

EFFECTS OF MODULATED VERY HIGH FREQUENCY FIELDS ON SPECIFIC BRAIN RHYTHMS IN CATS

S. M. BAWIN, R. J. GAVALAS-MEDICI AND W. R. ADEY

Department of Anatomy and Brain Research Institute, University of California, Los Angeles, Calif. 90024 (U.S.A.)

(Accepted January 25th, 1973)

SUMMARY

The effects of exposures to low intensity (1 mW/sq.cm or less), very high frequency (VHF) (147 MHz) electrical fields, amplitude-modulated at biological frequencies (1-25 Hz), were studied on untrained and conditioned chronically implanted cats. The fields were applied between two aluminum plates (identical voltages, 180° phase shift) firmly anchored to the floor of an isolation booth, especially designed for use of VHF fields. The animals were restrained in a hammock, the longitudinal axis of the body kept parallel to the field plates. EEG and EOG were recorded through a system of low pass filters on a Model 6 Grass electroencephalograph and an Ampex FR 1100 tape recorder; behavior was continuously observed through a closed circuit TV.

A series of animals was operantly trained to produce specific transient brain rhythms following periodic (every 30 sec) presentations of a light flash stimulus. The levels of performance were established (visual and spectral analysis) during conditioning and extinction schedules for a series of cats submitted to VHF fields amplitude-modulated at the dominant frequencies of the selected transient patterns and for a control group, in the absence of fields. The irradiated animals differed markedly from the control group in the rate of performance, accuracy (in terms of frequency bandwidth) of the reinforced patterns and resistance to extinction (minimum of 50 days *versus* 10 days).

The specificity of the frequency of the modulation was tested on another group of untrained animals where spontaneous transient patterns were used to trigger for short epochs (20 sec following every burst) the VHF fields amplitude-modulated at various frequencies. The experimental results indicated clearly that the fields were acting as reinforcers (increasing the rate of occurrence of the spontaneous rhythms) only when modulated at frequencies close to the biologically dominant frequency of the selected intrinsic EEG rhythmic episodes.

Various possible routes of interaction between the external fields and the CNS are discussed, and the hypothesis is offered that the amplitude-modulated VHF fields could influence the excitability of neuronal membranes.

INTRODUCTION

The damaging effects of ionizing electromagnetic radiations on biological systems have been intensively studied since the turn of the century. Little attention has been paid to the other end of the spectrum where radiations have millimetric to kilometric wavelengths. A new interest in possible implications of prolonged exposure to radio-frequency radiations arose from the rapid development of high powered equipment that followed World War II and the consequent widening of its domain of application (military, medical, industrial and scientific). During the past 25 years, numerous investigations have been made with fields mainly in the micro-wave range at intensities from 1 to 100 mW/sq. cm on humans, animals and protein suspensions *in vitro*.

A wide range of effects have been reported, including severe damage to the lens of the eye and to the testes, decreased amino acid incorporation in testes and liver, alterations in electrophoretic, immunologic and enzymatic activities of proteins, disintegration of myelin and denaturation of the collagen in the peripheral nervous system, disturbance in the vegetative nervous system, various cardiovascular changes and behavioral reactions such as avoidance, struggling or hypoactivity. These have been attributed mainly to thermal effects. Even the phenomena of pearl-chain formation in protein cultures and orientation of micro-organism in the presence of electromagnetic fields^{21,51} have been subjected to criticism and re-evaluation on grounds that they may be attributable to heating.

There is persistent controversy over thermal *versus* non-thermal effects, even though there is no clear evidence of biologically significant temperature changes in tissues exposed to low level irradiations in the radio-frequency range. Effects have been reported in low to moderately high levels of irradiations, where the fields did not obviously interact with the biological material via the thermal route for auditory responses^{15,40,41,52}, brain stem and cortical evoked responses^{16,54}, changes in reaction time in humans and animals^{18,20,27,34,59}, escape reactions in birds⁶¹⁻⁶³, dogs and cats^{35,36}, hypoactivity in rats^{12,28,29,33}, and alterations of conditioned responses^{24,59,60}.

Very few studies have dealt with the effects of electromagnetic fields on brain wave patterns. Much of the pertinent work has been done by Soviet and East European investigators. Their results as presented in translation are often obscure and generally refer to short latency synchronization of the cortical EEG^{3,4,8,19,25,26,53}. To the best of our knowledge, Gavalas *et al.*¹⁸ were the first to report specific changes in brain electrical activity of monkeys subjected to low level, low frequency electrical fields (7 Hz sine waves, 2.8 V p-p applied between large metal plates placed parallel and 40 cm apart). In addition to behavioral changes (shifts toward shorter inter-response times), spectral analysis of EEG samples taken after 3 or 4 h of exposure

revealed power peaks at 6–8 Hz in some specific brain locations (hippocampus, amygdala and centrum medianum). These pioneer studies strongly suggest that very low power electric fields are able to enhance or drive specific brain rhythms.

From the survey of the available literature it appears that the pulse repetition rate (or the frequency of carrier wave modulation) of high frequency radiation is a very important parameter among the field conditions eliciting behavioral and CNS effects. The results described in Gavalas' experiment were best developed after several hours of exposure. As a means of possibly reducing the time of exposure for a reliable, detectable change to occur, we decided to use weak VHF fields (147 MHz, intensity less than 1 mW/sq. cm) amplitude-modulated over a wide, low frequency range (0–30 Hz).

The possible impact of these electric fields amplitude-modulated at various biological frequencies was tested on conditioned (experiment I) and spontaneous (experiment II) transient EEG patterns.

MATERIAL AND METHODS

(A) Implantation of recording electrodes

Twelve adult female cats were chronically implanted with bipolar electrodes. The electrodes consisted of two parallel wires (enamelled stainless steel, 33-gauge, Driver Harris Co.) glued on a nichrome strut (20-gauge) and insulated with EpoxyLite (The EpoxyLite Corporation, South El Monte, Calif.) through 10 baking periods of 20 min (170 °C). The wires were cut 3–4 mm from the end of the strut and insulation stripped from the tip to provide a recording surface.

The implantation of electrodes was carried out stereotaxically under pentobarbital anesthesia (30 mg/kg body weight, i.p.). The electrode coordinates were chosen from Snider and Niemer's⁵⁶ stereotaxic atlas of the cat brain. Bipolar electrodes were implanted in the caudate nucleus (CdN), amygdala (Amyg), nucleus ventralis anterior of the thalamus (VA), centrum medianum (CM), hippocampus (Hipp), midbrain reticular formation (MBRF) and presylvian gyrus (PSG). Stainless steel screws were inserted through the cranium to make light contact with the dura mater. Two enamelled wires for monitoring eye movements were tied to the orbicularis oculi muscle on each side and led subcutaneously to the connecting plug on the skull. The animals were sacrificed at the end of the experiment, the brains fixed in formalin and cut in sections 80 μ m thick for identification of the electrode positions.

(B) VHF fields exposure techniques

An isolation booth (2.4 m \times 2.4 m \times 2.0 m) has been designed especially for use with VHF test fields. It was built with a frame of wood and covered inside and outside by No. 10 mesh copper screening. Lighting was provided by three 12 V, 25 W lamps, supplied by a 12 V battery (situated outside the room); light intensity was adjustable from the outside. Adequate ventilation was provided by a 2400 liter/

min blower forcing air into the booth and by a 1500 liter/min blower serving as a suction fan. A closed circuit TV camera was mounted on the wall of the room to allow behavioral observation of the animals. Power supply, transmitter and modulation function generator were located outside the shielded room. The power supply was designed to provide modulated high voltage to the transmitter (Viking 6 N 2, E. F. Johnson Company, Waseca, Minn.). The function generator (Model 202A, Hewlett Packard, Palo Alto, Calif.) provided sine waves for amplitude-modulation of the VHF carrier wave.

