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Alterations in brain electrical activity caused by magnetic fields: detecting the detection process

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Summary Static and 60 Hz magnetic fields, 0.78 gauss, were applied individually and combined to each of 20 human subjects during 2 sec epochs, and the effect on the EEG was determined by comparing the power spectrum obtained during field exposure with that from control epochs. All but one subject exhibited field-induced alterations in the EEG; most subjects exhibited increased EEG activity at 2 or more frequencies within 1-18.5 Hz. The field-induced changes were recorded more often at the central and parietal electrodes than at the occipital electrodes. The responses observed during application of combined static and alternating fields did not differ from the sum of the responses observed when the fields were applied individually, even though the exposure conditions were specifically chosen to favor the hypothesized ion-resonance mechanism of interaction involving Ca^{2+}. The data support the view that detection loci for magnetic fields exist within the nervous system.

Key words: Magnetic fields; EEG; Power spectrum; Ion resonance

Electromagnetic fields (EMFs) of various frequencies and strengths are produced by high-voltage powerlines, household appliances, radio and television antennas, radars, and industrial equipment. Epidemiological studies have shown a link between EMF exposure and cancer, particularly leukemia and brain cancer (Wertheimer and Leeper 1979, 1982; Lester and Moore 1982; Milham 1982; Lin et al. *1985;* Thomas et al. 1987; Preston-Martin et al. 1989).

The locus of EMF detection is unknown, but several lines of evidence and analysis suggest that it occurs in the nervous system. First, external energetic stimuli such as light and sound are detected by the nervous system, and it may have a comparable role in detecting external EMFs. Second, EMFs are associated with different forms of cancer (Wertheimer and Leeper 1979; Lester and Moore 1982; Milham 1982; Preston-Martin et al. 1989), and with non-cancerous disease conditions (Friedman 1981; Nordstrom et al. 1983; Perry and Pearl 1988), suggesting the existence of a centrally located detection process that can lead to loss of transcriptional control in cells of differing embryological origin, or lead to non-malignant disease. Third, the EMFs associated with disease in epidemiological studies and with biological effects in animals (Becker and Marino 1982) are spectrally disparate, and thus the detection mechanism must be capable of responding to signals over a broad bandwidth. It would be more parsimonious for such a mechanism to exist in only one or a few cell types, rather than in all the different cell types that actually manifest EMF-related effects or disease. Finally, the existence of a nervous-system capability for detecting non-light EMFs may have been an evolutionary development to facilitate compensation of the effects of geological and meteorological EMFs. In sum, these considerations suggested to us that the presence of an EMF causes signals in the nervous system that subserve detection and response.

The biophysical mechanisms of EMF detection are similarly unknown. One hypothesis is that the ionic permeability of membrane-channel proteins may be increased during application of EMFs (ion resonance), resulting in initiation of second messengers that ultimately lead to biological effects (Liboff 1985). In this view, for a given ion species, the strength of a static magnetic field and the frequency of a time-varying field determine whether resonance-mediated biological effects will occur. There is evidence for (McLeod et al. 1987; Liboff et al. 1990) and against (Hille 1988) this theory.

We hypothesized that EMFs are detected by the nervous system and studied their effect on the electroencephalogram (EEG) in human subjects to determine whether brief exposure caused a change in electrical

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activity. Additionally, we considered whether a resonant interaction with $Ca^{2\sim}$ was a likely biophysical mechanism by which EMFs affected the EEG. We describe here the observations that led us to accept the first hypothesis and reject the second one.

Methods

EMF exposure

Magnetic fields were produced using a pair of coils 130 cm in diameter, each consisting of 250 turns of copper wire; the coils were maintained parallel and separated by *65* cm (the Helmholtz condition) using a wooden frame (Bell and Marino 1989). The coil current was obtained from a function generator (Model 182A, Wavetek, San Diego, CA), and amplifier (Model 7500, Krohn-Hite, Avon, MA). The subjects sat with their eyes closed on a comfortable wooden chair in a dark room, with their feet on a wooden foot-stool placed just beyond the coils. The subject’s sagittal plane was perpendicular to the axis of the coils; the head and upper chest were within a magnetic-field region that was uniform to within 5% of its predetermined value (within 20% when the thorax and pelvis are included). The average 60 Hz background magnetic field at the location of the subject was 0.1 mG.

The equipment that controlled the coils and recorded the EEG was located about 15 m from the room occupied by the subjects. There were no visual or auditory cues to the subjects indicating the presence or absence of the magnetic field. The room was partially soundproofed, but occasional sounds that occurred irregularly in an adjacent corridor could be heard in the room.

EEG measurement

Gold-plated surface electrodes 1 cm in diameter (Grass Instrument Co., Quincy, MA) were placed at C-3, C-4, P-3, P-4, 0-1, and 0-2 (international 10—20 system) referred to linked ears; the ground was placed on the forehead. Electrode impedances were measured before and after each recording (Grass Model EAM SA, Grass Instrument Co., Quincy, MA); typically, the impedances were 2—3 kΩ.

