Neurobehavioral Effects of Power-Frequency Electromagnetic Fields

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Some laboratory experiments have suggested that power-frequency electric and magnetic fields (EMF) may be capable of influencing calcium efflux from cell membranes, pineal function, and circadian rhythms. As yet, however, no consistent, replicable laboratory model has been developed for any of these effects. Most assessments of human volunteers exposed to EMF have been negative, but occasional effects on vigilance or alertness and some modest effects on circadian rhythmicity have been reported. Several carefully performed studies of workers occupationally exposed to high electric-field strengths have failed to find effects on behavior or cognitive functioning. Although the bulk of human research on the effects of EMF on cognitive performance is negative, there has been less assessment of behavior and psychiatric symptomatology. Because some studies, in both humans and animals, have described effects of EMF on circadian rhythms, future research might concentrate profitably on the assessment of EMF in relation to depression and other cyclically mediated psychiatric disorders. — Environ Health Perspect 101(Suppl 4):101–106 (1993).

Key Words: Electromagnetic fields, 60-Hz fields, cognitive testing, behavior, suicide

Introduction

Assessment of the relationship between exposure to electromagnetic fields (EMF) and behavior and cognition in humans and animals is especially difficult. Three methodologic problems stand out. The first, which applies for the most part to animal studies, is that laboratory EMF exposure is not easily separated from concomitant exposures, such as noise, vibration, hair stimulation, and even mild electric shocks. When the outcome of interest is cancer or birth defects, these secondary exposures are unlikely to be confounding; but when changes in motor activity or circadian rhythm are found, or animals appear averse to an exposed location, the role of these other potentially noxious stimuli must be considered.

The second difficulty, a feature of both animal and human studies, is the subjective and transient nature of many behavioral and cognitive measures. Although mismeasurement can occur with any human health outcome, the condition most studied in relation to EMF, cancer, has the virtue of being based, in most cases, on tissue diagnosis. Characteristics of behavioral and cognitive measures, however, are their dependence on the specific conditions under which they are obtained, the cooperativeness of the subject, and the skills of the examiner.

The third difficulty, specific to human studies, is that many measures of cognition and behavior are correlated powerfully with socioeconomic status and educational background. Teasing out the impact of these factors can prove a challenge to investigators. These concerns should be kept in mind as one reviews the specific studies below.

A remarkable amount of the research in this field is not found in the peer-reviewed literature but in the form of reports to government agencies. Not only does this make retrieval of the findings difficult, but it indicates that many of the results described may not have been subjected to adequate peer review.

This manuscript was prepared as part of the Environmental Epidemiology Planning Project of the Health Effects Institute, September 1990 – September 1992.

Suggestions from the Laboratory

A wide variety of experiments has been performed to investigate the effects of EMF on several cellular, subcellular, and whole animal preparations. Major differences in experimental set-up, in frequency and intensity of EMF exposure, and in choice of end points characterize the literature as a whole. Although many findings have been reported, the vast majority have not been replicated consistently, partly because of the heterogeneity of the experimental models currently in use. So far, no single experimental model can be pointed to as a consistent biological marker of EMF exposure. In searching for clues for the more effective framing of epidemiological research, this paper concentrates on those laboratory findings that have been at least partly replicated in more than one laboratory.

Calcium Efflux

Among the few replicated laboratory findings in this field is the effect of 60-Hz electric-field exposure on the efflux of calcium across brain tissue cell membranes (*1–4*). Because calcium efflux serves as a messenger of electrochemical signals in the brain, it could be the basis for effects of EMF on behavior in the whole animal, although it is uncertain precisely what dysfunction would be predicted by this biochemical disturbance. Lovely has suggested a possible effect on memory skills (*5*).

Although the calcium efflux effect has been replicated, its direction has not. Bawin et al. found, in chick brain tissue, that calcium efflux decreased with EMF exposure (*1*), but Blackman et al. found, in the same preparation, an increase (*2,3*). Another surprising finding was an absence of gradient of risk with gradient of exposure; rather, only specific combinations of frequency and intensity produced the effects described. Moreover, these effect windows were not identical in the two sets of experiments. For Bawin et al., effects were seen at 10 V/m with frequencies of 6 and 16 Hz; for Blackman et al., an intensity window at 60 Hz was found for 35 to 43 V/m. Inasmuch as these precise effect windows were not hypothesized prior to the experiment, one cannot rule out the role of chance in their specification.

