CHAPTER 5

Effects of Electromagnetic Energy on the Nervous System

Introduction

The nervous system consists of the peripheral nerves, the spinal cord, and the brain. It is the means by which the organism receives information from the environment, and by which it controls its internal processes. With the exception of visual systems which are generally sensitive to only a small portion of the electromagnetic spectrum, most animals seem to lack specific receptors for EMFs. Thus, in most cases, EMFs cannot be consciously perceived unless they are so intense that they stimulate sensory nerves via the familiar phenomena of shock or heat. However, not all information gathered by the senses is processed at the conscious level, and there is no physiological principle that would preclude the subliminal detection of EMFs by the nervous system. Indeed, considering both the rich frequency spectrum of naturally-present EMFs that has existed throughout the evolutionary period, and its known relationship to geological, atmospheric, and cosmological phenomena, it would be surprising if the nervous system were not sensitive to low-level EMFs.

The nervous system is the body's master controller. An EMF effect on it could be expressed in two ways: an alteration in the properties or function of the nervous system itself, such as in its electrical, biochemical, or histological characteristics (primary effect); or an alteration in the body's systems or organs that are controlled by the nervous system, such as the endocrine or cardiovascular systems (indirect effect). In this chapter we describe the reports of primary effects on the nervous system—effects involving other organs and tissues are described in the succeeding three chapters.

Direct Effects

We used the salamander electroencephalogram (EEG) pattern as a means to monitor for possible direct effects of high-strength magnetic fields applied along a specific axis through the head (1). The field induced the onset of a slow or delta-wave pattern, and a large fluctuation in activity was seen as the field was slowly decreased from 1000 gauss to zero (see fig. 2.5). These observations were confirmed and extended by Kholodov (2) in 1966 in the rabbit EEG. He found that the presence of delta waves and the number of spindles (brief bursts of 8-12 Hz waves) were both increased by 1-3 minutes' exposure at 200-1000 gauss. In about half the animals tested these reactions lasted at least 30 seconds. In addition to these changes, which occurred after a latent period of the order of 10 seconds, Kholodov sometimes observed a desynchronization reaction (an abrupt change in the main rhythm) 2-10 seconds after the field was turned on (in I4% of the cases), or off (24%). He attributed the increase in spindles and slow waves to a direct action of the magnetic field on the nervous system and the more rapid, and relatively less frequent, desynchronization reaction to the electric field which was induced in the tissue as a result of the change in magnetic field during the turn-on turn-off. Chizhenkova (3) confirmed this hypothesis by exposing rabbits to 300 gauss for either 1 minute or 1.5 seconds. At the longer exposure period, the changes reported by Kholodov were observed, but following 1.5-second exposures only the desynchronization reaction occurred. In addition, Chizhenkova showed that a ten-factor reduction in the induced electric field (achieved by changing the magnetic field more slowly) had no effect on the number of spindles. Similar changes in the EEG due to EMFs of frequencies ranging from 50 Hz to 3 GHz have been reported (4, 72).

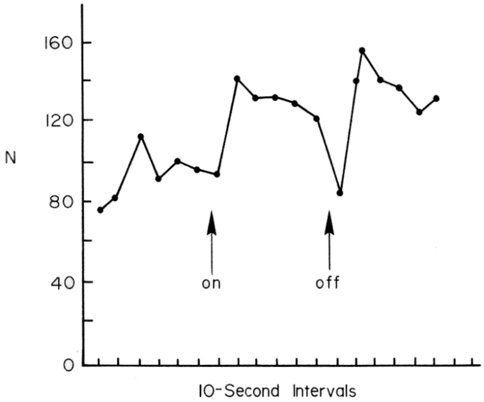

Fig. 5.1. Change in number of spindles in the rabbit induced by exposure to 300 gauss. N is the average number of spindles per 10-second periods that occurred during 604 exposures.