The EEG was filtered to pass 0.3—35 Hz, and then the signal was split and simultaneously recorded on an electroencephalograph (Model 6, Grass Instrument Co., Quincy, MA) and stored on a 40 Mbyte hard-drive after sampling at 200 Hz; the stored data were analyzed on a mainframe computer.

Subjects

Ten normal subjects were recruited from the general population, and 10 additional subjects (patients) were chosen from among those with neurological complaints who underwent a clinical EEG as a diagnostic procedure (Table I). The patients were identified for possible inclusion by an EEG technician, who noted the presence of a well-developed occipital alpha activity during the clinical EEG. Cooperative patients having this finding were asked to participate in the study, and those consenting and willing to remain in the laboratory area after completion of their clinical EEG were utilized. All subjects signed an informed-consent form approved by the IRB of the Louisiana State University Medical Center.

TABLE I

Some pertinent characteristics of the study subjects.

Number	Subject	Complaint	Clinical EEG
1	41 M	Seizures	Abnormal
2	23 M	Possible seizures	Normal
3	61 F	Hemifacial spasm	Normal
4	36 F	Psychosis	Normal
5	27 F	Headache	Normal
6	48 F	Seizures	Abnormal
7	31 F	Seizures	Normal
8	41 F	Seizures	Abnormal
9	25 F	Seizures	Normal
10	60 M	Paresthesias	Normal
11	35 M	None	
12	32 M	None	
13	31 M	None	
14	30 F	None	
15	31 F	None	
16	30 M	None	
17	36 M	None	
18	30 M	None	
19	36 F	None	
20	29 M	None	

Some patients exhibited abnormal EEGs, as later interpreted by the neurologist reading the clinical tracings and blinded to whether the patient was a study participant. No patient who had a seizure during the clinical EEG, or who had persistent focal slowing, was used. Generalized slowing was also excluded by the initial requirement of a normal alpha background. The 3 abnormal EEGs noted in Table I were: mild, intermittent left frontal spike, sharp and spike and slow-wave discharges (subject 1); intermittent higher voltage theta focally at C-4 and P-4 on the right (subject 6); shifting temporal theta with rare sharp waves (subject 8).

Procedure

Each subject underwent a block of trials involving exposure to a static magnetic field (B_{DC}), an alternating magnetic field (B_{AC}), combined static and alternating fields (B_{DC+AC}), and a sham magnetic field (a period during which all experimental conditions were maintained except for the presence of a magnetic field).

A trial consisted in the presentation of a field for 2 sec, followed by a 5 sec field-off interval. The control epoch for each field-on epoch was the immediately preceding 2 sec interval. If P(f) represents the power spectrum (the coefficients in the Fourier transform of the EEG at frequency f, averaged over 2 sec epochs), we hypothesized that P(f) differed reliably between field-on and field-off epochs, and therefore that the occurrence of such a difference was evidence that detection of the magnetic field had occurred. The effect of each field condition was assessed by comparing the EEG recorded during presentation of the field with the EEG recorded during the immediately preceding 2 sec off epoch. Approximately 60 trials were obtained for each of the 4 exposure conditions, and the first 50 artifact-free trials were used in the subsequent analysis. The 4 field conditions were presented in random order to different subjects.

Statistical design

The power coefficients at 1—18.5 Hz in increments of 0.5 Hz were obtained from the Fourier transform (Spectra, SAS Institute, Inc., Austin, TX). The coefficients were not normally distributed, either as obtained from the Fourier transform calculation, or after a variety of mathematical transformations. Consequently, for each subject and field condition, we used the non-parametric Wilcoxon signed rank test (Pfurtscheller and Aranibar 1977) to evaluate the hypothesis that the EEG during the field epochs did not differ from that measured during the corresponding control epochs.

To rationalize an a priori decisional process, it was necessary to establish that the likelihood of concluding that an effect occurred during the sham stimulus was acceptably small. At any Fourier frequency measured from any electrode, we chose $P < 0.05$ as the probability for accepting the existence of a difference between the control and sham-exposed epochs (“success”). Because multiple tests were to be performed (36 frequencies X 6 electrodes), conditions regarding the number of successes were adopted to establish an acceptable overall level of confidence in each decision. The a priori probability that successes would occur at the same frequency in a matched pair of bilateral electrodes (C-3 and C-4, P-3 and P-4, or 0-1 and 0-2) was $0.05 \times 0.05 = 0.0025$ (if the events were viewed as independent). The overall level of confidence of 36 tests performed at a probability of 0.0025 is $0.9975^{36} = 0.9138$, which was too low to exclude the role of chance, particularly since the existence of 3 pairs of electrodes has not yet been considered. We therefore required the existence of bilateral successes in at least two frequencies. From the binomial distribution, the probability of at least two pairs of successes (using $P = 0.0025$ as the a priori probability for each pair of successes) is $P < 0.0038$. The corresponding overall level of confidence in 3 tests (3 electrodes) is $0.9962^3 = 0.9886$, which corresponds to a probability of 0.011.

