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Extremely Low Frequency (ELF) Fields

White Paper

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In 1993, the AIHA Board of Directors adopted a position statement on human exposure to extremely low frequency (ELF) fields. The position statement was updated in 2002 because of developments in this area including publication of significant studies of potential health effects and reports of expert panels. Since 2002, consensus organizations have updated their recommendations based on the latest science.

Based on this information, the Nonionizing Radiation Committee has proposed to revise the 2002 position statement. The information contained in the white paper is a summary both of the biological and health effects associated with exposure to ELF fields and of the present exposure guidelines.

PHYSICAL CHARACTERISTICS

The electromagnetic spectrum includes frequencies that range from less than 1 Hz to 1025 Hz. The spectrum is normally described in subcategories that correspond to the similarities in how they are produced, how they interact with matter, and their application. The ELF spectral region includes the frequencies between 3 Hz and 3000 Hz. In this part of the spectrum, the fields are slowly time-varying and the wavelengths are quite lengthy. ELF fields are considered as separate, independent, nonradiating electric and magnetic fields at any conceivable observation point.

Electric fields are created by electric charges. The electric field, E, is defined by the magnitude and direction of the force it exerts on a static unit charge. The units of electric field strength are volts per meter (V/m), although they are often appropriately scaled in kilovolts per meter (kV/m). The magnetic flux density, B, characterizes the magnetic field strength, just as E characterizes the electric field. The units of B are the tesla (T), which is usually scaled to microtesla (mT) for workplace evaluations. Another unit of B that may be used is the gauss (G), which is usually scaled to milligauss (mG). (Note: 1 T = 10,000 G.)

Magnetic fields are created by moving charges, or currents. This principle applies to all fields, whether they are from magnets, power lines, or the earth. Just as the electric field is defined by the force on a unit charge, the magnetic field is defined by the magnitude and direction of the force exerted on a moving charge or current.

INTERACTION WITH MATTER/PEOPLE

Electric fields interact with humans through the outer surface of the body, inducing fields and currents within the body. Hair vibration or other sensory stimuli may occur in fields greater than 10 kV/m. A safety issue arises from currents induced in metal structures, which may produce shocks when humans contact the structure and provide a path to ground.

Time-varying magnetic fields induce electric fields (which in turn induce currents) in tissue in direct proportion to the magnetic flux density, the frequency of oscillation, and the radius of the current loop. The maximum current density induced in the human body in the normal residential environment is of the order of microamperes per square meter ($\mu A/m^2$). For electric arc welders it may be of the order of milliamperes per square meter (mA/m^2) or greater.

With photon energy directly proportional to frequency, it is readily apparent that ELF fields will cause neither ionization nor heating. Because the body is a relatively good conductor, the highest internal field that can be induced by an E-field strength in air is about 1 V/m, which leads to a mass-normalized rate of energy transfer of 10^{-4} watts per kilogram (W/kg), 4 orders of magnitude less than the resting metabolic rate (1 W/kg) (1). Pulsed magnetic fields can produce higher internal electric fields, but they are still too small to produce measurable tissue heating. Any interactions of ELF fields in air with humans are thus nonthermal.

BIOLOGICAL AND HEALTH EFFECTS

The search for biological and health effects of electromagnetic field (EMF) exposure has been accelerating for more than three decades. Results have been mixed, and their interpretation has been controversial, with little consensus on biological effects and virtually none on health effects that might arise from fields at the levels found in occupational or general community environments.

The next few paragraphs discuss so-called robust biological effects, that is, effects that are reproducible and generally accepted among researchers. This section is followed by a discussion of the more controversial nonrobust biological effects, which are found by some investigators but not by others who attempt to replicate their results. The section closes with an overview of the epidemiological studies into possible health effects of EMF.

The previous section described how the effect of fields exerts force on charged entities, creating currents, and how the relationships between fields and induced currents are quantified through the conductivity of the medium, for example, tissue. Organizations have recommended exposure limits for ELF-EMF based on the following correspondence between current density and biological effects[(2)]:

- 1-10 mA/m^2, minor biological effects have been reported.
- 10-100 mA/m^2, well-established effects occur, including effects on the visual and nervous systems.
- 100-1000 mA/m^2, stimulation of excitable tissue occurs, causing possible health hazards.
- 1000 mA/m^2 and above, extrasystoles and ventricular fibrillation can occur.