Three additional aspects of the Kholodov–Chizhenkova studies deserve mention: (1) the number of spindles observed after a change in the magnetic field increased regardless of whether the change was on-to-off or off-to-on (Fig. 5.1); (2) there was an after-effect in which the number of spindles remained elevated even when the field was turned off (Fig. 5.1); (3) the most reactive regions were the hypothalamus and the cortex, and the least reactive region was the reticular formation of the midbrain.

Kholodov found a desynchronization reaction, but no changes in spindles or delta waves, when rabbits were exposed for 1 minute to 500 kv/m DC electric fields (2). Lott and McCain (5) measured the total integrated EEG in rats before, during, and after exposure to a DC field of 10 kv/m (Fig. 5.2). They found a transient increase associated with either the application or removal of the field, a steady response that persisted during application of the field, and an after-effect. A 640 Hz pulsed field, 40 v/m maximum, also increased the total integrated EEG, particularly for readings from the hypothalmic region.

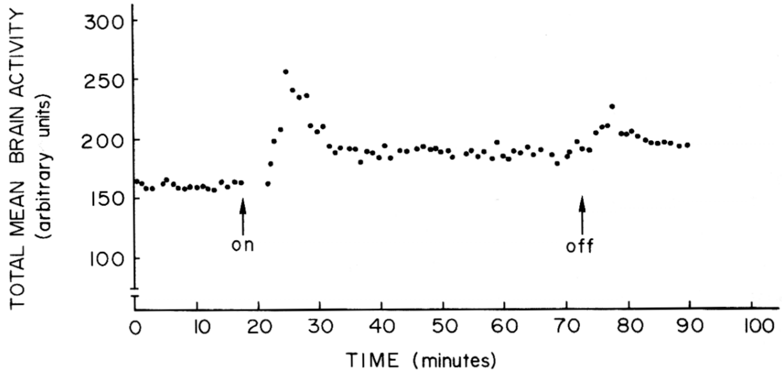

Fig. 5.2. Total brain activity of anesthetized rats exposed to a DC electric field of 10kv/m. Each point represents a mean of 9 experiments; readings were not taken for 6 minutes following application of the EMF.

At high frequencies, a different effect on the total integrated electrical activity was observed. Goldstein (68) exposed rabbits for 5 minutes to 700-2.800 $\mu W/cm^2$, 9.3 GHz, and found no EEG changes during the exposure period. Commencing about 10 minutes after exposure, however, there occurred an interval of decreased total integrated EEG that persisted for up to 15 minutes. The authors reported that the observed changes in the EEG resembled those induced by hallucinogenic drugs.

The nature of the EMF-induced EEG after-effect is determined by the exposure conditions and the physiological characteristics of the subject

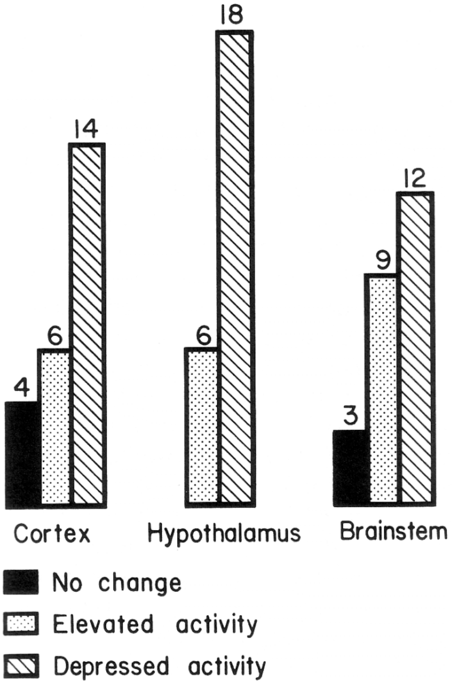

Fig. 5.3. Relation of EEG response from the cortex, hypothalamus, and brainstem due to exposure at 3 GHz. The numbers indicate rabbits with a given response.