In preliminary measurements, we found that when a unilateral success occurred due to chance, the probability of a second success at the same frequency was approximately twice that of the initial success. That is, the events were not truly independent, and the probability of a second success was approximately doubled when the first success occurred. Using $0.05 \times 0.1 = 0.005$ as the probability for occurrence of a bilateral pair, the probability of two or more successes in one electrode pair is $P = 0.0140$ and $P = 0.041$ in 3 pairs. Consequently, even though bilateral successes due to chance are not completely independent, the decisional process affords reasonable protection against false positive decisions.

In summary, our criterion for accepting an effect due to the presentation of a field was that it resulted in at least two bilateral successes in at least one pair of electrodes.

Magnetic fields

We studied low-strength static and 60 Hz magnetic fields because they are pervasive in the environment. Ca^{2+} was chosen for consideration of the ion resonance theory because of reports that it could interact with magnetic fields (Liboff 1985; McLeod et al. 1987; Liboff et al. 1990), and because of the importance of Ca^{2+} in neuroelectrophysiology. When colinear static and alternating magnetic fields are applied simultaneously to an object containing ions having a charge-to-mass ratio of q/m, a maximal interaction may occur when $2\pi f = (q/m)B_{DC}$, where f is the frequency of the alternating field and B_{DC} is the strength of the static field (Halliday and Resnick 1981). The choices of the calcium ion ($q/m = 4.8 \times 10^6$ coul/kg) and 60 Hz combined to fix the value of the static field at 0.78 gauss. $|B_{AC}|$ is apparently not determined by theoretical considerations, but optimal results have been reported with $|B_{DC}| = |B_{AC}|$ (McLeod et al. 1987). We therefore applied a static field of 0.78 gauss, a 60 Hz rms field of 0.78 gauss, and a combination of both fields to each subject. The Helmholtz coils were oriented in the North-South plane to prevent the geomagnetic field in the laboratory from adding to BDC (thereby vitiating the resonance conditions for Ca^{2+} defined by the equation given above).

Study hypotheses

The effect of BDC was evaluated in each subject using the Wilcoxon signed ranks test (Pfurtscheller and Aranibar 1977). The null hypothesis was that the EEG (as represented by the Fourier coefficients) did not differ during application of BDC, compared with the EEG measured during the control epochs. The hypotheses for B_{AC} and B_{DC+AC} were similarly posed and tested. The relevance of the ion resonance mechanism was evaluated by determining whether the combined fields altered the rate, pattern, or magnitude of responses, compared with the sum of the effects observed during application of the individual fields. The possibility that the subjects were more likely to respond to the combined fields compared with their responses to the individual fields was evaluated using the theorems of compound and total probability. The sign test (Snedecor and Cochran 1967) was used to examine the hypothesis that the combined fields resulted in an altered pattern of EEG sensitivity, compared with the separate fields. The magnitude of the responses observed using the combined fields was compared with the sum of the responses to the individual fields, using the paired *t* test.

Results

The EEG frequencies affected by presentation of the magnetic fields, and the source electrodes of the effects, are listed in Table II for each subject and field. No effects occurred with the sham field. Application of the fields altered brain electrical activity in 19 of 20 subjects. In most cases, the fields increased brain activity (indicated in Table II by an upward arrow), but many cases of field-induced decreases in activity at specific frequencies were observed (downward arrow). A subject was counted as having responded to the indicated field condition if either a significant increase or decrease was seen. The distribution of subject responses is shown in Fig. 1 for both patients (subjects 1—10) and normal subjects (11—20).

Observed changes in EEG power for representative patients are given in Fig. 2. In subject no. 1, for example, BDC (left column) caused a marked increase in activity from the P electrode at 1 and 1.5 Hz, and a smaller but statistically significant increase at 14 Hz; neither change was observed when BAC or the combined fields were applied (center and right columns, respectively). But application of BAC and the combined fields produced significant changes in brain electrical activity from the C electrodes (solid bars); comparable increases in activity

TABLE II

EEG frequencies affected by exposure to magnetic fields. B_{DC}, B_{AC}, B_{DC}+ B_{AC}, static magnetic field, alternating magnetic field, combined fields, respectively. C, P, 0 are the central, parietal, and occipital electrodes (international 10—20 system), respectively. Arrow direction indicates whether the power measured during presentation of the indicated field was greater (↑) or less (↓) than that measured during the control epochs.