The fields were applied between two aluminum plates (area 4100 sq. cm) firmly anchored to a wooden board attached to the floor in the center of the screened room. The flared configuration of the plates aimed at a uniform distribution of the applied voltages. The unbalanced coaxial transmission line from the transmitter was coupled to the plates by means of a 'balun' (coaxial cable, half a wavelength long) connecting the feeding point of one plate to the other, so that identical voltages were applied to the two plates with a 180° phase shift. A delta system of impedance matching minimized the standing-wave ratio on the transmission line and associated reflection of energy toward the transmitter. The transmitter output, at 147 MHz, was monitored by an inline wattmeter (Bird Electronic Corporation, Cleveland, Ohio, Model 43 Thruline). The output of the unmodulated VHF carrier was adjusted to provide adequate power on the field plates (maximum 1 mW/sq. cm) after deduction of the estimated losses in the room (40% of the total power output). Modulation percentage (up to 90%) of the VHF field was measured with a Tektronix type 360 indicator, connected through a diode detector to a wire loop (2 mm diameter) mounted on the wall inside the screened room. All lines were brought in and out of the booth through low pass filters of the 'feed through' type (approximately 120 dB attenuation at 147 MHz).

A wooden frame (a replica of a Horsley-Clarke stereotaxic apparatus) was mounted on a table between the field plates. The ear bars were used to restrain the animals. They were fitted in a cylinder cemented at the front of the implant, thus avoiding any painful pressure in the ear canals. The animals were free to sit or lie but no lateral movement of the head was possible. Microdot cables (Microdot Corporation, Pasadena, Calif.) connected the plugs attached to the skull to a board fixed in the ceiling of the booth. The lines were filtered as they exited from the roof and were then fed through another set of low pass filters, first into a Model 6 Grass electroencephalograph, then through R6 reverters into an Ampex FR 1100 tape-recorder.

(C) Testing protocols

Experiment I: effects of electric fields on conditioned brain patterns

To minimize interferences with the VHF fields, due to behavioral responses and/or gross body movements, we decided to directly condition specific patterns in specific brain locations, and to consider the overt behavior as a correlate of the conditioned responses^{7,13,14,57,58}. The animals were trained in an operant conditioning procedure with a negative reinforcement (electrical stimulation) applied directly

in the brain (frontal eye field of the PSG) as the unconditional stimulus (US). This US appeared unpleasant, although behaviorally, it produced only ocular movements^{43,46,50,67}. The patterns to be manipulated by means of operant reinforcement were selected during movement free periods, in order to place some limitation on behavior³⁹.

The operant schedule was first tested on two animals to maximize the efficiency of the procedure which was subsequently applied to 5 other cats.

The training paradigm consisted of a series of 100 flashes presented at fixed intervals (30 sec), followed (2.5 sec later) by electrical stimulation of the frontal eye field. The flashes (1 μ m sec, $18 \cdot 10^6$ beam candle) were delivered by a Strobotac type 1531-A (General Radio Co., Concord, Mass.) located in front and on the left (45° angle) of the fixed animal's head. A Grass stimulator (Model S4, Grass Instrument Co., Quincy, Mass.) coupled to the brain tissue through an isolation transformer (General Radio GR 587A), was used for stimulation of the frontal eye fields. The stimulator output was manually controlled by a switch. The stimulus was applied for 400 msec at a frequency of 400 pulses/sec. The duration of the pulses was 0.5 msec and the intensity of the current, measured with a 10 Ω series resistance was in the range of 300–500 μ A⁴⁶.

The patterns to be reinforced were selected from any one of the brain locations surveyed, during two control sessions of 50 min each (days 1 and 2). This selection was somewhat arbitrary. However, the same general principles were applied in each case: (a) the rhythms were always visually detectable from the background electroencephalographic activity; (b) the frequency bandwidth of the signals was narrow (desirably less than ± 2 Hz from the dominant frequency); (c) assuming a mean duration of 0.5 sec, the probability that at least one burst would be present in any 2.5 sec interval was never less than one-quarter. During two other sessions (days 3 and 4), two series of 100 flashes were presented to the animals. The operant response was defined as the occurrence of the selected patterns during the 2.5 sec epochs following the presentation of the flash (CS). The operant level was determined by averaging the number of operant responses from day 4 and day 2 (with a pulse as a flash stimulus marked on the recording). The criterion for conditioning, arbitrarily chosen in advance, required that the conditioned levels of performance at least doubled the pre-conditioning levels of occurrence of the patterns following the flash presentations.

In the first part of this experiment (part A) the animals were trained in the absence of fields during 10 daily sessions of 50 min each. They were then submitted to an extinction schedule (where the flashes alone were presented) during which they were tested every other day. The operant responses were considered extinguished when the performances were stabilized for 3 consecutive sessions at baseline levels.

During the second phase (part B) the animals were first reconditioned, using the same avoidance technique, during 4 sessions. They were then divided into two groups. The first series (2 cats) was overtrained for 6 days in the absence of fields before being resubmitted to extinction. The other series (3 cats) was irradiated continuously within session, with VHF fields amplitude-modulated at the dominant frequency of the par-

ticular EEG response under training, during overtraining and extinction. These animals were tested every 2 days during the first 20 days of extinction and every 3 days thereafter until return to operant levels. Daily performance was assessed by visual analysis of the EEG records. EEG epochs of 2.5 sec were selected for spectral analysis. These records covered 3 phases of training: at initial operant levels (specific rhythm pattern in epochs following the presentation of the flash); during the conditioning sessions (epochs following the US, responses and errors); and during extinction⁶⁹.

The data were processed at the Computing Facility of the U.C.L.A. Center for the Health Sciences (BMDX program IBM 360/91). The spectral resolution was set at 1.0 Hz over the range 0–32 Hz. The autospectra of the various structures surveyed were averaged in groups of 20, for each condition studied, within a particular session. The grouping of these separate epochs thus produced a sufficiently long data train to statistically validate 1.0 Hz spectral resolution for the bandwidth 0–32 Hz. The absolute power densities of each frequency band were normalized to the total power in each structure, and then displayed as 'per cent power' graphs.

Experiment II: effects of electrical fields on spontaneous transient EEG rhythms

Two animals were used in this complementary study. Two different patterns occurring in two different brain locations were selected for each animal in preliminary testing sessions. The selected EEG channels were filtered through two analog frequency-selectors (Universal active filters, Model FS61, Kinetic Technology Inc., Santa Clara, Calif.) externally tuned by coupled RC elements. The attenuation curves, regulated by external resistors, were set at the highest possible resolution (attenuation of 12 dB for frequencies 1.7 Hz away from the dominant rhythm). Triggering levels were experimentally adjusted, so that only clearly visible patterns were detected by the filter (peak of the attenuation curve). Both animals were then subjected to two baseline sessions of 50 min each, in the absence of fields. During the following days, the imposition of the VHF fields, amplitude-modulated at various frequencies, was sequentially triggered by the rectified output of each filter via an intermediate operational amplifier. The fields were applied during the whole length of each burst (minus the inherent filter delay) and during the first 20 sec following it. The occurrence of a second or third burst during the fields-on epochs recycled the chain of events, so that every occurrence was similarly reinforced. A final control was then made, during which neither filter triggered the VHF fields. The integrated filter outputs (negative pulse), recorded together with the ongoing EEG, were measured (in sec) and summed for each session.

