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Possible Health Hazards From Exposure to Power-Frequency Electric and Magnetic Fields — *A COMAR Technical Information Statement*

Summary

In recent years concerns have been raised about the biological effects of exposure to electric and magnetic fields at extremely low frequencies (ELF), particularly those associated with the distribution and utilization of electric power. In 1989, the Institute of Electrical and Electronics Engineers (IEEE) issued an "Entity Position Statement" which stated that "there is not enough relevant scientific data to establish whether common exposure to power-frequency fields should be considered a health hazard" and that "there is general agreement that more research is needed to define safe limits of human exposure to power-frequency fields."

After examination of relevant research reports published during the last ten years, COMAR concludes that it is highly unlikely that health problems can be associated with average 24-hour field exposure to power frequency magnetic fields of less than 1 μT (10 mG). Good laboratory evidence shows that magnetic fields 100 to 10,000 times higher than this level, either ELF sinusoidal or pulsed, can induce a variety of biological effects, including beneficial health effects such as bone or tissue healing. Many of the reports of effects of weaker fields should be considered preliminary, as some observations have not been reproduced in different laboratories, while others, observed in cells, have not been clearly connected to effects in intact animals. Also, the means of interaction of low-level ELF fields with cells, tissues or laboratory animals is not fully understood; therefore the health impacts of such weak fields on intact animals and humans, if any, cannot be predicted or explained. Further research is needed to confirm or negate reports of effects of weak fields, and to determine mechanisms and relevance of these effects to actual health hazards. Continued study in this complicated area will enhance our understanding of biological systems, as well as help identify levels and types of ELF exposure that may be deleterious to human health.

Introduction

Electric fields associated with the distribution and use of electric power are clearly hazardous under some conditions of exposure. Obvious hazards include shock and burn. Electrocution, an extreme form of electric injury, kills several hundred Americans every year. Such hazards normally require that currents be passed directly through the body by contact between an energized conductor and ground. In theory, exposure to strong power frequency magnetic fields, without contact with a conductor, can also result in shock and burn. However, these hazards require field strengths that are far higher than those normally encountered in the workplace or at home.

Magnetic fields above 50 mT can stimulate excitable tissues (muscles, nerves), and above 500 mT may cause ventricular fibrillation [1]. In residences and most workplaces, magnetic fields are typically below 1 μT (more usually below 0.5 μT, or 0.00001 times the flux density required to stimulate nerves) and electric fields are typically below 100V/m. Since European countries use a higher voltage, lower current power system, electric fields are stronger and magnetic fields weaker than in the US, where the bulk of surveys have been done. Swanson and Kaune reported that the mean magnetic flux density in US homes is about 0.07 μT, with lower levels in Europe [2]. Environmental exposure to power-frequency electric fields greater than 100 V/m is rare in the US except near high-voltage power lines, although a person can experience localized fields of tens of thousands of volts per meter close to domestic appliances such as electric blankets, and wiring.

Public concern and scientific controversy has arisen about reports of possible links between exposure to electric or magnetic fields in the home or workplace and disease (various forms of cancer, in particular). Electric fields have received less attention, partly because they are readily shielded by building materials, so that fields due to overhead power lines are very much weaker inside a building than outside [3] [4]. The few studies looking at cancer incidence associated with measured electric fields have found no correlation [5, 18, 24, 29].

For two reasons, this controversy has been difficult to resolve. First, the controversy encompasses aspects of physics, engineering, biology, biochemistry and epidemiology, and few scientists can fully grasp all of these subjects. Second, the reported effects are mostly very weak, so that both alternative hypotheses (fields either are or are not associated with disease) can logically be supported.

This Technical Information Statement is concerned with putative health hazards, principally cancer, from exposure to power-frequency electric and/or magnetic fields at levels typically found in the home and workplace [2]. In general this means electric fields below 100 V/m and magnetic field levels below 10 μT, though in some occupational settings electric fields above 10 kV/m, or magnetic fields greater than 1000 μT are encountered. The document focuses on scientific developments over the past three years related to this issue, and is addressed to a technical but nonspecialist audience.