Subject	B_{DC}	B_{AC}	B_{DC+AC}
1	P↑; 1,1.5,14	C↑; 18, 18.5	C↑; 18.5 C↓; 9.5, 15.5
2	C↑; 6,7,8,9,10—18.5 P↑; 9, 10, 12, 16, 16.5, 17.5, 18.5 O↑; 16, 16.5	C↑; 1,1.5,3,12—18.5 C↓; 9.5 P↑; 1—2, 13.5—14.5, 16, 16.5, 17.5—18.5 P↓,; 9.5	C↓; 9.5 C↑; 1, 1.5, 2.5—5.5, 11.5—18.5 P↑; 1,4,4.5,14,15.5—18.5
3	—	C↑;1,3.5,5,18,18.5 P↑; 1,2.5,3.5,4.5,5, 18.5	C↑;1,1.5 P↑; 1—2.5,5,6
4	—	C↑; 1—2,3	C↑; 1—3,4,5.5, 16.5, 17.5—18.5 C↓; 11
5	O↑;17 O↓;6	P↑;8 P;1.5	
6	—	—	O↑; 2.5, 17.5—18.5
7	O↑;15,18	O↑;1 O;10.5	
8	—	—	P↓; 8,17.5
9	—	—	C↓,; 3,7,10
10	—	C↑;14.5 C↓;9	—
11	C↑; 14.5, 16, 17—18 O↑;7.5,10,18	C↑; 1—2,3,3.5,4.5,8.5,14,14.5, 15.5—18.5 P↑;1,7.5	C↑; 1—2.5, 3.5, 15—18.5
12	C↓; 2.5, 18.5		C↑;16 C↓;1 P↑;16 P↓;1
13	O↑; 6.5, 18	O↑; 1—3.5,5,15, 16.5, 17.5—18.5	O↑; 1—7.5, 12, 12.5, 13.5—14.5, 15.5—16.5, 17.5—18.5
14	—	C↑; 1,2.5, 13.5, 18.5 P↑; 2.5, 13.5	—
15	—	C↑;1C;8,15.5	—
16	—	C↑; 1,16—18.5 P↑; 1,18,18.5	C↑; 1, 1.5, 2.5, 3.5, 4.5, 14.5—18.5
17	—	O↑; 16—18.5 O↓; 9	O↑; 1,2,16,17—18.5 O↓; 9
18	—	C↑;6,12	C↑;1.5,18
19	—	P↑;2.5 P↓;11	—
20	—	—	—

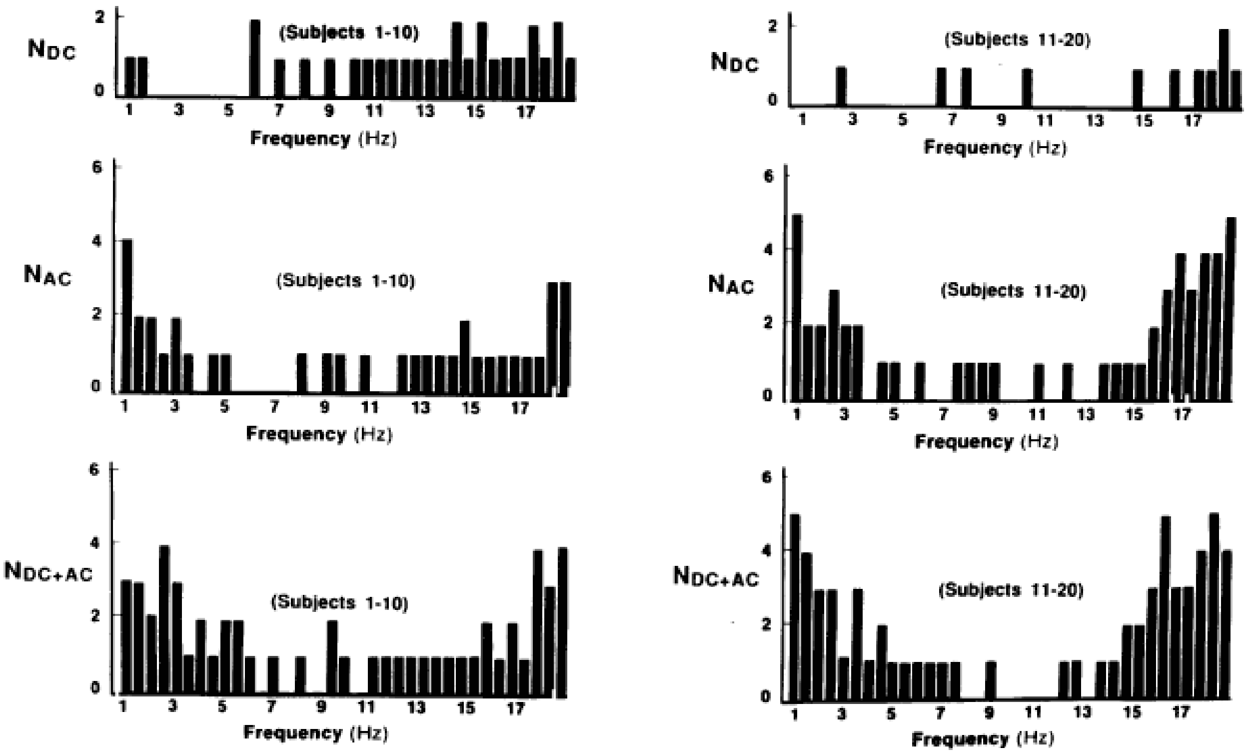

Fig. 1. Number of subjects that responded to the magnetic fields as a function of the frequency at which the responses were observed. N_{DC}, N_{AC}, N_{DC+AC}, number that responded to the static magnetic field, alternating magnetic field, and combined fields, respectively. Subjects 1—10 were neurological patients; 11—20 were normal subjects. A subject was counted as having responded to the indicated field condition if either a significant increase or decrease was seen. Data from Table II.