RESULTS

Experiment I

(A) Operant conditioning of specific transient brain rhythms

(1) Behavior. All animals followed very similar behavioral patterns during

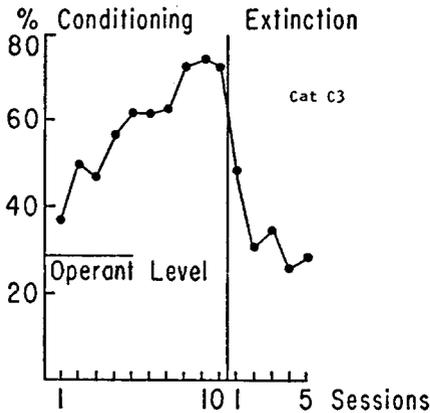


Fig. 1. Performances of cat C3 (centrum medianum—14 Hz) during conditioning and extinction. Data normalized over the total number of CS presentations within session.

their first conditioning and extinction. They rapidly learned to use the intertrial intervals to shift position and relax, while the onset of the flash would immediately stop any behavioral activity for a few seconds. The level of motor activity increased during the first days of extinction. Following that rebound in free behavior the animals started to ignore the CS and progressively shifted from their fixed 'performing' attitude towards complete relaxation, spindle and slow wave sleep.

Learning and extinction curves were practically identical for all animals. Fig. 1 illustrates the level of performance in the case of animal C3 (centrum medianum rhythm) during training and extinction; the data were normalized over the total number of CS presentations within a session. Less than 7 sessions were required for the animals to double their operant levels (criterion of conditioning). They were then overtrained 3 or 4 days, during which the performances stabilized and remained at 70–80% until day 10. The extinction profiles were very sharp in each case. The performances dropped rapidly to baseline levels in less than 6 days (third extinction session).

(2) *Transient rhythms analysis.* The most clearly visible rhythms were found in the visual cortex (cats C1, C2 and C5), the hippocampus (cats C4, C5, and C7) and the centrum medianum (cats C3 and C6).

The fully developed responses exhibited increased amplitude and sharply defined peak frequencies, *i.e.*, 16, 6 and 3 Hz in the visual cortex, 4.5–3 Hz in the hippocampus and 13–16 Hz in the centrum medianum.

Fig. 2 illustrates a conditioned response in the centrum medianum (cat C6) together with its autospectral profile (average of 20 epochs of 2.5 sec each). At the end of extinction, amplitudes were again similar to those during pre-conditioning sessions and the spectral profiles shifted from sharply defined peaks to more or less extended plateaux or to different frequencies.

(B) Effects of amplitude-modulated VHF fields on conditioned brain rhythms

(1) *Behavior.* All 5 animals (as previously mentioned, C1 and C2 were excluded

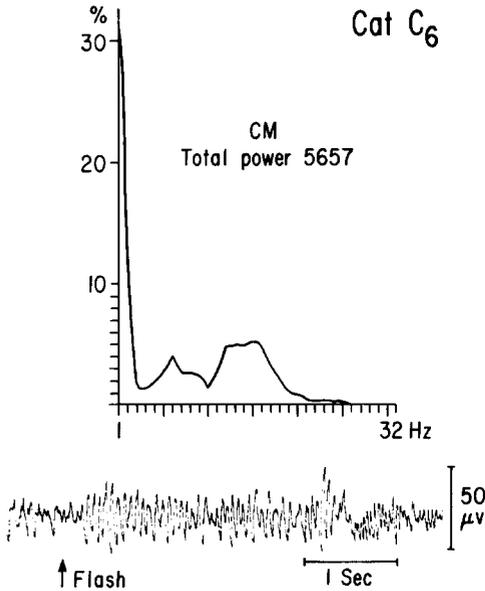


Fig. 2. Centrum medianum patterns and their spectral profile (average of 20 epochs of 2.5 sec each) Cat C6. Conditioning day 10.

from this phase of the experiment) doubled their extinction (and operant) levels in 4 days, at a much faster rate than during the first conditioning.

Two cats (C3 and C7) served as controls and were overtrained (sessions 5–10) then extinguished in the absence of fields. The 3 other animals (C4, C5 and C6) were irradiated with the 147 MHz fields, (amplitude-modulated at 4.5 Hz, 3 Hz and 14 Hz, respectively) during overtraining and extinction.

The two control cats maintained regular levels of performance during the training sessions, but never exceeded their previous achievement. There were long periods of time where the animals would not perform at all due to sleep or inattention. The extinction conducted in the absence of fields was again very rapid. The performances dropped to 40% during the first session. Thereafter, both animals alternated epochs of spindle, slow wave and paradoxical sleep until the end of the experiment (5 sessions, 10 days).

By contrast, the irradiated cats remained quiet but fully awake during the 6 overtraining sessions. The performances presented irregular peaks and eventually all levels were equal if not superior to the highest scores obtained during the first conditioning. These conditions remained unchanged during the first part of the extinction schedule (25 days for cat C4, 40 days for C5 and C6). Drowsiness, slow wave sleep and REM epochs then started to occur at the end of the testing periods until approximately day 55 when this behavior was suddenly replaced again by alertness and restlessness. The animals ceased performing and returned to their behavior at operant levels, characterized by periods of high activity, alternating with epochs of drowsiness. They completely ignored the flash in the last 3 sessions. Fig. 3 compares the recon-

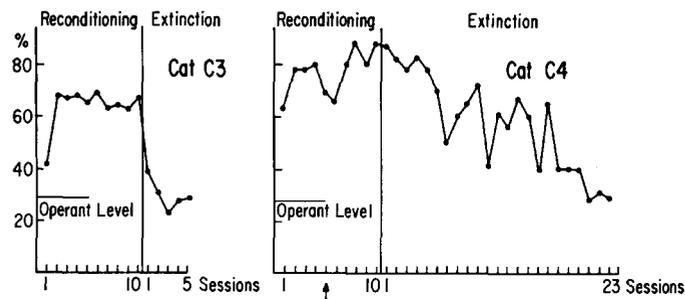


Fig. 3. Comparison of performance of cats C3 (centrum medianum 14 Hz—no field) and C4 (hippocampus 4.5 Hz—VHF field amplitude-modulated at 4.5 Hz) during reconditioning and extinction. Data normalized over the total number of CS presentations within session. The arrow indicates the first day of exposure to the fields.

ditioning and extinction curves of cats C4 (VHF field amplitude-modulated at 4.5 Hz) and C3 (control).

(2) *Transient rhythms analysis.* All patterns were well developed and very similar to the previous fully conditioned response on day 4 of the retraining schedule.

The profile of the response in the two control cats remained stable during overtraining (day 5–10) in the absence of fields. Spectral analysis merely confirmed the visual observations, that is, the peaks of the responses (13–14 Hz in CM, cat C3; 4 Hz in Hipp, cat C7) were still clearly defined but the background EEG activity was slower and of higher amplitude than in the first training schedule. Without reinforcement, these responses extinguished readily, as in the first extinction.

The patterns of the responses of the irradiated animals (C4, C5 and C6) contrasted sharply with the low EEG background activity and the generalized high amplitude seen in the two control animals.

Spectral analysis revealed subtle but very interesting changes in the reinforced patterns of the cats exposed to the fields in the finding of a concentration of power densities around the imposed frequency of the modulation.

