from brain tissue. International Union of Radio Sciences, *Symposium on Bioeffects of Electromagnetic Waves*, Washington, D.C., 1977. *Radio Sci.* In press.
17. Schwarz, G.: A basic approach to a general theory for cooperative intramolecular conformation changes of linear biopolymers. *Biopolymers 5:*321-24, 1967.