Detection of Health Hazards From Low-Level Exposure To Environmental Agents

Adverse health effects such as cancer from chronic exposure to low levels of a physical or chemical agent are frequently characterized by a long time between exposure and the appearance of the effect. Such effects are typically identified and characterized by methods of risk assessment. For a review of cancer risk assessment as it applies to electromagnetic fields, see [6]. In identifying human carcinogens, it is important to consider all relevant information, although experts vary in how they weigh the different types of evidence available. Data are drawn from epidemiological studies, appropriate animal studies, and appropriate in-vitro (cellular) studies.

These different kinds of studies have different advantages and disadvantages:

Epidemiology, which is the study of the risk of disease and its determinants in the human population, provides direct evidence about health in human populations. However, epidemiologic studies of exposures to environmental agents or conditions are often difficult to interpret, because of the complexity of human populations. In addition, epidemiology is unsuitable for detecting small risks, or for detecting risks that are confined to small, but unidentified, subpopulations. In studies involving low levels of exposure, results are often inconsistent and reported associations between exposure and disease are weak, and it is typically unclear whether an observed association is caused by the exposure or a confounding factor in the study.

Laboratory studies, on cells or animals, can be used to assess the potential of an agent for causing or contributing to cancer. They cannot, however, prove that an agent will cause cancer in humans. Animal studies can be closely controlled, both in the uniformity of the test animals and in their exposure. A major carcinogen assay involves standardized laboratory animal studies, using a standard protocol, in which multiple groups of animals are exposed to an agent at various levels. Such tests are designed to detect dose-response relationships (i.e. an increase in disease with increasing exposure), or more rapid disease progression in individual animals. They typically involve very high exposure levels, and their relevance to human situations (where the exposure may be much lower) is often uncertain. Risk assessors use epidemiologic evidence to confirm results from animal studies, and vice versa.

In-vitro (cellular) studies may yield information about mechanisms of action of a chemical or physical agent, but their relevance to disease in intact organisms may be uncertain. They permit investigators to study the response of specific cells or tissues, but isolated cells may not respond in the same way as when they are within an intact animal. In-vitro studies attempt to control many different variables (temperature, light, vibration, growth medium, cell density and others in addition to the magnetic field parameters). They should be replicable in other laboratories. However, there may be a period of several years before a significant result is replicated, or fails replication in independent laboratories. Many reports of effects therefore must be still considered preliminary as insufficient time has elapsed to complete replication studies. Replication does not require exact duplication of an experiment, but it requires the completion of similar experiments with results that reinforce the conclusions of the original study.

Risk assessment necessarily is an uncertain process. One cannot prove that an agent does not cause cancer. Conversely, except for very few cases (e.g. tobacco smoke) no study is likely to be definitive, and judgments about the carcinogenicity (or noncarcinogenicity) of an agent have a certain level of uncertainty. Thus, agencies such as the Environmental Protection Agency (EPA) or International Agency for Research on Cancer (IARC) classify potential human carcinogens according to the strength of evidence available, weighing all relevant evidence according to the assumptions used by each agency, a method called by them a "weight of evidence" approach.

For these reasons, when examining evidence related to the issue of power frequency fields and cancer it is necessary to consider all relevant evidence, including studies reporting no effect of the fields, with due attention to the relevance of the study to carcinogen identification, and the quality of the study. Moreover, all three study types (epidemiology, animal testing, in vitro studies) are subject to many different sources of error, and independent replication is needed in different laboratories (or human populations) before results can be considered established.

Previous Expert Reports

The scientific literature related to power frequency fields and health is very large, with several thousand papers in the peer-reviewed literature. More than 100 epidemiological studies, and many animal and in-vitro studies, have been reported that bear on the question of cancer and power-frequency electric or magnetic fields. Many expert committees have examined this literature; reports include ORAU[7], NRPB[8], NRC[9], the NIEHS Working Group[10], and WHO[11]. All have concluded the evidence for carcinogenicity of weak 60-Hz magnetic fields is not sufficient to confirm an effect, due to limitations in the available data set.