Daily controls with the fields amplitude-modulated at different frequencies for short epochs of time and with brief field-off conditions failed to produce any changes or any artifactual patterns in those highly stable responses. No change was ever elicited in the recorded brain activities by application of fields in the absence of conditioning procedure.

Fig. 4 is a comparison of the autospectra of the hippocampal activities of animal C4 in the cases of correct and incorrect responses during irradiation with the fields modulated at 4.5 Hz (peak frequency of the response). It can be seen that the peak shifted away from the imposed frequency when the animal was not performing. The hippocampal responses shifted to 2–3 Hz as the performances returned to operant levels.

The first exposure to the VHF fields, modulated at 3 Hz, produced sharp responses with peaks at 2 Hz in the hippocampus and visual cortex of cat C5. During the following sessions, the hippocampal rhythms shifted towards 3 Hz but the cortical

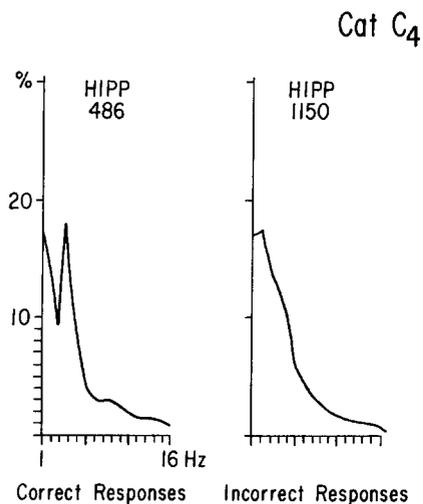


Fig. 4. Comparison of the autospectra (average of 20 epochs of 2.5 sec each) of the hippocampal patterns (cat C₄) in cases of correct and incorrect responses during exposures to VHF fields amplitude-modulated at 4.5 Hz. Reconditioning day 5.

activity remained centered at 2 Hz. Fig. 5 compares the autospectra of the visual cortex and hippocampus in cases of correct and incorrect responses during the fourth day of irradiation.

The reconditioned centrum medianum pattern of cat C₆ was centered around 12 Hz. During the first exposure to the fields modulated at 14 Hz, the response appeared as a plateau between 13 and 15 Hz, and in subsequent sessions, this plateau narrowed to a sharp peak at 14 Hz. Fig. 6 compares the autospectra of the centrum

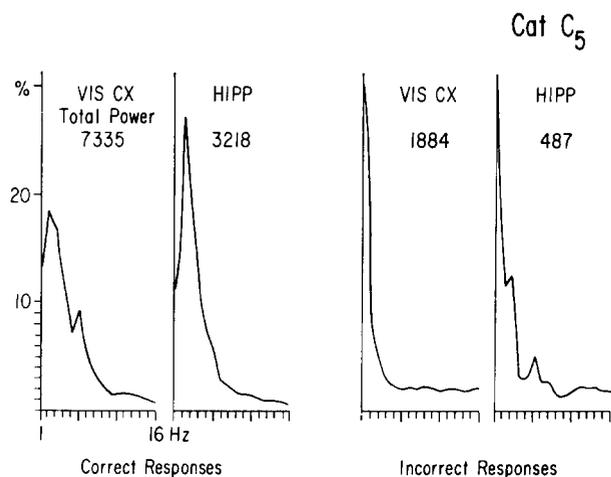


Fig. 5. Comparison of the autospectra (average of 20 epochs of 2.5 sec each) of cortical and hippocampal patterns of cat C₅ in cases of correct and incorrect responses during exposure to VHF fields amplitude-modulated at 3 Hz. Reconditioning day 8.

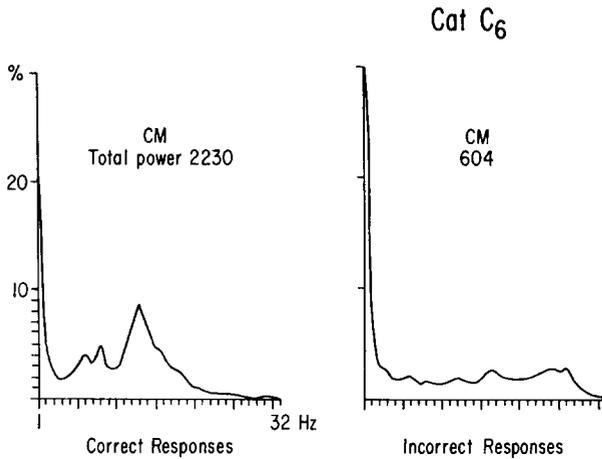


Fig. 6. Comparison of the autospectra (average of 20 epochs of 2.5 sec each) of the centrum medianum patterns of cat C₆ in cases of correct and incorrect responses during exposures to VHF fields amplitude-modulated at 14 Hz.

medianum activities in cases of responses and errors, during the tenth day of the extinction schedule.

Experiment II

Two mutually exclusive rhythms (14 Hz in centrum medianum and 10 Hz in presylvian gyrus, cat R1) and two concurrent patterns (13 Hz in caudate nucleus and 4 Hz in centrum medianum, cat R2) were selected for manipulation in the VHF fields.

Experimental schedules were drawn up for each animal and are presented below.

Cat R1

<i>Session</i>	<i>Experimental condition</i>
1 and 2	Control — no field.
3 and 4	14 Hz filter triggering VHF fields amplitude-modulated at 14 Hz.
5 and 6	10 Hz filter triggering VHF fields amplitude-modulated at 10 Hz.
7 and 8	10 Hz filter triggering VHF fields amplitude-modulated at 3 Hz.
9	Control — no field.

Cat R2

<i>Session</i>	<i>Experimental condition</i>
1 and 2	Control — no field.
3 and 4	4 Hz filter triggering VHF fields amplitude-modulated at 4 Hz.
5 and 6	13 Hz filter triggering VHF fields amplitude-modulated at 13 Hz.
7	Control — no field.

Exposures to 147 MHz VHF fields triggered by spontaneous brain rhythms

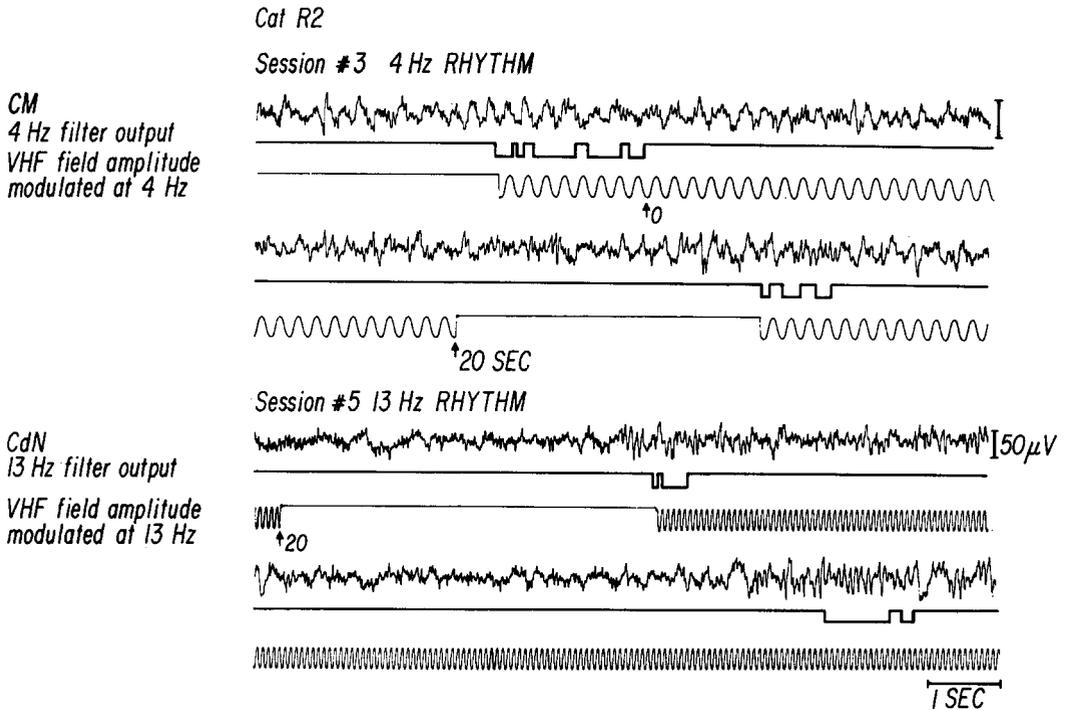


Fig. 7. Selected patterns and mechanisms of reinforcement. Cat R2. Sessions III and V.