Blackman, in replicated experiments, also found that the calcium efflux effect induced by EMF exposure was sensitive to prenatal (egg) exposure to 50- and 60-Hz fields at a variety of intensities (*6*). Gunderson, working with chick spinal cord (as contrasted to chick brain), failed to find effects of EMF exposure on calcium efflux (*4*).

Pineal Function and Circadian Rhythms

Two studies have noted depression in nighttime melatonin production in rats (*7,8*). Related changes seen in single investigations include period shifts in norepinephrine, serotonin, and dopamine secretion (*9*), and reductions in cerebrospinal fluid and 5-hydroxyindole acetic acid without period shifts (*10*). These studies, which point to EMF effects on the pineal gland or the suprachiasmatic nucleus, are paralleled by laboratory findings of the effect of EMF exposure on circadian rhythms.

Dowse and Palmer (*11*) and Ehret (*12*) were able to show either entrainment of mice, phase delays, or other changes in metabolic rhythms with electric-field exposure. The Ehret studies used very high field strength (130 kV/m), which may limit the importance of their findings. The Dowse and Palmer studies are among those that have been criticized for lack of singularity of the experimental exposure; Roberts (*13*) has argued that noise and corona discharges might account for the findings. Dowse (*14*) later showed phase changes in the locomotor activity of drosophila. Ehret and co-workers' success in entraining mice rhythms was not paralleled by their experiments in rats (*15,16*), whose body temperature, activity, and food intake cycles were not affected by exposures of 4.5 to 55 kV/m at 60 Hz.

Sulzman and Murrish (*17*) showed some effects on the circadian rhythmicity of food intake and oxygen consumption in squirrel monkeys with fairly high exposures (26–39 kV/m), but not all exposed animals showed the effect. The circadian cycle of fungal spore formation, however, seems unperturbed by magnetic fields as high as 32 G (*18*).

Although not a study of rhythmicity, the work of Thomas et al. (*19*) has implications for human cyclical disorders, such as bipolar depression. Four of five rats exposed to a combined 60-Hz magnetic field and magnetostatic field of 26 μT showed consistent, large increases in their responses to a differential reinforcement of low rate schedule in which a food pellet resulted only if the rat pressed a lever twice 18 to 24 sec apart. Because the exposure corresponded to the cyclotron resonance condition for lithium ions, the authors speculated that the effect might be related to efflux of lithium ions in brain cells, paralleling the changes that might be occurring with lithium carbonate treatment of bipolar disorders.

Human Studies

Three kinds of investigations in humans have been reported: *a*) neurobehavioral testing or assessment of experimentally exposed volunteers, *b*) assessments of occupationally exposed workers, *c*) correlational studies of EMF residential exposure with suicide.

Neurobehavioral Effects in Volunteers

Human volunteers exposed to EMF have been studied for changes in circadian rhythmicity, verbal reasoning, attention skills, mood, and perception of electric fields. The literature is modest, and several reports are not in the peer-reviewed press [e.g., Johansson et al. (*29*) and Rupilius (*30*)—cited by Stollery (*20*), also Sander et al. (*21*), Fotopoulos et al. (*22*), and Graham et al. (*23–25*)—cited in Gamberale et al. (*26*), and Roberge (*35*), and Stopps and Janischewskyj (*36*)—cited in Broadbent et al. (*33*)].

Several of the human studies do not choose as outcomes the best-known and most reliably administered behavioral and cognitive measures. Idiosyncratic choice of test procedure seems the norm, and replication of the same cognitive or behavioral test by more than one investigator is rare.

A remarkable and much-cited study of the effect of EMF (*27*) exposure on circadian rhythm is an example of this experimental idiosyncrasy. The investigators constructed two underground chambers, one of which was lined with material that prevented entry of the earth's natural electro-magnetic field into the chamber. Both chambers avoided any indication of solar time (no windows, clocks, etc.). With humans living in these chambers for 3 to 8 weeks at a time, it was found that the naturally occurring circadian rhythms were lengthened about 15 minutes by shielding but shortened about 70 minutes when an electric field of 2.5 V/m at 10 Hz was applied to the shielded room. These changes represent less than a 5% change from the natural 24- to 25-hour cycle and are not known to carry any clinical significance.