at 18.5 Hz were seen under both conditions, but application of the combined fields produced significant decreases at *9.5* and 15.5 Hz, which were not observed when only BAC was applied. In subject no. 4, B_{DC} did not affect brain electrical activity; when it was applied simultaneously with B_{AC}, however, larger and more numerous changes in brain electrical activity from the C electrodes were observed, compared with B_{AC} applied alone. Subjects no. 6 and 8 responded to neither B_{DC} or B_{AC}; both, however, responded to the combined fields by exhibiting either an increase in activity at the O electrodes (subject no. 6) or a decrease at the P electrodes (subject no. 8). Subject no. 7 exhibited yet another response pattern: she responded to B_{DC} with a relatively small increase in 0 electrode electrical activity at the higher frequencies, strong changes (increase at 1 Hz, decrease at 10.5 Hz) during application of B_{AC}, but no response during application of the combined fields. Fig. 3 depicts representative examples of similar results obtained from normal subjects.

Table III compares the effect of simultaneous field application with that due to application of the individual fields. For each subject and each field condition, the mean difference in power at the frequencies significantly affected by the field (listed in Table II) were summed. For subject 1, for example, the values were 2157, 2243, and 300 μV^2 at 1, 1.5 and 14 Hz during application of B_{DC} (Fig. 2); thus, the total change in power during application of B_{DC} was 4700 μV^2. Application of B_{AC} and B_{DC+AC} produced 700 and 3100 μV^2, respectively (Fig. 2). Consequently, the sum of the effect on the EEG produced by the individual fields was 4700 + 700 = 5400 μV^2, compared with 3100 μV^2 when the fields were applied simultaneously. The overall results of a similar analysis for all subjects is given in Table III. The total EEG power (the sum of the absolute values at each frequency that was significantly affected by the indicated magnetic fields) did not differ significantly between the conditions examined, suggesting that the fields did not act synergistically.

Discussion

Two second exposure epochs involving static or 60 Hz magnetic fields caused statistically significant changes in the EEG in 19 of 20 subjects tested. Overall, 35% of the subjects responded to B_{DC} (Table II), which consisted of a static field, 0.78 gauss, applied orthogonally to the geomagnetic field. If we assume that the geomagnetic field at the latitude of our laboratory was 0.5 gauss, then the magnetic condition to which the subjects actually