Fig. 7 illustrates the two patterns selected in animal R2, together with the integrated filter outputs and the triggered fields.

There were no significant changes in the total filter outputs and in the rates of occurrence of the transient bursts in either cat during the first two control sessions. These values were thus grouped and averaged over the two days for each animal.

Both animals reacted similarly to the imposition of the fields, even though the experimental conditions were purposely made different:

(1) Two fields-on sessions were required before substantial, reliable changes from the baselines occurred.

(2) The shifts from one modulation frequency to another (session 5) induced temporary increases in the previously enhanced rhythms (14 Hz in cat R1, 4 Hz in cat R2) which disappeared during the second exposure to the new modulations.

(3) The following increases of the total filter outputs (in sec) of the reinforced patterns were due to increases of the rates of occurrence of these rhythms; the mean durations of the bursts remained unchanged.

(4) The mean lengths of the fields-on epochs increased steadily with the performances (in terms of the number of spontaneous bursts) of the animals.

(5) During the last session, in the absence of fields, all outputs returned to the previous control values.

VHF field as an Operant Reinforcer
 Centre Median - 14 Hz
 Pre-Sylvian Gyrus - 10 Hz

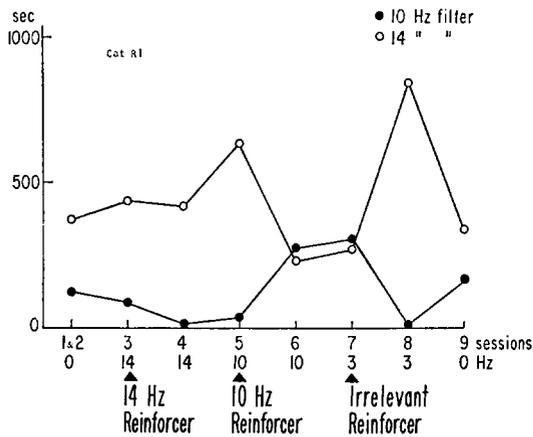


Fig. 8. Selective reinforcement of intrinsic EEG rhythmic episodes by VHF fields. Cat R1. Experimental conditions: no field (0), VHF fields amplitude-modulated at 14 Hz, 10 Hz and 3 Hz (see text).

The imposition of the fields modulated at a frequency (3 Hz) different from the triggering one (10 Hz, cat R1, sessions 7 and 8) lead to dramatic decrease of the 10 Hz rhythm (presylvian gyrus) and increase of the non-reinforced patterns (14 Hz, centrum medianum). These results provided strong evidence that the modulation was indeed responsible for enhanced and decreased occurrence of rhythm seen in previous sessions. This experiment was not repeated with the second animal since, in this case, both rhythms were present at the same time in the EEG and still selectively reinforced by the two different modulations with performances identical to those seen in cat R1.

Fig. 8 illustrates the experiment for cat R1. The total time recorded for each filter during each session is shown on the ordinate. The experimental conditions for each day are symbolized on the abscissa by the symbols: 0 (no fields), 10 Hz, 14 Hz and 3 Hz (frequency of the amplitude-modulation).

DISCUSSION

The experimental data indicate that low level VHF fields, amplitude-modulated at specific frequencies, produce marked effects on conditioned specific brain rhythms (enhanced regularity of the patterns, sharpening of the spectral peaks around the central frequency of the response, extremely prolonged resistance to extinction). These effects cannot be attributed to the conditioning procedure, since the results started to diverge from the two controls only after imposition of the fields. Nor can they be attributed to the choice of brain location (and/or task) since the two control cats were conditioned to produce responses similar to those of the irradiated animals. The innumerable tests conducted within every session (variation of the frequencies of modula-

tion and field-off conditions imposed for short epochs), the sharp contrasts in the EEG between correct *versus* incorrect responses, the finding that the specific activities were localized in the structures subjected to reinforcement together with the eventual return to baselines, strongly suggest a genuine biological transduction in the CNS, which could be described as an enhancement of frequency-related biological rhythms.

The results obtained in the second experiment indicate that it is indeed possible to selectively enhance various brain rhythms by reinforcing their spontaneous occurrence with short irradiations by the fields, amplitude-modulated at appropriate frequencies. Therefore, the hypothesis is offered that the fields were acting as effective contingent reinforcers in both experiments.

The shielding wires were continued up to the animal's head, leaving only very short lengths of unshielded conductor between the leads and the brain. Therefore, they provided adequate attenuation for the fields picked up by the inner conductor. Also, taking into account the considerable mismatch of impedance between recording cables, electrodes and brain tissue, we concluded that the antenna effects on the leads could induce only very small potentials at the tip of the electrodes.

Nevertheless, spectral analysis might be expected to reveal residual voltages so induced and rectified at the electrode-tissue contact. Such effects would be expected to appear uniformly at all electrodes and to be present, unchanged, during the fields exposure.

In fact, no evidence of generalized or sustained artifact was seen in any animals. The EEG changes reported here were anatomically localized, highly specific in terms of frequency and associated with transient patterns. Therefore, we feel confident that the tissue effects are not attributable to direct injection of field voltages via electrodes.

The possibility of thermal effects due to overall or local heating seems equally remote. First, the fields intensities used in all experiments were of the order of 1 mW/sq. cm of field plate area, or less. The heat production resulting from exposures to incident power density of this order has been estimated to be less than 10% of the average basal metabolic rate and therefore almost insignificant³⁷. Secondly, theoretical calculation of the distribution of heating potentials induced by electromagnetic energies have shown that 'hot spots' were generated inside conducting spheres (5 cm radius, electrical characteristics similar to those of biological tissues) only for frequencies well above 250 MHz, the maximum effects being seen around 900 MHz³⁰. Third, diffuse heating could hardly explain the prolonged resistance to extinction followed by return to baseline in the conditioned animals and the selective increase of the rate of occurrence of spontaneous transient EEG rhythms.

On the other hand, it is clear that these effects may have been mediated via peripheral receptors. The current controversy regarding peripheral *versus* central receptors cannot yet be resolved. It can only be stated that we do not yet know of transducers that could relay specific information about the frequency of the modulation of the VHF fields, only to localized brain structures involved in frequency related activity. Destruction of visual, olfactory, vestibular and auditory inputs, or hypothalamic and thalamic (posterolateral ventral nucleus) lesions and sections of the spinal cord at the level of C1 have been reported to be without significant influence

on the observed fields effects^{5,16,26}. Evoked responses in the cortex of the dog⁵⁴ and in the cat's brain stem¹⁶ were elicited by pulsed electromagnetic exposure. In the latter case, the response was abolished by careful shielding of the head alone. These experimental findings seem to be in favor of a more direct action of the fields upon the CNS.