(6-11). For example, following a 30 minute exposure at 100 µW/cm^2, 3 GHz, most of the rabbits tested exhibit either depressed or elevated slow-wave activity, and the relative number in each group varied with the location from which the EEG was recorded (6) (Fig. 5.3). The activity in the hypothalamus and the cortex was highly correlated in individual animals-it was either elevated or depressed simultaneously in both regions. After a 1 week exposure (1 hr./day) depressed EEG activity was the characteristic response (6), and after 3-4 weeks the after-effect phenomenon was no longer present (7). Dumanskiy observed a similar pattern in rabbits from exposure to 1.9-10 µW/cm^2, 50 MHz (8); after 2 weeks, EEG activity was elevated, but after 2. months' exposure significant slow-wave inhibition occurred. Such inhibition was also found after 4 months' exposure at 1-10.5 µW/cm^2, 2.5 GHz (9).

Servantie showed that the EEG could be entrained by a pulsed EMF (10). For 1-2 minutes after a 10-day irradiation period at 5000 ,µW/cm^2 the EEG of rats exhibited the pulse-modulation frequency of the applied 3-GHz field. Bawin (44) also observed the production of specific EEG rhythms, and the reinforcement of spontaneous rhythms, by pulsed EMFs.

Effects of EMFs have been reported on other aspects of neuroelectric behavior, such as evoked potentials (12, 13, 73), neuronal firing rate (14, 15), latency and voltage threshold (16),and response to drugs (73).

One of the American scientists who pioneered the study of EMF effects on the nervous system is Allen Frey; his work has included studies of the effects on evoked potentials (12.), behavior (17), and hearing phenomena (18). In 1975 Frey reported an increase in the permeability of the blood–brain barrier (the selective process by which capillaries in the brain regulate transport of substances between the blood and the surrounding neuropil) of rats exposed to 2400 µW/cm2 (continuous) or 200 µW/cm^2 (pulsed) at 1.2 GHz (19). Frey found that dye injected into the bloodstream appeared in the brain of exposed animals, but not the control animals, and that the pulsed EMF was more effective than the continuous signal in opening the barrier, even though the average power level of the pulsed signal was only one-tenth that of the continuous signal. Frey's findings were confirmed and extended by Oscar and Hawkins in 1977 (20). They reported that continuous and pulsed EMFs both increased brain-tissue permeability, but that, depending on the particular pulse characteristics, pulsed energy could be either more or less effective than continuous-wave energy. Effects were observed at average powers as low as 30 µW/cm^2. Preston et al., on the other hand, failed to find an effect on the permeability of the blood-brain barrier even at thermal-level EMFs (21). Frey concluded that Preston's failure resulted from an inappropriate choice of statistical procedures (11).

Biochemical studies of EMF-induced changes in brain tissue have yielded remarkably similar results at widely different frequencies. Fischer et al. (22) found that 50Hz, 5300 v/m, resulted in an initial rise of norepinephrine in rat brain, and a subsequent decline below the control level (Fig. 5.4 A). Grin (23) observed the same sequence of changes at 2.4 GHz, 500 µW/cm^2 (Fig. 5.4 B); at 50 µW/cm^2, however, the norepinephrine level in Grin's study rose continuously throughout the exposure period.

Noval et al. (24) found that the activity of choline acetyltransferase (ChAC)—a neuronal enzyme which catalyses the synthesis of acetylcholine—was significantly reduced in the brainstem portion of brains from rats exposed to 10-100 v/m, 45 Hz, for 30-40 days; ChAC activity in the cerebral hemispheres was not affected by the field. Cytochrome oxidase activity in rat-brain mitochondria was significantly reduced after 1 month's exposure at 1000 and 1000 µW/cm^2, 2.4 GHz; no effect was found at 10 µW/cm^2 (25).