This work is considered "probably the most significant work on the effects of electromagnetic fields on circadian rhythms" (*28*); yet it is unlikely to be replicated by other investigators because of the expense of the experimental arrangement, the need for human volunteers to spend a great deal of time in what is surely an unpleasant setting, and the modest effects observed even under these strenuous conditions.

Stollery (*20*) examined 76 volunteers in a cross-over trial. The subjects (all male) were exposed to a 500-μa current (50 Hz) via skin electrodes. In the control situation, no current was passed, but the blindness of the experiment was partly compromised by the ability of some subjects to perceive the electric field. No effects were found on self-reported stress, semantic reasoning, vigilance, or concentration. Some effects were found on a subset of the vigilance test (time taken to identify nontarget numbers), on arousal, and on some parts of the syntactic reasoning test. However, these effects were restricted to the second day of this 2 day experiment and thus were found only in one half of the experiments.

Studies by Johansson (*29*) in Sweden and by Rupilius (*30*) in Germany apparently failed to show neurobehavioral effects of exposures of 20 kV/m. With exposure to 100 kV/M, Kanz (*31*), cited in Knave et al. (*32*), found subjective reports of changes in hearing and taste and "pains in the nerves." How the subjects knew that the origin of their pain was neural is not clear.

Graham and colleagues have performed several experiments on young, male, human volunteers exposed to 60-Hz electric and magnetic fields at a variety of field strengths (*23–25*). Among behavioral and cognitive parameters assessed, mood, simple reaction time, memory span, fatigue, and decision-making ability were not consistently affected by the exposure, though some effects were seen in some exposure conditions, particularly with a fast, intermittent pattern of electric-field exposure. More consistent effects were noted in slowing of the heart rate.

Studies of Occupationally Exposed Workers

A wider variety of neurobehavioral outcomes has been studied in workers exposed occupationally to EMF. These studies have assessed reaction time, vigilance, short-term memory, perception, psychiatric symptoms, self-reported memory loss, and manual dexterity. Several of these tests have been used in more than one study. EEG findings have been assessed in two studies. Moreover, a group of four occupational studies, to be described in detail, verified the occupational exposure through measurement of electrical and/or magnetic fields in the workplace.

Early studies of electrical workers in the Soviet Union have not been considered useful contributions. These studies described nonspecific symptoms, such as dizziness and headache, in workers with unmeasured and uncertain exposure, and the studies failed to include controls.

Knave et al. (*32*) assessed 53 Swedish men who had worked for more than five years in high-voltage (400 kV) substations. An equal-sized control group consisting of low-voltage (220/380 V) distribution workers was matched individually to the exposed cohort by location, age, and duration of employment. No adverse effects of high-voltage exposure were found in eight psychological performance tests (reaction time, two memory tests, manual dexterity, addition, tapping, perceptual speed, and matrices), nor on EEG examinations, nor on self-reported (on a standardized questionnaire) anxious or depressive symptoms. In fact, for several tests, scores were higher for the exposed group, who had a higher level of educational achievement than the controls. Control for educational background in the analyses was not attempted.

Broadbent et al. (*33*) interviewed 390 electrical power transmission and distribution workers and obtained exposure measurements in 287 of them. No correlation was found between either measured or estimated EMF exposures and self-reported headaches, anxiety, obsessional or somatic symptoms, depression, or episodes of forgetfulness.

Baroncelli et al. (*34*) examined four groups of male employees who worked in and around the 258 electric power substations (220 kV) of the Italian State Railways. The four groups were defined by the number of hours per week they were estimated to have been exposed to maximum electric-field strength. One group, employed in the same departments as the others, had no exposure, while the other three groups were exposed for 1, 10, and 20 hr per week. No differences were found among the four groups in acoustic reaction time, visual reaction time, IPAT-anxiety state, and state-trait anxiety.