Recalling the approximation, joules (J) » 6 B (at 60 Hz), magnetic fields of the order of 1 mT would lead to current densities in the range of 6 mA/m^2.

Phosphenes

Phosphenes are the sensation of flickering light within the eye. The sensation appears to result from stimulation of retinal tissue and from any number of agents (e.g., pressure, mechanical shock, chemical substances, and sudden fright). If the agent inducing phosphenes is ELF fields, then it is termed *electrophosphenes* or *magnetophosphenes*, depending on the field that causes them.

Phosphenes occur when the induced current density is of the order of 10 mA/m^2 or more. Studies have demonstrated that the sensitivity to phosphenes is greatest around 20 Hz. In general, B-field intensities must be on the order of 10 mT for the production of magnetophosphenes.

Calcium Efflux

In vitro experiments have examined effects on doubly ionized, radioactive calcium occurring in windows of field frequency and power. A chemical exposure analogy would be as if a little benzene were harmful but a greater amount were not, and a still greater amount were again harmful.

In the first of these studies[3], a modest increase in the exchange of calcium-45 with a physiologic bath was observed for sectioned chick brain exposed to a 147-MHz carrier wave amplitude modulated at 16 Hz. Other modulation frequencies did not produce as large an effect, and exposure to just a 16-Hz E field had the opposite effect, decreasing efflux.

Later work suggested that the effect depended on the relative orientation and strength of the earth's magnetic field, and that it occurred in windows of field frequency and intensity and even temperature of the experimental preparation[4-7].

Genetic Effects

Genetic toxicology studies have found no reliable effects, but there are scattered positive findings[8-10].

Reproduction and Development

Studies with test animals have examined a variety of species with exposure to E or B fields. There have been scattered positive findings for exposure to test animals but no consistent, reproducible observations[11]. For example, in a multigenerational study, female miniature swine were exposed to 60-Hz E fields of 35 kV/m for 20 hr/day. When these and an unexposed control group were bred with unexposed males, the control group had a greater rate of fetal malformations than the exposed group.

This result reversed in a second breeding. Breeding of the offspring produced similarly conflicting results.[12] Because of the ambiguities in the swine study, a study using a similar protocol was performed with rats (E field = 0, 10, 65, and 130 kV/m).[13] There were no significant increases in litters with malformations among exposed animals.

Six laboratories in North America and Europe examined the effect of B-fields (1 µT and pulsed at 100 Hz) on chicken embryos.[14] Data from two laboratories and pooled data from all laboratories found a significant increase in abnormal embryos in the exposed groups. However, the interaction between the incidence of abnormalities and the laboratory doing the experiment was also significant; that is, the effect of exposure differed significantly among laboratories.

Flux densities of 1 or 0.61 mT at 60 Hz were used in two studies of reproductive and developmental toxicology in rats. There was a significant difference the number of fetuses per litter in the 1-mT group in the first experiment, but this was not observed in the replicate study. There were no significant differences in fetal body weight or the incidence of malformations among the exposure groups.[15] Other researchers exposed pregnant rats (0.002, 0.2, and 1 mT at 60 Hz) and found no significant differences in developmental abnormalities.[16]

Reviews of human studies are available[11,17]. Evaluations examined residential exposure (appliances, especially electric blankets), occupational exposure other than VDT use (e.g., substations), and VDT use. End points evaluated include spontaneous abortion, congenital malformations, preterm delivery, low birth weight, and intrauterine growth retardation. A few scattered positive findings have been reported but no trends established. However, there have been relatively few studies of exposures to sources other than VDT operation. A number of methodological limitations are addressed in the review articles cited above.

Effect on Melatonin

The possible effects of ELF fields on levels of the pineal hormone melatonin have been investigated. Animal studies have demonstrated effects on melatonin from E fields[18,19], B fields[20], and no effects[21-24]. Other effects include the following: E-field exposure decreased serum melatonin but not pineal melatonin levels[25]; pulsed static B fields affected melatonin if exposure was during the mid- or late-dark phase, but not when exposure was during the daytime or early dark phase[26]; short-term B-field exposure affected pineal and nocturnal serum melatonin, while long-term exposure affected just nocturnal serum melatonin[27]; and lastly, serum melatonin was not affected by daytime E- and B-field exposure with a slow onset[28], but it was reduced by variable exposure with a rapid onset/offset[29].