Cholinesterase is the neuronal enzyme that destroys acetylcholine, thereby permitting re-establishment of the membrane potential; alteration in blood cholinesterase levels reflects changes in the functional state of the

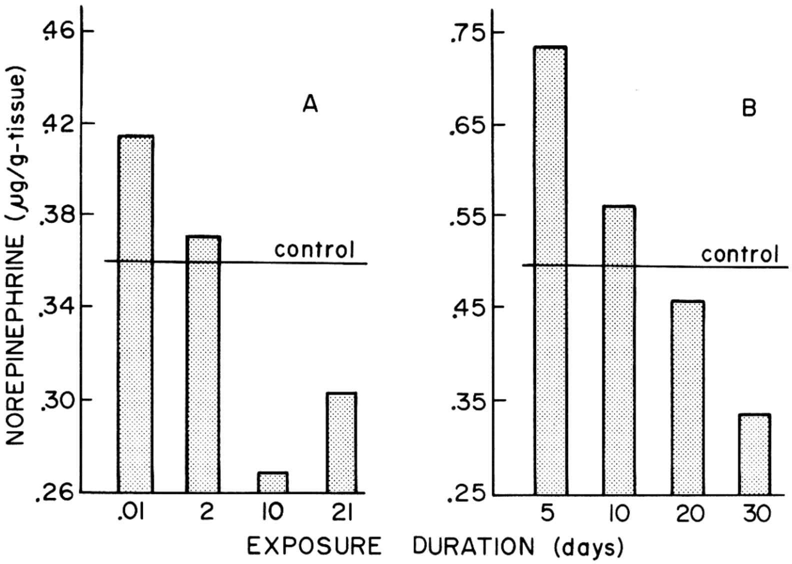

Fig.5.4. Norepinephrine levels in rat brain following exposure to EMFs: *A*, 5300 v/m, 50 Hz; *B*, 500 μW/cm^2, 2.4 GHz.

nervous system. Chronic exposure to both low-frequency (22) and high-frequency (32) EMFs have produced lowered blood cholinesterase levels.

Microscopic studies of brain tissue of EMF-exposed animals have disclosed several kinds of functional histopathological effects. Kholodov (2) reported changes in brain tissue of rabbits and cats exposed to 200-300 gauss for up to 70 hours. In the sensorimotor cortex he found hyperplasia, hypertrophy, atrophy, and dystrophic nerve lesions. In an attempt to confirm Kholodov's observations, Friedman and Carey (26) exposed rabbits to 11-210 gauss DC and 5-11 gauss at 0.1-0.2 Hz for up to 60 hours. Four of the 12. exposed rabbits and 2 of the 13 controls exhibited some histopathological change consisting principally of scattered granulomata in the meninges and the cortex, often associated with vascular proliferation, leukocyte infiltration, and small Gram-positive organisms. They concluded that their results could not be reconciled with those of Kholodov, but rather were consistent with a sub-clinical encephalitozoonosis which was exacerbated by a stressor effect of the magnetic field. In a subsequent electronmicroscopic study, Kholodov and his colleagues demonstrated EMF-induced changes—granular material in the Golgi complex in the rat pituitary—which seem clearly to be related to increased synthesis, and not a zoonosis (27).

Tolgskaya and colleagues have conducted many studies of the histopathological effects of EMFs (28). In 1973 they described results of a time study of the effects of 3 GHz, 60-320 µW/cm2 (1hr/day for 22 weeks) on the morphology of the hypothalamus of the rat (29). After 2-3 weeks of exposure there was an increase in neurosecretory material in cells in the anterior region and along fibers of the hypothalamohypophysial tract. At 4-5 weeks similar results were seen, but at 22 weeks the picture was quite different-neurons were smaller with some atrophy, and little secretory material was seen. Six weeks following termination of exposure the rats exhibited a normal histological appearance.

Behavioral Effects

Most of the major paradigms used in behavioral research have been employed successfully to establish the existence of EMF-induced behavioral effects. These include studies of spontaneous activity, reaction time, and conditioned responses.