Nevertheless, Schwan⁴⁹ calculated (by direct application of Laplace's equation) the potential evoked across a biological membrane by microwave fields perpendicular to the nerve axis. He found values 10^5 – 10^6 times smaller than the resting potential and therefore concluded that 'according to all modern concepts of neurophysiology about excitation, this just cannot stimulate nerves'. It is not clear, however, what was meant exactly by stimulation or excitation of a biological membrane. The fact that extracellular electrical fields influence the activity of adjacent neurons has been repeatedly evidenced during the past 15 years. For example, Terzuolo and Bullock⁶⁴ showed that extracellular voltage gradients as low as 1 mV/mm alter firing rate in the stretch receptor neurons of the crayfish and Nelson³⁸ reported comparable findings in the spinal motoneurons of the cat. In Nelson's study, the estimated external field strength was of the order of 5–10 mV/mm and short latency facilitation was observed in the single motoneurons tested during synchronous antidromic stimulation of many adjacent neurons. The author suggested that neuronal geometrical organization, as seen in the cerebrum and the hippocampus, could be much more favorable for electrical interaction between cells or groups of cells than the amorphous arrangement of spinal cord neurons. For the whole organism, Rommel and McCleave⁴⁴ have reported that a DC gradient as small as $6 \mu\text{V}/\text{cm}$ is an effective conditional stimulus in the eel, again raising the question of central *versus* peripheral receptors.

There is evidence in the literature that slow potentials, originating in neurons, may combine extracellularly to form electroencephalographic signals. Prominent extracellular positive potentials were recorded synchronously with long latency, long duration, postsynaptic potentials evoked in thalamic neurons during recruiting responses⁴². These positive waves were attributed to the summation of postsynaptic potentials of the involved neurons. Slow membrane fluctuations (3–5 Hz; 5–36 mV) synchronous with the electroencephalographic theta rhythms were observed in pyramidal hippocampal neurons¹⁷. Similar fluctuations were observed in cortical neurons of the cat by Elul^{9,11}. The spontaneous variations of the resting potential were found to resemble and parallel the EEG recorded in the same area (sensorimotor cortex). The amplitude distribution of the EEG was found to follow a normal curve while the neuronal distribution was definitely non-Gaussian. This seems to indicate that the neuronal generators involved in the formation of the local EEG are independent or at least non-linearly related. On the other hand, brief periods of EEG synchronization during spindle sleep and mental task performances^{2,10} were characterized by skewed amplitude distributions and similar statistical analyses have been conducted on the human alpha rhythm by Saunders⁴⁵ to lead to comparable results. In addition to the work of Fujita and Sato¹⁷ on the hippocampal electroencephalographic and intracellular activities, oscillatory neuronal rhythms have been recorded and compared with the electroencephalographic patterns in cortical and pyramidal tract neurons^{6,23}, and it seems reasonable to acknowledge the existence of brief transient epochs

where the EEG and neuronal activity could be strongly correlated. If the EEG signals picked up by a macroelectrode reflect the slow undulations of the membrane potential of a surrounding population of neurons, rhythmic electroencephalographic patterns could result, for example, from transient increase (in a limited frequency bandwidth) of one activity shared by this population or from an increase in the number of neuronal generators involved in frequency-related activities.

Our data do not provide any specific information about the mechanism underlying the formation of the EEG, nor do they indicate ways in which neuronal susceptibility to surrounding electric fields may occur. The following short discussion is thus necessarily based on previous hypotheses and assumptions.

Schwan⁴⁹ has shown that electromagnetic radiations below 300 MHz readily penetrate biological material, while most energy of higher frequency signals is absorbed in skin. VHF fields would thus infiltrate the tissues with the depth of penetration proportional to the inverse square root of the frequency, assuming a fairly constant tissue resistivity in that frequency range. So, an amplitude-modulated 147 MHz field could by its mere presence in the extracellular space, play the role of one or many wave generators and contribute to the total electrical activity seen by the tip of the electrode. New induced activity was never seen in any brain structure under study, while pre-existing rhythms were repeatedly and exclusively enhanced by exposure to fields modulated at the dominant frequency of the transient bursts. This does not preclude a non-biological interference. It is possible that the field's strength is insufficient to become the dominant component in the medium, but might be large enough to contribute to an existing energy band (creating an artificial cooperativeness among frequency-related energies). This possibility cannot be excluded but it does not explain the increase in the spontaneous occurrence of short patterns, as seen when the fields were tentatively used as reinforcers, nor the differences seen in the performances and behavior of the two groups of conditioned animals.

The power absorbed as a function of the depth has been calculated for typical living material by Vogelman⁶⁶. It was shown that for a 10 mW/sq. cm field intensity in air, the power even in the first 0.1 cu. cm of tissue would never exceed 1 mW for a cross section of 1 sq. cm at all frequencies below 3 GHz. The maximum field strength induced in the tissues by VHF fields of 1 mW/sq. cm intensity would be of the order of 10–20 mV/mm, thus in the same range as the extracellular electrical fields recorded around the spinal neurons.

The mechanisms of interaction between intercellular low electrical fields and neuronal membranes remain to be elucidated. However, some hypotheses can be made in the light of the relatively new concepts of a 'greater membrane of brain cells' as described by Lehninger³¹ and Schmitt⁴⁷. This greater membrane is composed of a lipid-protein inner layer (inner zone) and a diffuse external coat of polysaccharides, glycoproteins and lipoproteins. It is suggested that conformational changes (resulting, for example, from interference with external cations and water) taking place in the outer layer could induce conformational changes in the inner zone proteins.

The existence of an 'electrogenic protein' undergoing conformational changes in the presence of electrical forces had been postulated by Schmitt and Davison⁴⁸ in

1965; the underlying assumption was that those changes would affect the triggering of membranous pores, therefore modulating the excitability of the cell. Extensive studies of these membranous proteins (for example: Wallach and Zahler⁶⁸; Lenard and Singer³²; Singer and Nicholson⁵⁵) led to a new model of the inner zone of the greater membrane. In this model phospholipid bilayers alternate with globular protein sections, the polar end of the proteins being in contact with the aqueous phase, the hydrophobic end being hidden inside the membrane. Protein-protein interaction as well as oligosaccharide-protein interaction could thus occur in the outer layer to form glycoproteins and lipoproteins, as suggested by Schmitt⁴⁷ in 1969. A model proposed by Adey¹, and based on the greater membrane concept, envisages a modification of calcium binding to polyanionic macromolecules on dendritic structures in the genesis of slow waves in dendrites of cerebral neurons. It also envisages a role for calcium in 'membrane amplification' by cooperative processes as a possible basis for susceptibility of central neurons to weak environmental electric fields.

Possible mechanisms of interaction of electromagnetic fields with molecular systems have been proposed, notably by Vogelhut⁶⁵ and Illinger²². Illinger's studies, based on quantum-mechanical models, suggested that biological interactions between RF radiations and biopolymers could occur through segmental rotation of the random coils of the molecules (resulting in fluctuations from the equilibrium distribution of tertiary structures) and/or through quasi-rotational motion of the water molecules forming a sheath about the helical structure (primary and secondary structures) of the biopolymers. The importance of the water-bound molecules was similarly stressed by Vogelhut⁶⁵ who suggested that the variations in the transport properties of the membranes under RF radiations were due to transformation of the hydrated water phase of the globular proteins. Here, hydration states are sharply dependent on divalent cation binding, particularly of calcium.