The National Institute of Environmental Health Sciences (NIEHS) Working Group concluded that there is weak evidence that exposure to E and B fields alters melatonin in rodents but not in sheep or baboons[30].

The outcome of 12 studies on possible ELF-induced effects on melatonin in humans has been reviewed by the NIEHS. Five laboratory studies were negative, but one laboratory and six observational studies demonstrated some effects on melatonin or its urinary metabolite, 6-hydroxymelatonin sulfate (6-OHMS)[30]. In later studies, no statistically significant effects were reported in female garment factory workers[31], men exposed to an electric sheet[32], and women[33] and men exposed to intense B fields at night[34]. A decrease in nocturnal melatonin was observed in women in another study[35], while others have suggested a reduction in 6-OHMS associated with work in an electrical substation or with 3-phase fields[36].

Cancer Studies

Note: Because of the large number and complex nature of published studies, this section will draw largely on findings from critical reviews published in either the peer-reviewed literature or by expert panels.

A number of cancer types have been evaluated. The types studied most often in relation to ELF exposure are leukemia, brain cancer, and breast cancer. Experiments with test animals have examined initiation, promotion, and copromotion in models of mammary cancer, skin cancer, brain cancer, leukemia, and lymphoma.

The findings are complex to interpret and do not demonstrate any clear trends. McCann and colleagues reviewed the published literature and concluded that “a weak promoting effect of MFs (magnetic fields) under certain exposure conditions cannot be ruled out categorically based on available data”[37]. Boorman et al. examined the literature on mammary cancer finding that “The totality of rodent data does not support the hypothesis that 50 or 60 Hz magnetic-field exposure enhances mammary cancer in rodents, nor does it provide experimental support for possible epidemiological associations between magnetic-field exposure and increased breast cancer risk”[38].

For human studies, evaluations have included both residential and occupational settings and children and adults. A number of useful review articles and meta-analyses are available including general(30,39-42) and topical reviews of leukemia(43-49), brain cancer(44,50,51), and breast cancer(52-54).

Early occupational studies, here defined as prior to 1993, often utilized job titles and information from death certificates. In general, many of these studies found no-to-modest increases in risk of leukemia and brain cancer and no dose-response effect(44).

Early studies of childhood cancer utilized wire coding to classify residences with regard to potential magnetic-field intensity and spot measurements. Generally, these studies demonstrated a weak association with leukemia(61).

Some studies have utilized spot and personal measurement strategies and detailed numerical models to estimate exposure. Three studies examined the risk of power company workers in the United States, Canada, and France (see Table 1 below). Of these, one reported no increase in risk of leukemia and brain cancer(55), while the others found an increase in risk of leukemia(56) and brain cancer(57). A combined analysis of the data from the three studies found that the relative risk (RR) per 10 mT-yrs was 1.09 (95% CI = 0.98 to 1.21) for leukemia and 1.12 (95% confidence interval, CI = 0.98 to 1.28) for brain cancer(45).

Table 1: Summary of Three Power Industry Studies

Study	Sahl et al. (1993)(55)	Theriault et al. (1994)(56)	Savitz et al. (1995)(57)
Exposure	Above mean	Above 90th (15.7 µT-years)	Above 90th measure µT-work years or 18.8 µT-years
Brain cancer RR (95% CI)	0.81 (0.48-1.36)	1.95 (0.76-5.00)	2.29 (1.15-4.56)
Leukemia RR (95% CI)	1.07 (0.80-1.45)	1.75 (0.77-3.96)	1.11 (0.57-2.14)
AML RR (95% CI)	-----	2.68 (0.50-14.50)	1.62 (0.51-5.12)

A meta-analysis of 38 studies of occupational B-field exposure and leukemia reported a pooled RR = 1.18 (CI = 1.12 to 1.124). The highest pooled RR (1.55, CI = 1.10 to 2.19) was for the chronic lymphocytic leukemia subtype (12 studies)(46). The NIEHS Working Group found limited evidence of an increased risk of chronic lymphocytic leukemia in workers and exposure to ELF magnetic fields(30). The Advisory Group on Non-ionising Radiation (AGNIR) of the United Kingdom's National Radiological Protection Board (NRPB) concluded that a review of occupational cohort studies on leukemia and ELF exposure are equivocal at best(41).