Two large reviews sponsored by prestigious organizations have appeared in the last two years. The first of these, by a panel sponsored by the National Research Council - National Academy of Sciences (NRC/NAS) appeared in 1997. Though noting the association in the epidemiology studies between "wire codes" (a measure of residential proximity to power lines) and childhood leukemia, the NRC/NAS report concluded, "Based on a comprehensive evaluation of published studies relating to the effects of power frequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard." [9]

The second report, by the Working Group on EMF of the National Institute of Environmental Health Sciences (NIEHS) appeared in July 1998. This report concluded "there is limited evidence that residential exposure to ELF magnetic fields is carcinogenic to children on the basis of the results of studies of childhood leukemia" and "there is limited evidence that occupational exposure to ELF magnetic fields is carcinogenic to humans on the basis of results of studies of chronic lymphocytic leukemia (CLL)."[10] The Working Group considered ELF magnetic fields a "possible human carcinogen (Group 2B, Appendix B)" (as defined by IARC), based on the human epidemiologic evidence. It also concluded that evidence from experiments on laboratory animals does not support a conclusion of carcinogenicity, and that evidence is weak that fields below 100 μT have any biological effects. It noted that studies of cells in vitro and of mechanisms provide some evidence that ELF magnetic fields stronger than 100 μT may affect processes or end-points commonly associated with carcinogenesis.

The NIEHS Working Group used the IARC scheme for classifying potential human carcinogens, which imparts specific technical meanings to the phrases above. In particular, "limited evidence" is defined as "a positive association has been observed between exposure to the agent, mixture or exposure circumstance and cancer for which a causal interpretation is considered by the Working Group to be credible, but chance, bias or confounding could not be ruled out with reasonable confidence." Also, a Group 2B classification (possible carcinogen) is used "for...exposure circumstances for which there is *limited evidence* of carcinogenicity in humans and less than *sufficient evidence* of carcinogenicity in experimental animals," among other possibilities.

These two reports are the most recent and detailed reviews of the relevant science prior to 1998 by large groups of scientists. COMAR recommends that the reader of the NIEHS Working Group Report also read its Appendix A where the procedures and terms used in the report are clearly defined, and Appendix B, the statement on animal carcinogenicity by a minority of the Working Group. A report by the World Health Organization (WHO)[11] reviews further research needs, and complements the two reports cited above.

More Recent Evidence

Several major epidemiological studies have appeared, which are summarized below. (Readers are referred to the original sources for more details.)

- Gurney et al. [12] found no association of brain cancer in children with residence near power lines, and no association of brain cancer with childhood or fetal exposure to fields from electrical appliances.
- Preston-Martin et al. [13] [14] found no association between brain cancer in children and residential magnetic fields or use of electric blankets or water bed heaters.
- Linet et al. [15] found no association of childhood leukemia with types of wiring outside the home. The authors interpreted their data as indicating a non-significant excess of childhood leukemia with measured fields above 0.2 μT, though the association was borderline and the authors' interpretation was subject of some controversy. The same workers [16] found no consistent associations between childhood leukemia and use of various electric appliances during pregnancy or childhood. They reported significant associations with use of electric blankets, hair dryers/curling irons, and television/video game use, but there was no dose-response trend in the results.
- Michaelis et al. [17] found an excess of childhood leukemia associated with residential exposures to power frequency magnetic fields. This association was statistically significant for children 4 years of age or less and for median night-time magnetic field, but not for all children and with exposures measured in terms of median 24-hour magnetic field levels.
- McBride et al. [18] found no statistically significant association between childhood leukemia and magnetic field exposure measured in terms of wire codes, directly measured magnetic fields, or directly measured electric fields. Field measurements were obtained using field meters that were carried by subjects for 48 hours.
- Tynes et al. [19] reported no increased risk for cancer for children living near high voltage power lines in Norway.

Versakalo et al. [20] found no statistically significant increase in cancer in adults living within 500 meters of a high voltage power line.

- Li et al. [21] reported an increase in leukemia (but not brain or breast cancer) in adults living within 50 meters of a high voltage power line.
- Feychting et al.[22] found no statistically significant association between breast cancer in females and calculated levels of magnetic fields in the subjects' homes. The data, however, are weakly suggestive of an association, but only for pre-menopausal women.
- Gammon et al. [23] found no association between electric blanket use and breast cancer incidence among younger women.