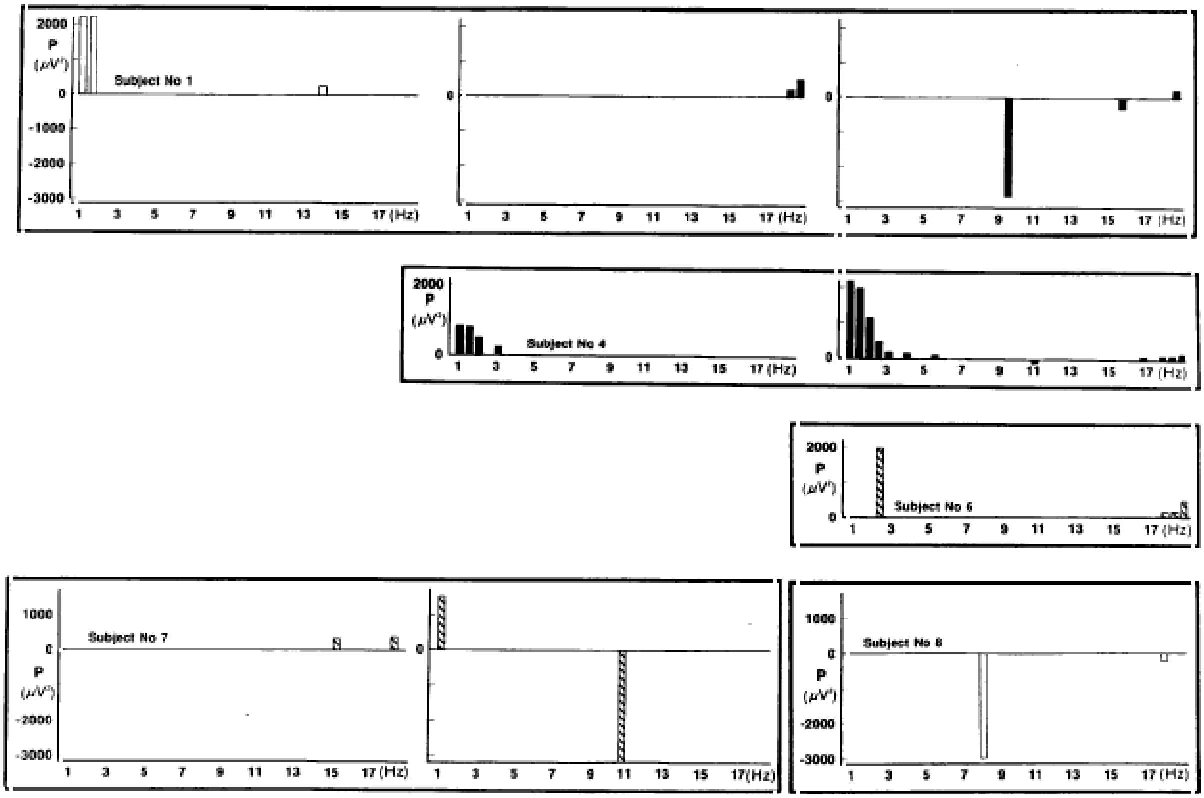

Fig. 2. Change in EEG power (P) from representative patients (subjects 1—10) that responded to the magnetic fields. $P = P_B — P_0$ where P_B and P_0 are the mean power values recorded during the field and control epochs, respectively. The magnetic fields corresponding to each column of graphs were B_{DC} (left), B_{AC} (middle) and B_{DC-AC} (right). Graphs enclosed within a panel are data obtained from one subject. Only significant results are displayed. Solid, open and cross-hatched bars represent data from C, P and O electrodes, respectively. The off-scale values were: subject 1, 24, 514, 8718 at 1 and 1.5 Hz, respectively; subject 4, 4192; subject 7, —8100.

responded consisted of a change in magnitude of the static field from 0.5 to 0.93 gauss (the effective magnetic field due to the vector addition of 0.5 and 0.78 gauss), and a corresponding change in direction (rotation of the resultant field toward the horizontal). Since the subjects were motionless in the static field, direct detection of the magneto-static field, rather than Faraday induction, is a more likely mechanism underlying the field-detection process. Such an interaction occurs in bacteria (Blakemore et al. 1988), and birds (Southern 1988), as assessed by behavioral responses to the field. Magnetic particles that might be involved in static-field detection have been reported in human subjects (Baker et al. 1983).

Seventy percent of the patients and 80% of the normal subjects responded to BAC (Table II). Our criteria for concluding that a response occurred (a success) was that presentation of the field resulted in at least two pairs of statistically significant changes in the EEG frequencies measured from the C, P, or O electrodes. There are several possibilities regarding the direction of differences in two bilateral pairs: the differences might correspond to increased or decreased power in the exposed vs. control epochs, or one instance of each case might occur. Previously (Bell et al. 1991), we required that the changes must occur in the same direction and found that detection occurred in 50% of 14 normal subjects exposed for 2 sec epochs to 0.25—5.0 gauss, 40 Hz. Since no false positives occurred in that study, we removed the condition as an a priori requirement in this study for concluding that a subject detected a magnetic field. Subjects 5, 7, 10 and 19 would have been scored as non-detectors for BAC under the criteria employed previously (Bell et al. 1991). Since no false positives were seen during sham exposure in this study despite removal of the additional condition, our a priori statistical criteria for the acceptance of a field-induced change may still have been too stringent, and resulted in type 2 statistical errors (incorrect acceptance of the null hypothesis). The possibility of type 1 statistical errors (incorrect rejection of the null hypothesis) also exists because the method developed to analyze the EEG has not yet been verified by independent investigators. Beyond statistical considerations, other potential sources of error include unrecognized movement artifacts, interference due to respiration, and electrical artifacts caused by induced 60 Hz potentials that may have been manifested at frequencies below 18 Hz. Additionally, the effect of the cut-off frequency of 0.3 Hz has not been determined; it is possible

TABLE III

Comparison of the magnitude of the observed changes in EEG power at frequencies at which field sensitivity was observed during application of the combined fields (B_{DC+AC}) vs. the magnitude of the changes observed during application of the individual fields (B_{DC} + B_{AC}). The total EEG power is the sum of the absolute values of the power at each frequency that was significantly affected by the indicated magnetic fields. B_{DC} + B_{AC}, sum of power changes seen during sequential presentation of B_{DC} and B_{AC}. B_{DC+AC}, sum of power changes seen during simultaneous presentation of the fields. The mean and standard error are listed. Frequency-specific power changes for representative subjects are shown in Figs. 2 and 3. The probability *(P)* that the means differed was determined by the paired test. NS, not significant *(P*> 0.05).

Subjects	Total EEG power (μV^2)		
	B_{DC}+B_{AC}	B_{DC+AC}	*P*
1—l0(patients)	5238±1895	3417±1018	NS
11—20(normals)	7501±1856	4100+1577	NS
1—20 (all subjects)	6369±1315	3758± 911	NS

is possible that field-related DC effects may have been truncated by the particular choice of cut-off frequency.