Gamberale et al. (*26*) studied 26 linesmen during 2 working days immediately before and immediately after performing a simulated routine inspection on a 400 kV power line. On one of the days the power line was in operation; on the other, it was not. The workers worked on the line from 10:00 a.m. to 2:30 p.m. except for a 30-min lunch break, which was taken in a trailer placed under the line to insure continuity of exposure. No differences were found in the exposure and control conditions in a variety of self-reported symptoms, such as wakefulness, stress, concentration, energy level, headache, and anorexia. No changes were noted in a variety of tests of color word vigilance, time to pair symbols and digits previously presented as pairs, and number of presented digits that could be remembered. Simple reaction time did not differ overall between the two conditions, but the improvement from morning to afternoon testing seen in both conditions (possibly a practice effect) was slightly, but significantly, less in the exposed condition, even though both reaction times were better in the exposure condition. This latter observation was the only significant difference among the dozens of behavioral variables assessed.

Each of these four studies included a measure of exposure over and above the worker's job classification. In three studies, Knave et al. (*32*), Broadbent et al. (*33*), and Gamberale et al. (*26*), study subjects wore an exposure meter during or shortly before the period of investigation.

Knave et al. (*32*) measured electric-field strengths at a height of 1.8 m in the high-voltage substations using a field intensity meter but did not provide the findings in their paper. The study subjects also wore dosimeters for an unspecified period of time, during which the percent of time spent exposed to four ranges of electric-field strength (<5, 5–10, 10–15, 15–20 kV/m) was measured for four different types of work. It was found that less than 5% of work time was spent in a field of 10 kV/m or greater during inspection work, "every-day" work, and testing, but that revision of breakers (which involves ascent to the same level as the breaker, 6–8 m) involved exposure above 10 kV/m for 34% of the time and above 15 kV/m 16% of the time.

Broadbent et al. (*33*) had their workers wear a single-channel electrochemical exposure meter strapped to their left arms for two weeks closely preceding the questionnaire administration. About 10% of the sample received exposures above 6.6 kV/m. They concluded that their subjects received exposures an order of magnitude lower than those of Knave et al. (*32*). Gamberale et al. (*26*) used a BE-log dosimeter, which detects both electric and magnetic fields, and which was worn during both the exposed and control conditions. Average exposure was 2.8 + 0.35 kV/m, and 23.3 + 4.2 μT in the exposed condition.

Baroncelli et al. (*34*) did not obtain personal dosimetry but measured electric-field and magnetic-flux density at two substations (all Italian railway substations apparently were built to identical specifications). Electric fields ranged from 1 to 5 kV/m and magnetic fields ranged from 4 to 15 μT at 1.5 m. Two unpublished Canadian studies cited by Broadbent (*33*) failed to find neurobehavioral effects in workers.

Epidemiologic Studies of Suicide and Depression

Two English studies have assessed, each in a different way, the distance between the last known address of 598 suicides and of 598 control subjects (selected randomly from the electoral register) and overhead high-voltage transmission lines.

In the first publication (*35*), exposure was assessed based on calculations of the maximum electric- and magnetic-field strength at any address using the known configurations of voltage, current, orientation, and other factors specific to the nearest high-voltage transmission line. Three relationships are presented: the proportion of addresses in both series with estimated electric fields exceeding 0.1, 0.5, and 1.0 V/m; the number of rank-ordered pairs (based on ranking the case and control series separately on electric-field exposure) in which the value for the suicide address exceeded the control address; and, within each of the three defined electric-field thresholds (0.1, 0.5, 1.0 V/m), the number of suicides and controls fitting into each decile of exposure.

The proportion of addresses above the 0.5 and 1.0 V/m threshold is slightly higher among controls, but no statistical test or measure of association is presented. The number of pairs in which the controls exceeded the suicide in electric-field exposure was significantly more than the converse condition. Within each exposure level, a significant difference between the two groups for exposure is reported, but inspection of the data does not indicate this is necessarily based on higher exposure deciles among the suicide victims.

This fairly strong result, indicating suicides were less exposed to electric and magnetic fields, is interpreted by the authors as evidence that a correlation between the two variables had been established, but that it is a relationship whose direction (i.e., whether suicides were less or more exposed to EMF than controls) is uncertain. They state their conclusion as follows: "It is not possible to determine whether more or less than the expected number of suicides occurred at the higher field-strength addresses" (*35*).