Guenel et al.[24] reported no significant associations between occupational exposure to power-frequency electric fields and adult cancers.

- Miller et al.[25] found no consistent associations between estimated occupational exposure to magnetic fields and certain types of leukemia or between cumulative electric field exposure and the occurrence of all leukemia.
- Feychting et al. [26] found no association between occupational or residential exposure to magnetic fields and adult brain cancer, but did find elevated risks of certain leukemias with combined home and work exposure to magnetic fields.
- Harrington et al.[27] and Rodvall et al.[28] found no significant association between brain cancer and occupational exposure to ELF magnetic fields.
- Kheifets et al.[29] found no association between adult leukemia and occupational exposure to electric fields. The investigators also reported that occupational exposure to electric fields is poorly correlated with occupational exposure to magnetic fields (the 5 occupations with highest magnetic field exposure include 3 of the 5 occupations with highest electric-field-exposures).
- Savitz et al.[30] found a weakly elevated risk of lung cancer associated with occupational exposure to pulsed magnetic fields, but no consistent trends with increasing exposure to either pulsed or steady ELF magnetic fields.

If different studies, varying in design, show consistent associations between exposure and disease, the case for causation is strengthened. By contrast, the generally well-designed studies cited above had inconsistent results, and it remains unclear whether any of the associations they reported were actual effects of the fields. These studies, however, had limited ability to detect weak associations between exposure and disease, particularly for the most highly exposed individuals (where sample sizes were small). For example, most residential studies included few homes with magnetic field levels above 0.2 μT. A major exception is the study by McBride et al. [18] which included 49 homes with measured magnetic fields above 0.2 μT (out of 399 homes of cases). Moreover, this study was the only one that determined the exposure of the subjects directly by measuring fields on their persons. The investigators found no association between childhood leukemia and magnetic field exposure, either in terms of directly measured fields or wire codes.

The problem of small sample size can be addressed by pooling data from several studies, a process called meta-analysis. No current meta-analyses (including all relevant published epidemiologic data) are available; meta-analyses of some aspects of the literature have been published recently by Wartenberg[31] (childhood leukemia) and Kheifets et al.[32], [33] (occupational leukemia and brain cancer). Some epidemiologists question whether meta-analysis is appropriate with EMF studies because of wide variation in experimental procedures between studies.

To summarize the recent epidemiology results: the larger studies with comprehensive exposure assessment [13], [14], [15] do not provide compelling evidence for a causal link between residential exposure to magnetic fields and cancer. They are sufficient to categorize power-frequency magnetic fields as a possible carcinogen, according to the specific meaning of the term in the IARC guidelines. Opposing this, the work of McBride et al.[18] supports the contention that such fields are not related to childhood leukemia, at least.

Recent animal studies, not included in the NAS/NRC and NIEHS reviews, include:

- Yasui et al. [34] and Mandeville et al.[35] found no increased incidence of any cancers among rats exposed for their lifetimes to power-frequency magnetic fields at levels of 0.002, 0.5, 1 and 2 mT.