When motor activity was evaluated by tilt cages, traversal of open-field mazes, or other ambulatory behaviors, it was found that the responses depended on the characteristics of both the measuring system and the applied EMFs. Eakin and Thompson (30) used 320–920 MHz, 760 $\mu W/cm^2$, for 47 days and found that the exposed rats were more active than the controls during the first 20 days of exposure, and less active thereafter. These results were confirmed and extended by Eakin in 1970 when hypoactivity was reported following prolonged exposure to 150-430 $\mu W/cm^2$ (31). Roberti et al. (32) failed to find an effect due to 3–10 GHz for 7 days at 1000 $\mu W/cm^2$, but Mitchell et al. (33),who exposed rats to 2.45 GHz at about 600 µW/cm2 for 22 days (5 hr/day), found an EMF-induced hyperactivity in the exposed animals compared to both their pre-exposure baseline and the activity of sham-exposed controls. The field-induced activity changes in each of these studies were measured during periods when the animals were removed from the field. When activity was measured during exposure to a modulated 40-MHz electric field (34), it first increased, then decreased, during the 2-hour exposure period. This result supported an earlier finding by the same group that the field caused a similar pattern of change in the emotional response of rats as measured by the Olds self-stimulation response (35).

The pattern of a dual effect upon performance—stimulation or inhibition, depending on the circumstances—has not emerged at the low frequencies, most such studies having found only increased activity. At 1000 v/m, 60 Hz (5 days) (36), and 60,000 v/m, 50 Hz (3 hr) (37), the nocturnal activity of rodents was increased. An increase in activity in two strains of mice was also seen following exposure to 17 gauss at 60 Hz (38). Other spontaneous behaviors have been found to be susceptible to EMFs, including pain-induced aggression (I7), escape (75), avoidance (76-78), and sleep pattern (79).

A standard behavioral measure of a subject's ability to respond to changes in its environment is its reaction-time to a visual or auditory stimulus. In several studies this has been altered by low-frequency EMFs. According to Konig and Ankermuller (40), at 1 v/m, 10 Hz and 3 Hz are associated with a decrease and increase, respectively, in human reaction time as compared to the field-free situation. In an experimental design in which each subject was exposed to two frequencies in the 2-12 Hz range, at 4 v/m, Hamer found a longer reaction time at the higher frequency (41). Friedman et al. applied magnetic fields of 0.1 and 0.2 Hz to separate groups of male and female subjects, and for both groups he found a longer reaction time at the higher frequency compared to the lower frequency (42). Persinger et al. found no difference in the mean reaction time in either males or females due to 0.3-30 v/m, 3-10 Hz, but he did find a significant difference between the sexes in the variability of the response to a given field (43).

As measured by a task consisting of the addition of sets of five two-digit numbers, a 60 Hz, 1-gauss field altered the ability to concentrate in human

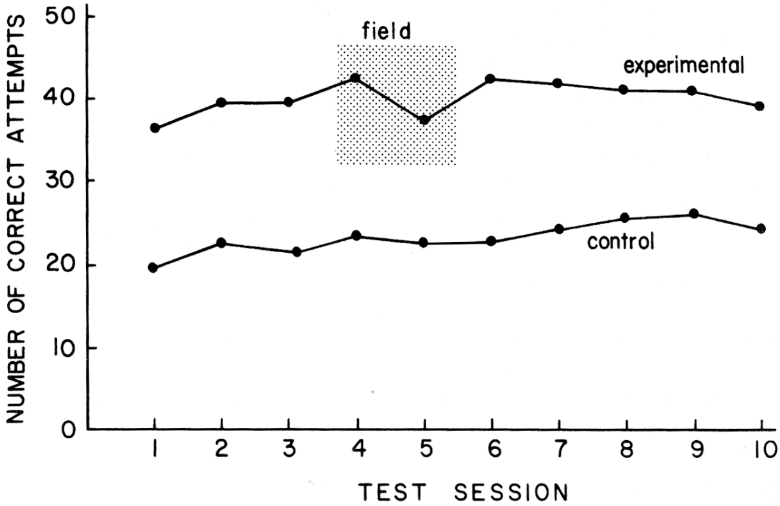

Fig. 5.5 Average performance of the experimental and control groups on the Wilkinson Adding Task. The subjects were confined to the test facility throughout the study, and were unaware of the exact timing of the 24-hour exposure period.

subjects (Fig. 5.5) (39). All 6 experimental subjects demonstrated a decline in performance in the second test session of the exposure period, and all 6 improved in the first test session of the postexposure period. In contrast, the control subjects showed no consistent changes.