In a second paper (*36*), the group measured magnetic-field strength 0.5 m from the front door of all but 12 of the 1196 subjects described in the previous study. The mean magnetic-field strength was 867 μG in the suicides, 709 μG in the controls, a significant ($p < 0.05$) difference, but one that represents just one-seventh of the pooled standard deviation of more than 1000 μG. Of the suicides, 47% had magnetic-field exposures above the median as compared to 39% of controls ($p < 0.01$). The authors provided a calculation [challenged by Bonnell et al. (*37*)] indicating the median magnetic field measured in their study (400 μG) could induce an electric field inside the human body similar to that found to affect behavior in monkeys (i.e., 3.5–4.0 V/m). Noteworthy are the authors' conclusions that most of this magnetic field must have come from indoor appliances and wiring and not the high-voltage transmission lines, which were assumed to produce no more than 50 μG in the residences.

Perry et al. (*38*) continued the theme of this work in the same region of England by measuring magnetic fields at the addresses of patients discharged from the hospital with depression and myocardial infarction. Again, the addresses were compared with addresses of controls obtained from electoral registers. The only statistical result presented is the one-sided probability (0.033) associated with the regression coefficient for suicide case status prediction of measured magnetic field, controlled for electoral ward and distance from the nearest roadway (thought to contribute to noise and pollution and thus possibly confounded with depression). No relationship was found for myocardial infarction. The average field strength was considerably higher than in the previous study, 2.26 μG in the depressive patients, 2.07 μG in controls.

In an earlier paper, Perry and Pearl (*39*) found that residents of an apartment block nearer to the main electrical supply cable, and to the corresponding higher magnetic field, were more likely to be admitted to the hospital both for depressive illness and myocardial infarction than residents of the same block living at a greater distance from the supply cable.

This series of epidemiologic papers leaves much to be desired. The influence of confounding factors that might link depression or suicide to place of residence or to use of electrical appliances is not addressed. Indeed, there is virtually no exploration of the sociodemographic characteristics of the compared populations. Suicide victims and patients with depression are unlikely to be comparable to a random sample of individuals who are well and stable enough to be entered onto the electoral rolls. Although little work has been done on the socioeconomic aspects of power-line and electric-cable siting, it would not be surprising if there were associations between, for example, urbanization and crowding and location of EMF exposure sources. These variables might, in turn, be linked to depression or suicide.

More recently, a British study of suicide by occupational classification reported essentially no relation with job titles associated with EMF exposure. A slight excess of suicide was seen in radio and TV mechanics in two vital data sets obtained a decade apart, but this group did not have particularly high occupational EMF exposure (*40*).

Implications for Future Epidemiologic Research

Hypotheses Worth Pursuing

At times, epidemiologic research is in a position to pursue in the population clues about disease causation that are reflective of well-established pathophysiological mechanisms. More often, however, having such variables available is an unattainable luxury. Indeed, in many of the triumphs of epidemiology, the biological mechanisms were revealed after, and not before, the epidemiologic association had been established. This was true for smoking and lung cancer, prenatal diethylstilbestrol (DES) and vaginal cancer, aspirin and Reyes syndrome, prenatal rubella and cataract, cholera and water supply, and a host of other epidemiologic discoveries.

However, in each of the examples listed above, and perhaps in virtually all epidemiologic discoveries, there was a body of knowledge that made the association biologically plausible. Both cigarette smoke and DES were known laboratory carcinogens (though not known to produce the specific disease studied by epidemiologists); aspirin is a liver mitochondrial toxin, and prenatal viral infections have long been known to produce fetal damage. A reading of John Snow's 1854 treatise on cholera and water supply will show how he adhered closely to known biological principles and evidence even though microbes were not yet known causes of disease. True epidemiologic associations do not emerge out of the blue.

Thus, even if the mechanisms of the disease in question have not been worked out fully, an important epidemiologic precept is, or ought to be, that epidemiologic studies must have a serious biological basis. Studies that simultaneously examine suicide and ischemic heart disease, such as those of Perry et al. (*38,39*), appear to have no basis in plausible biology. No laboratory experiment points to an effect of EMF on a biological mechanism common to suicide and to ischemic heart disease, if such a mechanism exists.