- Boorman et al.[36] and McCormick et al.[37] found no consistent effect on any cancer rates for any group of mice or rats exposed for a lifetime to power-frequency 2 or 200 µT or 1 mT magnetic fields. One of two groups of mice exposed to a 1 mT field experienced an increase in mortality, but this was not evident in rats or in any of the other mouse groups.
- Several studies have been done of skin cancer in mice treated with a carcinogenic chemical and exposed to magnetic fields of 0.5 - 2 mT [38], [39], [40], [41], [42]; all found no effect of steady AC magnetic fields, but one[42] found that mice subjected to pulsed fields (with transients) developed significantly more tumors than mice subjected to steady fields.
- Kumlin et al.[43] found that UV production of skin tumors in mice was weakly, but significantly, enhanced by exposure to magnetic fields (1.3 - 130 µT). Mice genetically altered to be more prone to skin cancer were not significantly more sensitive to magnetic fields.
- Sasser et al.[44] and Morris et al.[45] found no effect on progression of leukemia transplanted into rats exposed to 1 mT magnetic fields.
- Shen et al.[46] did not find lymphoma promotion in mice treated with a carcinogen and exposed to strong (1 mT) magnetic fields.
- Harris et al.[47] and McCormick et al.[48] found no increased incidence of lymphoma in lymphoma-prone mice exposed to 1 µT - 1 mT power-frequency magnetic fields.
- Mevissen et al.[49] found that 50 µT magnetic field exposure of rats treated with carcinogens increased their incidence of breast cancer, but did not affect tumor growth in individual animals. A previous study[50] found that 100 µT exposure had effects opposite these.
- Ekstrom et al.[51] and Boorman et al.[52] in two separate studies found no effect of power-frequency 100, 250 or 500 µT magnetic fields on promotion of chemically-induced breast cancer among rats.
- Lai and Singh [53] found an increase in DNA strand breaks in brain cells of rats exposed to 0.1, 0.25 and 0.5 mT magnetic fields.

In reviewing these studies, the reader should keep in mind that most of these studies involved many different comparisons of different sets of data. It is likely that some of the "statistically significant" differences that are uncovered by such a process are actually due to chance (the multiple comparison effect). For this reason researchers look for internal consistency within studies (trends towards stronger effects with increasing field strength, similar reactions in related species, for example) and when such consistency is lacking scientists consider results as weak even if a study reports positive effects.

To summarize the animal studies cited above: 1) large lifetime studies have not found any increase in cancers; 2) promotional studies of skin tumors in mice are suggestive of an effect, but the results are inconsistent; 3) promotional studies of leukemia and lymphoma have been negative; 4) promotional studies of breast cancer have been inconsistent and recent large studies are negative; and 5) the study looking at DNA strand breaks needs support from further studies before it can be interpreted.

These studies, especially the projects examining lifetime exposure at high intensity [35], [36], [37], [47], [48] are sufficiently consistent to swing the body of informed scientific opinion away from possible links between weak (environmental or occupational, approximately less than 10 µT) power frequency fields and cancer.

Implicit in the discussion above is the assumption that steady but weak alternating magnetic fields would produce effects of the same kind, but fewer or weaker, than would strong alternating magnetic fields. Laboratory research on pulsed ELF fields, and on fields created by transient signals, is not sufficiently mature to draw conclusions at this point. Exposure of humans to transient magnetic fields is very difficult to determine, even though such fields are very common in our environment (being produced, for example, by electrical switches in power systems). Other biological changes were observed in some studies, but they are not sufficiently consistent to be convincing, though they do merit further study. These effects include (all from different studies) changes in the immune system, increased kidney disease and increased growth of lymphoma cells in the liver. The WHO review[11] presents detailed recommendations for research in this area.

Other Issues Related to Health and Safety

The question of possible health effects of power frequency electric or magnetic fields covers a wide range of subjects. One confirmed effect of ELF magnetic fields is to enhance bone growth; this is accomplished with pulsed magnetic field waveforms on the order of 100 µT, with and without concurrent static magnetic fields of comparable magnitude[54]. Other issues related to possible health and safety of power frequency fields not directly involving human cancer include:

1. Magnetic and electric fields and melatonin in animals. Some studies suggest that exposure to power-frequency electric or magnetic fields reduces the normally occurring increase in nighttime secretion by the pineal gland of the hormone melatonin. The pineal is the remnant of a third eye, and its secretion is normally responsive to day length as sensed through the eyes (light intensity). The sensitivity of melatonin production to ELF fields was first noted by Wilson et al.[55], [56] who exposed rats to an environmental electric field of 1.7 to 1.9 kV/m, although this result could not be replicated by later investigations. Several studies have reported an effect of magnetic fields on melatonin secretion in rodents [57], [58], [59], [60] but initial studies of humans are not supportive of a similar effect [61], [62], [63] and the animal studies themselves are inconsistent [64], [65], [66], [67], [68], [69]. The health significance of this effect, even if it occurs in humans, is unclear. However, some experts have suggested that melatonin may limit progression of cancer by acting as scavenger of free radicals [70], [71].