Preponderantly, detection of BAC was associated with increased EEG power during presentation of the field, compared with the power observed during the control epochs (Table II). This result is opposite to that found previously (Bell et al. 1991) when subjects were exposed to 0.25—0.5 gauss, 40 Hz. Several lines of reasoning dissuaded us from the view that the difference in field strength between the two studies was important in determining the difference in direction of the observed effects (Becker and Marino 1982). Frequency may have been the responsible factor: since all subjects in this study were exposed to environmental 60 Hz electric and magnetic fields throughout life (23—61 years), the EEG response to 60 Hz magnetic fields may have been conditioned in some manner, and consequently not representative of responses at other frequencies.

Low-frequency magnetic fields have been associated with cancer following exposure of up to 18 years (Wertheimer and Leeper 1979), and with altered serum triglycerides following exposure for 1 day (Beischer et al. 1973). In such instances, mechanistic speculation appropriately involves considerations of field interactions with the particular cells that actually exhibit the observed pathology (Adey 1988). For example, one might envision a field-lymphocyte interaction in which the EMF promotes a previously initiated cellular change, resulting in cancerous growth, or a field interaction with enzymes catalyzing

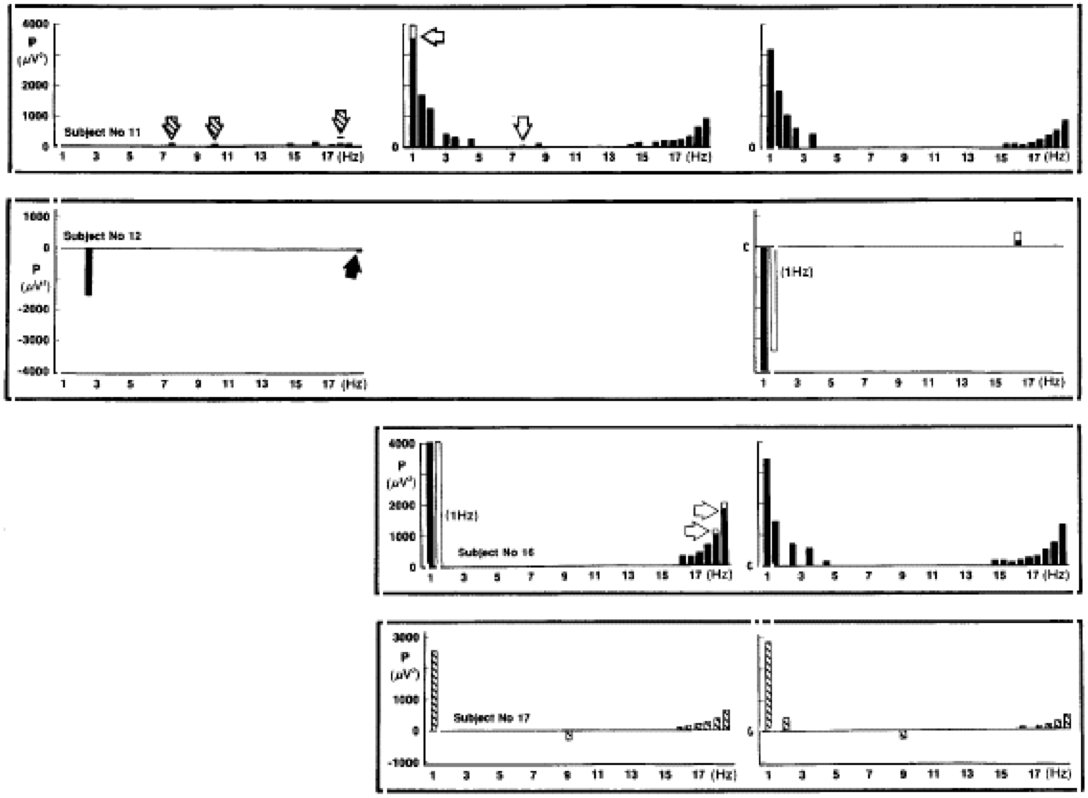

Fig. 3. Change in EEG power (P) from normal subjects (subjects 11-20) that responded to the magnetic fields. P = $P_B – P_0$ where P_B and P_0 are the mean power values recorded during the field and control epochs, respectively. The magnetic fields corresponding to each column of graphs were B_{DC} (left), B_{AC} (middle), B_{DC+AC} (right). Graphs enclosed within a panel are data obtained from one subject. Only significant results are displayed. Solid, open and cross-hatched bars represent data from C, P and O electrodes, respectively. Small but statistically significant differences are indicated by arrows. The off-scale values were: subject 16, 8094, 5132 at the C and P electrodes, respectively.

intermediary metabolism, resulting in altered blood fat levels. The effect on EEG described here, however, was manifested following exposure for only 2 sec. Probably, there exists no mechanism for changing CNS activity so rapidly other than one involving detection of the external stimulus by cells within the nervous system itself. The data, therefore, seem to require that alterations in patterns of spike potentials (Bialek et al. 1991) or subthreshold changes in membrane potentials (Schmitt et al. 1976) must occur as a consequence of the presentation of the field. Perhaps the simplest process consistent with the observed data is a membrane channel having energy states that become non-degenerate in the presence of an EMF, leading to non-threshold changes in membrane potential and consequent changes in spontaneous rhythmic electrical activity that is perceived centrally as an afferent signal.