There exists, therefore, a possibility that an externally applied electrical field could influence the activity or excitability of a population of cells, and that the changes seen in the gross recordings would reflect true neuronal phenomena.

ACKNOWLEDGEMENTS

This investigation was supported in part by the Air Force Office of Scientific Research of the Office of Aerospace Research under Contract 44620-70-C-0017; by the National Aeronautics and Space Administration under Grant NGR 05-007-195; by the Office of Naval Research under Contract N00014-69-A-0200-4037; and by the Marie Curie Fellowship of the AAUW, 1971-1972.

Grateful thanks is given to Mr. R. Stahl and Mr. P. Kaminsky for the design of the VHF equipment, Mrs. M. Peppel for the editing of the manuscript, Mrs. J. Sells for the preparation of illustrations; and to Mrs. M. Lee for the histological preparations.

REFERENCES

- 1 ADEY, W. R., Organization of brain tissue: is the brain a noisy processor? *Int. J. Neurosci.*, 3 (1972) 271–284.
- 2 ADEY, W. R., ELUL, R., WALTER, R. D., AND CRANDALL, P. H., The cooperative behavior of neuronal populations during sleep and mental tasks, *Proc. Amer. Electroenceph. Soc.*, (1966) 86.
- 3 BARANSKI, S., AND EDELWEJN, Z., Electroencephalographical and morphological investigation upon the influence of microwaves on the central nervous system, *Acta physiol. pol.*, 18 (1967) 517–532.
- 4 CHIZHENKOVA, R. A., The role of different brain formations in EEG reactions of rabbits to a constant magnetic field and electromagnetic fields of ultra high and supra high frequencies, *Zh. vyssh. nerv. Deyat. Pavlova*, 17 (1967) 313–321.
- 5 CHIZHENKOVA, R. A., Electrical reaction of the rabbit cerebral cortex to various electromagnetic fields, *Zh. vyssh. nerv. Deyat. Pavlova*, 17 (1967) 1083–1090.
- 6 CREUTZFELDT, O. D., WATANABE, S., AND LUX, H. D., Relations between EEG phenomena and potentials of single cortical cells. II. Spontaneous and convulsoid activity, *Electroenceph. clin. Neurophysiol.*, 20 (1966) 19–37.
- 7 DELGADO, J. M. R., JOHNSON, V. S., WALLACE, J. D., AND BRADLEY, R. J., Operant conditioning of amygdala spindling in the free chimpanzee, *Brain Research*, 22 (1970) 347–362.
- 8 EDELWEJN, Z., An attempt to assess the functional state of the cerebral synapses in rabbits exposed to chronic irradiation with microwaves, *Acta physiol. pol.*, 19 (1968) 897–906.
- 9 ELUL, R., Dipoles of spontaneous activity in the cerebral cortex, *Exp. Neurol.*, 6 (1962) 285–299.
- 10 ELUL, R., Specific site of generation of brain waves, *Physiologist*, 7 (1964) 125.
- 11 ELUL, R., Brain waves: intracellular recording and statistical analysis help clarify their physiological significance. In *Proceedings of the 1966 Rochester Conference on Data Acquisition and Processing in Biology and Medicine*, Vol. 5, Pergamon Press, Oxford, 1968, pp. 93–115.
- 12 ERSHOVA, L. K., AND DUMANSKII, YU. D., Cortical biopotentials in rabbits under the effect of low intensity electromagnetic fields with radio frequency waves, *Fiziol. Zh. (Kiev)*, 15 (1969) 777–780.
- 13 FOX, S. S., AND AHN, H., Identification of functional bioelectric configurations in spontaneous activity of the brain. In *First Annual Meeting of the Society for Neurosciences*, Washington, D.C., 1971, p. 81.
- 14 FOX, S. S., AND RUDELL, A. P., Operant controlled neural event: formal and systematic approach to electrical coding of behavior in brain, *Science*, 162 (1968) 1299–1302.
- 15 FREY, A. H., Human auditory system response to modulated electromagnetic energy, *J. appl. Physiol.*, 17 (1962) 689–692.
- 16 FREY, A. H., Brain stem evoked responses associated with low-intensity pulsed UHF energy, *J. appl. Physiol.*, 23 (1967) 984–988.
- 17 FUJITA, Y., AND SATO, T., Intracellular records from hippocampal pyramidal cells in rabbit during theta rhythm activity, *J. Neurophysiol.*, 27 (1964) 1011–1025.
- 18 GAVALAS, R. J., WALTER, D. O., HAMER, J., AND ADEY, W. R., Effect of low-level, low-frequency electric fields on EEG and behavior in *Macaca nemestrina*, *Brain Research*, 18 (1970) 491–501.
- 19 GVOZDIKOVA, A. M., ANAN'EV, V. M., ZENINA, I. N., AND ZAK, V. I., Sensitivity of the rabbit's central nervous system to a continuous super-high frequency electromagnetic field, *Biul. eksp. Biol. Med.*, 58 (1964) 63–68.
- 20 HAMER, J., Effects of low level, low frequency electric fields on human reaction time, *Commun. behav. Biol.*, 2 (1968) No. 2A.
- 21 HELLER, S. H., Cellular effects of microwave radiation. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiations*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 116–121.
- 22 ILLINGER, K. H., Molecular mechanisms for microwave absorption in biological systems. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 112–115.
- 23 JASPER, H., AND STEFANIS, C., Intracellular and oscillatory rhythms in pyramidal tract neurons in the cat, *Electroenceph. clin. Neurophysiol.*, 18 (1965) 541–553.
- 24 JUSTESEN, D. R., AND KING, N. W., Behavioral effects of low level microwave irradiation in the closed-space situation. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 154–179.