2. Cardiovascular diseases. Recent studies of humans have revealed temporary, reversible changes in heart rate variability in humans exposed to 20 µT magnetic fields [72]. At least one epidemiology study reported an association between occupational magnetic field exposure and death due to arrhythmia or acute myocardial infarction, though not chronic heart disease [73].

3. Immune system effects. Some studies have reported biological changes in rodents which the investigators interpreted as suppression of the immune system[74]. Other laboratories have not found similar effects [75]. However, these studies used various combinations of field strength and exposure duration, and study in this area is very preliminary. Such effects have not been seen at lower field strengths typical of most environmental exposure (2, 20 µT).

4. In-vitro (cellular) effects. Many experiments have been carried out to study the effects of ELF magnetic and electric fields on cells in culture. Many experiments have given evidence for field-mediated effects at the cell membrane. One established effect is the increase in transport of calcium across cell membranes under exposure to strong (over 1 mT) power-frequency magnetic fields [76]. However, no experimental evidence exists at present to

relate these changes to cancer initiation or growth. Further, most reliable results were obtained with field levels that are far larger than the fields implicated by the epidemiological findings. Several studies have reported effects on cells from exposures to magnetic fields of a few microtesla (comparable to ordinary environmental levels) and either magnetically induced or directly applied electric fields within the culture medium in the microvolt-per-meter range [77], [78], [79], [80], [81], or microvolt-per-centimeter range[82]. However, most of these studies have not been independently replicated in more than one laboratory, and in at least one case replication attempts have been unsuccessful [83], [84], [85], [86]. One apparently robust effect is a reduction in the ability of melatonin to inhibit cancer growth in cultured cells after they were exposed to 1.2 μT magnetic fields[81]. The health significance of all these studies remains unclear.

5. Mechanistic studies. Several theoretical models have been proposed to explain ways by which low-level electric and magnetic fields might affect biochemical processes. More recent studies along these lines include [87], [88], [89], [90], [91], [92], [93], [94]. Limited experimental support exists for some of the theoretical models, in particular the radical pair mechanism[95], [96], [97], a possible explanation for observed in-vitro effects. However, experimental evidence has been insufficient for any of these models to gain widespread acceptance by the scientific community, and the physical basis of many such models has been severely criticized [98], [99], [100].

Conclusions

COMAR members believe that the data are not sufficient to support the conclusion that a causative link exists between weak power-frequency magnetic fields and cancer. The recent studies summarized above, and earlier studies summarized in the NRC/NAS and NIEHS reviews, lead us to conclude that there is little cause for concern among most of the population.

Numerous open scientific questions remain about possible biological effects of power frequency fields. Many of the reported biological effects remain poorly understood. Most of these effects have no clear relation to human health and safety, and many involve acute high-amplitude exposure. Therefore they do not provide a basis for developing environmental exposure limits, or standards, at ambient levels. They do, however, create uncertainties that make it difficult to arrive at scientific consensus for safety standards. COMAR believes it is important for scientific funding agencies to identify the most important of these still-open questions and direct sufficient funds to resolve them. Effects still in need of explanation and/or verification in different laboratories include: (a) studies reporting effects of low intensity magnetic fields in in vitro preparations, (b) epidemiological results suggesting health effects of relatively large ELF fields in occupational settings, and (c) the therapeutic effects (e.g. bone healing) of magnetic fields of time-averaged magnitude well below shock and nerve stimulation thresholds. It is particularly important for the sake of safety standards that experimental results be repeatable, support each other, show a logical pattern leading to a plausible biological mechanism, and have clear implications for human health.

COMAR also concludes that, since the publication of the 1997 NRC report, no convincing evidence has emerged to change the main conclusion of that review. The scientific evidence does not support the existence of cancer or other health and safety hazards from exposure to power frequency fields at levels that are encountered in normal residential or most occupational environments (24-hour average magnetic fields below 1 μT, which characterizes the exposure of more than 99.5% of the U.S. population). Costs to society of major changes in the use of electrical power would be enormous, and are not justified by the present state of knowledge in this field.

Contributors

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