Detection of B_{DC} occurred at the O electrodes as often as at the C and P electrodes combined (5 times in each instance); in contrast, with B_{AC}, detection at the O electrodes occurred only 3 times, compared with 18 times at the C and P electrodes. The increased frequency of detection of B_{AC} at the C and P electrodes approached statistical significance ($P = 0.092$, χ^2) and may indicate that the neural structures that provide the largest relative contribution to the signal measured at the C and P electrodes are the site of detection or processing of the information indicating the presence of BAC. In rabbit studies (Bell et al. 1992) we found no evidence that the EEG was affected by 2 sec exposures to 1 gauss, 20 Hz when sampled from an occipital scalp electrode. The result was therefore consistent with the observation here that the occipital is a relatively insensitive scalp location for the detection of EEG effects due to B_{AC}.

Among the patients, the likelihoods that the individual and combined field would be detected were identical, but among the normal subjects detection of the combined fields was less likely (Table IV). Our experimental design does permit a determination of whether the difference arose because of sampling errors, increased sensitivity to the individual fields among the normal subjects, or their decreased sensitivity to the effect of combined fields. Overall, 80% of the subjects detected B_{DC} or B_{AC}, or both, and 65% detected the combined fields (Table IV). The pattern of detection by the subjects during application of the combined fields did not differ significantly from that seen when the fields were applied individually (Fig. I and Table V). Thus the action of the combined field could not be distinguished from the sum of the actions of the individual fields. Similarly, when the magnitude of the field-induced changes in EEG power using the combined fields was compared with the sum of the responses observed when the fields were applied separately, the two cases could not be distinguished (Figs. 2 and 3, and Table III). Thus, neither the rate, pattern, nor magnitude of the EEG changes manifested by the subjects provided good evidence that the responses with the combined fields differed from those observed when the fields were applied individually. For these reasons, the hypothesized mechanism of interaction involving preferential extraction of energy from the magnetic field by channelized Ca^{2+} was not supported by the observations.

TABLE IV

Probability of a response to individual and combined field conditions. *P*(AC, DC), the probability of a significant response to B_{DC} or B_{AC}, or both. *P*(AC+DC). the probability of a response to B_{DC+AC}. Data from Table II.

Subjects	*P(DC,* AC)	P(DC + AC)
1—10 (patients)	0.7	0.7
11—20 (normals)	0.9	0.6
1—20 (all subjects)	0.8	0.65

TABLE V

Comparison of the distribution of EEG frequencies at which field sensitivity was observed during application of the combined fields with the sum of the distributions observed for the individual fields. The distributions for NDC+AC, $N_{0\sim}$, and NAC are shown in Fig. 1. *P*, probability that NDC+AC differed from Noc +NAC by the sign test. NS, not significant *(P*> 0.05).

Subjects	Number of cases		*P*
	$M_{DC+AC} > N_{DC} + N_{AC}$	$N_{DC+AC} < N_{DC} + N_{AC}$	
1—10 (normals)	8	15	NS
11—20(patients)	11	12	NS
1—20 (all subjects)	19	27	NS

Proof of ion resonance requires a showing of a relative maximum or minimum in a dependent variable as the frequency of the alternating field is varied through the theoretically predicted value, while holding constant the magnitudes and spatial relationships between the static and alternating fields (McLeod et al. 1987). The magnitude of the dependent variable in our study (mean Fourier coefficient) was not determined from a single measurement, but from an experiment involving multiple presentations followed by statistical analysis to determine whether the measured value actually differed from the baseline. It was not possible to perform multiple experiments (corresponding to multiple values of the frequency of the alternating field) on individual subjects because such a procedure would have required isolation of the subject for an unacceptably long time. Thus, although we found no evidence that the resonance conditions altered the subjects' response to magnetic fields, compared with the responses when the fields were applied individually, the procedure employed was not optimal for such a determination.

The patients were less likely than the normal subjects to detect the individual fields (Table IV), and the observed changes in EEG power were smaller in the patients than the corresponding changes among the normal subjects (Table III). Three patients had abnormal clinical EEGs (subjects 1, 6, 8, Table I), and their magnetic-field responses were less characteristic in several respects, compared with the other subjects. Subject 1 exhibited a marked response to B_{DC} at 1 and 1.5 Hz; the magnitude of the response was 6 times greater than the strongest response seen in any patient at any frequency during exposure to BDC. In only 3 subjects was the observation of a response confined only to the condition of combined fields (B_{DC+AC}); in all 3 cases the subjects were in the patient group, and in 2 cases the clinical EEG was judged abnormal (subjects 6 and 8). Taken together, these data may indicate reduced or altered field sensitivity in subjects with neurological symptoms, but further studies employing well-defined inclusion criteria and clinical assessment norms are required to determine whether reactions of patients and normal subjects are indeed different.

In summary, the subjects exhibited altered EEG power following brief exposure to static and low-frequency magnetic fields. Consequently the results support the hypothesis that electromagnetic fields can be detected in the nervous system.

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