For more than a decade, Ross Adey and his colleagues have sought to understand the molecular mechanisms that underlie field-induced behavioral changes. In the late 1960's they reported that low-frequency EMFs altered the timing behavior in humans (41) and monkeys (50). The effects were frequency-dependent in the 2-12. Hz range, and later results suggested that they increased with dose (51). In 1973, they reported that cats exposed to 147-MHz EMFs, modulated at 0.5-30 Hz, exhibited altered EEGs (44). The idea that evolved from these studies and others (53), was that extremely weak EMFs-I0-5 v/m, as calculated on the basis of the simple spherical model described in chapter 2-could alter neuronal excitability, and presumably timing behavior and the EEG, if they were in the physiological frequency range (the EEG). An in vitro system involving calcium binding to brain tissue was then chosen to study the effect of weak EMFs on ionic movement under a hypothesis that altered ion-binding and the associated conformational changes constituted the mechanism of the EMF-induced effects. A complex series of results were then obtained concerning the levels of pre-incubated calcium that were released into solution: at 147 MHz, there was an increase when the EMF was modulated at 6- 10 Hz, but no increase at 0.5-3 or 25-35 Hz (65); with EMFs of 6 and 16 Hz, there was a decrease at 10 and 56 v/m, but not at 5 or 100 v/m (66); there was no change in calcium at 1 Hz or 32 Hz, at either 10 or 56 v/m (66); at 450 MHz, modulated at 16 Hz, there was an increase (67). Some of these results have been confirmed (71). The salient features of the *in vitro* studies were: (1) the emphasis on calcium; (2) the opposite results obtained following low-frequency and high-frequency EMF exposure; and (3) the existence of frequency and field-strength ranges where the effects were at a maximum. None of these features were seen in the *in vivo* studies. Grodsky proposed a cell-membrane model involving cooperative charge interactions as a partial explanation of Adey's results (80), but their molecular basis still remains speculative (52).

There have been reports of the effects of EMFs on conditioned responses in both operant (44-51, 74) and respondent paradigms (8, 54-58). In the operant studies, the effect of the EMFs was usually established on the basis of changes in discrete movement by the test subjects. For example, Thomas (74) found that a pulsed EMF of 1000 µW/cm2, 2.45 GHz, altered the effect of chlordiazepoxide on behavior. The drug produced a change in the bar-pressing rate which was potentiated in the presence of the EMF. In the respondent studies, typically, the field-induced effects were more gen eralized and consisted of responses such as impaired endurance (57). The use of EMFs as conditioned stimuli during periods preceding aversive stimuli has frequently (59-61), but not always (62-64), failed.

Summary

EMFs produced a broad array of impacts on the nervous system, ranging from changes in the electrical activity of specific areas of the brain, to systematic changes such as clinical zoonosis, enzyme increases, and alterations in specific and diffuse behavior. The most important characteristic of the reported effects was that the energy imparted to the organism under study was far too low to have energetically driven the observed changes via passive or classical processes such as ionization, heating, or gross alteration in the resting potential of membranes in excitable tissue. It was the metabolism of the organism, therefore, which furnished the energy, and the applied EMFs functioned primarily as eliciting, triggering, or controlling factors for the observed biological changes. There have been no systematic studies with one type of EMF, one organism, and one experimental paradigm. Consequently, it is difficult to generalize regarding the direction or trend that will likely be exhibited by specific nervous system parameters when they are measured under conditions which differ from those already studied. In this sense the present studies are unsatisfactory. But this problem can be remedied by future studies and it does not detract from the fundamental conclusion that nonthermal EMFs can cause electrical, biochemical, functional, and histopathological changes in the nervous system.