A particular risk in exposure-based epidemiology, such as environmental epidemiology, is that the exposure of interest will be assessed in relationship to any disease, symptom, or complaint available for study, regardless of biological plausibility. Under such circumstances, whether because of chance or bias, associations surely will be demonstrated. Biological plausibility is an important constraint not just on the interpretation of results but on the design of studies.

In the field of neurobehavioral relationships to EMF, there has been considerable expenditure on laboratory experiments but a failure to develop a consistent experimental model that would lend itself to extrapolation to epidemiologic research. In the absence of this mechanism, what directions ought to be pursued?

There appear to exist two sets of biological mechanisms in this area where findings have been replicated. The first is calcium efflux across the cell membrane; the second is in the function of that part of the nervous system involved in circadian rhythmicity.

A limitation of the calcium efflux model is that it seems to lend itself to a large variety of disease states. Pending the prediction of a specific neurobehavioral finding based on this model, even whole animal researchers, let alone epidemiologists, have nowhere to turn if they wish to verify this model on their study populations.

On the other hand, rhythmicity, both circadian and seasonal, is a potentially powerful mediator of psychiatric state in humans. Psychiatric disorders of rhythmicity, such as seasonal-affective disorder and premenstrual syndrome, are well established. There exists, therefore, a plausible biological basis for linking these disorders, or similar ones, to EMF exposure. In the present state of laboratory-based knowledge, the hypothesis that EMF exposure might be a contributing cause to depressive illnesses seems worthy of epidemiologic assessment.

Studies Worth Undertaking

Although most scientists have a conscious or unconscious bias in favor of studies that produce positive findings, the most impressive human studies in the EMF-neurobehavior field are the careful investigations of cognitive performance in occupationally exposed men, studies whose results are negative.

Inasmuch as the subjects of these studies had been exposed occupationally for a considerable period of time, usually years, and their exposure in typical work situations had been measured and found to exceed the general population exposure by orders of magnitude, the absence of any real effects on a variety of cognitive measures must be viewed as a strong and reassuring negative result. These studies suggest there is little or no value to larger scale epidemiologic research that attempts to link cognitive outcomes to EMF exposure.

The strength of these studies indicates that populations occupationally exposed to high intensities of electric- and magnetic-field exposure are likely to be excellent candidates for studies of the incidence or prevalence of depression in relation to EMF exposure. A few questionnaire items in several of the occupational studies [e.g., Broadbent et al. (*33*), Knave et al. (*32*), Gamberale et al. (*26*)] assessed mood and similar parameters. However, standardized instruments for the detection of depression were not used, and none of the studies had a large enough sample to detect elevated levels of clinical depression. Inasmuch as women are more liable to depression, at least at younger ages, it will be important to look carefully for exposed female populations. To clarify the linkages to the abnormalities of rhythmicity observed in the laboratory setting, it will be necessary to screen especially for seasonal disorders, and this may require studies that cover several seasons or that take account of the menstrual cycle in the assessment of depressive symptoms.

These studies will be more valuable if conducted using prospective cohort or matched-exposure approaches, as contrasted to the case–control method. Important information is conveyed by using a sampling of the actual work experience to demonstrate that the exposures are indeed high rather than relying on estimates based on work classification. Case–control studies of depression in relation to occupational exposure might be of some value but are unlikely to have access to measured exposures. Moreover, employees in whom exposure causes major health effects may leave the work force and thus be excluded from case–control studies.

Occupational studies obviate some of the unresolved issues surrounding residential EMF exposure. It is surprising that wiring codes and electrical distribution patterns in neighborhoods have not been studied sociologically. Is it likely that neighborhoods in the United States, so carefully segregated by income and class, have identical distributions of overhead transmission lines, transformers, and electrical substations? One needs only to think of the expression "the other side of the tracks" to note the possible association of social class with exposure to the electricity associated with railroads. Until we have a better understanding of these patterns of association, all epidemiologic studies based on residential exposure will remain suspect for confounding, particularly for neurobehavioral health issues, all of which are powerfully linked to social class and economic opportunity.

For this reason, case–control studies of depression in relation to residential exposure to EMF do not seem a promising avenue of research, at least until the above-noted issues have been addressed.

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