- 25 KHOLODOV, YU. A., Changes of electrical activity of rabbit cerebral cortex in the action of UHF electromagnetic fields, *Biul. eksp. Biol. Med.*, 56 (1963) 42-46.
- 26 KHOLODOV, YU. A., Influence of a UHF EM field on the electrical activity of a neurally isolated strip of the cortex of the brain, *Biul. eksp. Biol. Med.*, 57 (1964) 98-101.
- 27 KONIG, H., AND ANKERMULLER, F., Über den Einfluss besonders niederfrequenter elektrischer Vorgänge in der Atmosphäre auf den Menschen, *Naturwissenschaften*, 21 (1960) 486-490.
- 28 KORBEL, S. F., Behavioral effects of low intensity UHF radiation. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 180-184.
- 29 KORBEL, S. F., AND FINE, H. L., Effects of low intensity UHF radio fields as a function of frequency, *Psychonom. Sci.*, 9 (1967) 527-528.
- 30 KRITIKOS, H. N., AND SCHWAN, H. P., Hot spots generated in conducting spheres by electromagnetic waves and biological implications, *IEEE Trans. Biomed. Engng.*, BME-19 (1972) 53-58.
- 31 LEHNINGER, A. L., The neuronal membrane, *Proc. nat. Acad. Sci. (Wash.)*, 60 (1968) 1055-1101.
- 32 LENARD, J., AND SINGER, S. J., Protein conformation in cell membrane preparations as studied by optical rotatory dispersion and circular dichroism, *Proc. nat. Acad. Sci. (Wash.)*, 56 (1966) 1828-1835.
- 33 LOVANOVA, YE. A., Survival and development of animals with various intensities and durations of the influence of UHF. In A. A. LETAVET AND Z. V. GORDON (Eds.), *Biological Action of Ultrahigh Frequencies*, Academy of Medical Sciences, Moscow, 1960, pp. 52-56.
- 34 LOVANOVA, YE. A., AND TOLGSKAYA, M. S., Change in the higher nervous activity and interneuron connections in the cerebral cortex of animals under the influence of UHF. In A. A. LETAVET AND Z. V. GORDON (Eds.), *Biological Action of Ultrahigh Frequencies*, Academy of Medical Sciences, Moscow, 1960, pp. 69-74.
- 35 MCAFEE, R. D., Physiological effects of thermode and microwave stimulation of peripheral nerves, *Amer. J. Physiol.*, 203 (1962) 374-378.
- 36 MICHAELSON, S., DUNDERO, R., AND HOWLAND, J. W., The biological effects of microwave irradiation in the dog. In *Proceedings of the Second Annual Tri-Service Conference on Biological Effects of Microwave Energy*, Defense Documentation Center, Alexandria, Va., 1958, pp. 175-188.
- 37 MUMFORD, W. W., Heat stress due to RF radiation. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 21-34.
- 38 NELSON, P. G., Interaction between spinal motoneurons of the cat, *J. Neurophysiol.*, 29 (1966) 275-287.
- 39 OLDS, J., AND HIRANO, T., Conditioned responses of hippocampal and other neurons, *Electroenceph. clin. Neurophysiol.*, 26 (1969) 159-166.
- 40 PRESMAN, A. S., The role of electromagnetic fields in physiological processes, *Biofizika*, 1 (1964) 131-134.
- 41 PURAHICK, H. K., AND LAWRENCE, J. L., Modulated alternating current energy to stimulate audition in totally deaf humans, *25th Annual Meeting of the Aerospace Medical Association, Miami, Fla.*, (1964).
- 42 PURPURA, D. P., AND COHEN, B., Intracellular recording from thalamic neurons during recruiting responses, *J. Neurophysiol.*, 25 (1962) 621.
- 43 ROBINSON, D. A., AND FUCHS, A. F., Eye movement evoked by stimulation of frontal eye fields, *J. Neurophysiol.*, 32 (1969) 637-648.
- 44 ROMMEL, S. A., JR., AND MCCLEAVE, J. D., Oceanic electric fields: perception by American eels?, *Science*, 176 (1972) 1233-1235.
- 45 SAUNDERS, M. G., Amplitude probability density studies on alpha and alpha-like patterns, *Electroenceph. clin. Neurophysiol.*, 15 (1963) 761-767.
- 46 SCHLAG, J., AND SCHLAG-REY, M., Induction of oculomotor responses by electrical stimulation of the prefrontal cortex in the cat, *Brain Research*, 22 (1970) 1-13.
- 47 SCHMITT, F. O., Brain cell membranes and their microscopic environment, *Neurosci. Res. Progr. Bull.*, 7 (1969) 281-300.
- 48 SCHMITT, F. O., AND DAVISON, P. F., Brain and nerve proteins: functional correlates. Role of protein in neural function, *Neurosci. Res. Progr. Bull.*, 3 (1965) 1-87.
- 49 SCHWAN, H. P., Interaction of microwave and radio frequency radiations with biological systems. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 13-20.

- 50 SCOLLO-LAVIZZARI, G., Anatomische und physiologische Beobachtungen über das frontale Augenzentrum der Katze, *Helv. physiol. pharmacol. Acta*, 22 (1964) C42-C43.
- 51 SHER, L. D., AND SCHWAN, H. P., *Mechanical Effects of AC Fields on Particles Diffused in a Liquid: Biological Implications*, Ph. D. dissertation, Univ. Penn., Philadelphia, Contract AF 30 (602), ONR Techn. Rep. 37, 1963.
- 52 SHEYVENKHMEN, B. YU., Effects of the action of an ultra-high frequency field on the audio sensitivity during application of electrodes in the zone of projection of the aural zone of the cortex, *Probl. Fiziol. Akustiki*, 1 (1949) 122-127.
- 53 SHLIAFER, T. P., AND IAKOVLEVA, M. I., Influence of electromagnetic fields of ultra-high frequencies on impulse activity of the cerebral cortex neurons, *Fiziol. Zh. (Leningr.)*, 55 (1969) 16-21.
- 54 SIMON, R. C., AND HOSHIKO, M., Evaluation of electrostimulation of hearing by evoked potential. In N. L. WULFSOHN AND A. SANCES, JR. (Eds.), *The Nervous System and Electric Currents, Vol. 12*, Plenum Press, New York, 1971, pp. 15-18.
- 55 SINGER, S. J., AND NICOLSON, G. L., The fluid mosaic model of the structure of cell membranes, *Science*, 175 (1972) 720-730.
- 56 SNIDER, R. S., AND NIEMER, W. T., *A Stereotaxic Atlas of the Cat Brain*, Univ. Chicago Press, Chicago, 1961.
- 57 STERMAN, M. B., HOWE, R. C., AND MACDONALD, L. R., Facilitation of spindle-bursts sleep by conditioning of electroencephalographic activity while awake, *Science*, 167 (1970) 1146-1148.
- 58 STERMAN, M. B., WYRWICKA, W., AND CLEMENTE, C. D., EEG correlates of behavioral inhibition, *Condit. Reflex*, 4 (1969) 124-125.
- 59 SUBBOTA, A. G., The effect of a pulsed super-high frequency SHF electromagnetic field on the higher nervous activity of dogs, *Biul. eksp. Med.*, 46 (1958) 1206-1211.
- 60 TALLARICO, R., AND KETCHUM, J., Effect of microwaves on certain behavior patterns of the rat. In C. SUSSKIND (Ed.), *Proceedings of the Third Annual Tri-Service Conference on Biological Effects of Microwave Radiating Equipments*, Defense Documentation Center, Alexandria, Va., 1959, pp. 75-76.
- 61 TANNER, J. A., Effect of microwave radiation on birds, *Nature (Lond.)*, 210 (1966) 636.
- 62 TANNER, J. A., AND ROMERO-SIERRA, C., Bird feathers as sensory detectors of microwave fields. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 185-187.
- 63 TANNER, J. A., ROMERO-SIERRA, C., AND DAVIE, S. J., Non-thermal effects of microwave radiation on birds, *Nature (Lond.)*, 216 (1967) 1139.
- 64 TERZUOLO, C. A., AND BULLOCK, T. H., Measurement of imposed voltage gradient adequate to modulate neuronal firing, *Proc. nat. Acad. Sci. (Wash.)*, 42 (1956) 687-694.
- 65 VOGELHUT, P. O., Interaction of microwave and radio frequency radiation with molecular systems. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 98-100.
- 66 VOGELMAN, J. H., Physical characteristics of microwave and other radio-frequency radiation. In S. F. CLEARY (Ed.), *Symposium Proceedings. Biological Effects and Health Implications of Microwave Radiation*, BRH/DBE 70-2, PB 193898, Rockville, Md., 1970, pp. 7-12.
- 67 WAGMAN, I. H., Eye movements induced by electrical stimulation of cerebrum in monkeys and their relationship to bodily movements. In M. B. BENDER (Ed.), *The Oculomotor System*, Hoeber, New York, 1964, pp. 18-39.
- 68 WALLACH, D. F. H., AND ZAHLER, P. H., Protein conformation in cellular membranes, *Proc. nat. Acad. Sci. (Wash.)*, 56 (1966) 1552-1559.
- 69 WALTER, D. O., Spectral analysis for electroencephalograms: mathematical determination of neurophysiological relationships from records of limited duration, *Exp. Neurol.*, 8 (1963) 155-181.