The manner and location at which the EMFs were detected and the means by which their existence was first communicated to the central nervous system—a clear prerequisite for any of the reported effects—cannot be determined from the present studies. The site of reception may be the central nervous system itself. Support for this can be found in studies in which brain electrical activity changes occurred instantaneously with the presentation of the field. By analogy with the modes of detection of other stimuli such as light, sound, or touch, it might also be suggested that the peripheral nervous system is the locus of EMF detection. This point can only be resolved by future studies—carefully designed to eliminate the recognized difficulties in recording electrical activity during EMF exposure (44)—in which nervous system electrical activity and the DC potentials are recorded during EMF exposure of the central and peripheral nervous systems separately.

Because the nature of the reception process of EMFs is unknown, it is not possible to determine whether it is mediated differently for EMFs with different frequency or amplitude characteristics. In contrast to this, the subsequent physiological events seem to proceed via common pathways regardless of the frequency of the applied EMF. Thus, altered brain electrical activity was found at 640 Hz (5), 3 GHz (6), and 9.3 GHz (68). Similarly, 50 Hz, (22), and 2.4 GHz (23) fields each produced comparable changes in enzyme levels in the brain. With regard to behavioral endpoints (reaction time, motor activity, conditioned responses), identical effects were found using EMFs that span the spectrum. Moreover, the EMF-induced effects were relatively independent of the type of applied field—whether electric or magnetic. For example, DC electric and magnetic fields each produced desychronization in the EEG (2), and low-frequency electric and magnetic fields each altered human reaction time (41, 42). Despite the observed nonspecificity of the biological effects with regard to the frequency or type of applied field, other characteristics of the applied EMFs did have a significant effect on the biological response. Pulse width and modulation frequency, for example, were important parameters in blood–brain barrier penetration, interresponse times, and the self-stimulation response. Sometimes, pulsed EMFs produced biological effects at much lower average incident energy levels than was obtained with continuous-wave EMFs, and in some cases only the pulsed EMF elicited an effect. Exposure duration also was an important factor in the elaboration of some effects. Thus, in general, the bioeffects were relatively independent of frequency and field type, but other signal characteristics were important in the development of the observed responses.

Dose:effect relationships were not manifested within or between studies. For example, in one instance a ten-factor increase in the strength of the applied field did not produce a corresponding increase in the brain enzyme level (24), and in a second case it produced a change opposite to that found at the lower field strength (23). The general absence of dose:effect relationships suggests that the EMFs had a trigger effect which was relatively independent of their magnitude. The field-induced effects, moreover, were time-dependent phenomena and for this reason, from a dose:effect viewpoint, it is not possible to compare the results of studies which used different exposure periods (36, 37).

The physical characteristics of the applied EMFs partially determined the biological effects. Another important—perhaps, in some cases, principal—factor in the production of such effects was the physiological state of the subject. About half the rabbits in Kholodov's study, for example, ex hibited the sustained delta pattern: in the remaining animals it did not appear or it appeared only briefly. Bychkov found elevated and depressed EEG activity, or no effect at all, depending on the particular animal. The behavioral studies involving reaction time and motor activity clearly suggest that the subject's state of arousal was an important element in determining the direction, and perhaps the existence, of a field-induced effect. In all such cases, some factor, or combination of factors, peculiar to each animal was crucial in the elaboration of the effect. Sometimes—the zoonosis in the Friedman study, for example—such an operative factor was apparent. More frequently, however, they were simply uncontrolled variables (see chapter 8).

The overall pattern of the nervous system studies was one of detection and adaptation to the applied EMFs; an electrically diverse range of fields produced similar kinds of electrical, metabolic, and behavioral changes in the nervous system. At first glance it seems difficult to understand how different stimuli could produce similar responses, but this was exactly the situation which led Hans Selye, in 1936 (69), to propose his now established theory of biological stress (70): diverse stimuli—heat, cold, trauma, crowding, and many others—elicit a common physiological adaptive response in the organism. The response syndrome consists of measurable changes in the biochemistry, physiology, and histopathology of the neuroendocrine system, and in the organs and functions that are responsive to it. Any stimulus which elicits the syndrome is, by definition, a stressor. The idea that the electromagnetic field is a stressor is developed further in the succeeding chapters.

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