A pooled analysis of childhood leukemia found no increase in risk for B-fields < 0.4 mT, while the RR = 2.00 (95% CI = 1.27 to 3.13) for children with residential exposure 30.4 mT(47). Wartenberg performed a meta-analysis for childhood leukemia finding the following RR values: 1.1 (0.9 to 1.3) for spot measurements, 1.2 (0.9 to 1.5) for calculated fields, 2.7 (0.8 to 8.7) for wire codes by spot measurements, and 1.6 (0.5 to4.6) for wire codes by 24-hour measurements. He estimates 175 cases of leukemia by wire code data and 240 cases by spot measurements with the following assumptions: exposure causes leukemia; the studies are accurate and representative; and exposure follows a log-linear relationship(49). In a review of the literature, both the NIEHS Working Group and the International Agency for Research on Cancer (IARC) found limited evidence for an increased risk of childhood leukemia and residential exposure(42).

Kheifets and colleagues have reviewed the literature on brain cancer. In meta-analyses they reported a pooled RR = 1.21 (CI = 1.11 to 1.33) in 1995[50] and a pooled OR = 1.16 (95% CI = 1.08 to 1.24) in 2001. In the latter review, Kheifets states that there is "little support for an association between residential EMF exposure and childhood or adult brain cancer"[51]. In a review of three major studies of utility workers, the estimated combined RR/10 mT-yrs was 1.12 (95% CI = 0.98 to 1.28), as noted above[45]. Members of the NIEHS Working Group[30] and IARC[42] concluded that there was inadequate evidence of brain cancer in adults and children, while AGNIR concluded evidence from cohort studies was equivocal[41].

The risk of breast cancer and ELF exposure has been evaluated in men and pre-, peri-, and postmenopausal women. Erren reviewed 48 published studies and included studies with estimates of RR (24 for women and 15 for men) in a meta-analysis. The average RR = 1.12 (95% CI = 1.09 to 1.15) for women and 1.37 (95% CI = 1.11 to 1.71) for men demonstrates a small increase in risk of breast cancer[52]. After reviewing the literature, other researchers have suggested that this is an area requiring further research[53,54].

Over the years, a number of expert panels have addressed the question of ELF exposure and cancer. Three of these mentioned earlier are the NIEHS Working Group, IARC, and AGNIR. All three groups examined an extensive volume of scientific literature in their assessments. Based on their evaluations, the NIEHS Working Group classified ELF magnetic fields as a Group 2B (possibly) carcinogen for childhood leukemia and chronic lymphocytic leukemia in workers.

IARC found limited evidence for an excess cancer risk on the basis of childhood leukemia from exposure to high residential magnetic fields, and it placed ELF magnetic fields in Group 2B. IARC found inadequate evidence for all other cancer types in children and adults from exposure to ELF electric and magnetic fields[42]. AGNIR, led by Sir Richard Doll, found "some epidemiological evidence that prolonged exposure to higher magnetic fields is associated with a small risk of leukemia in children"[41]. Both IARC and AGNIR cite a value of 0.3 to 0.4 mt when referring to high levels of residential exposure.

In 2007, the World Health Organization published one of the most comprehensive evaluations of ELF exposure and adverse health effects in an Environmental Health Criteria Monograph on ELF, including more recent studies than the 2002 IARC designation and found no change in the classification of evidence between ELF exposure and cancer as limited[58]. Since these reviews of the evidence, a more recent evaluation of cancer development and ELF exposure has shown similar results, with no new evidence that would justify a change in the early findings of the IARC (2002) and WHO (2007) reviews[59]. Recent studies also corroborate these findings[60-63].

EXPOSURE GUIDELINES

Ideally, exposure guidelines and standards are established on the basis of an accepted mechanism of interaction, dose-response studies in animals, and epidemiological evidence of similar effects in humans. None of this has occurred for ELF fields. No accepted, biologically plausible mechanism has been advanced to explain how fields interact with biological systems to yield observed *in vitro* responses, much less disease in an organism. In fact, the field parameter or parameters to be measured, because of their possible biological significance, are unknown.

The traditional approaches — that "more is worse" and that time-weighted average or even peak exposures are the quantities of interest — have been called into question by studies suggesting that effects occur in windows of frequency and power. The choice of exposure metric is thus made difficult by the lack of knowledge about interaction mechanisms and the lack of a clearly defined, exposure-associated health effect.

The current biological basis for the exposure guidelines includes acute effects to central nervous system tissues. Effects that are often cited include phosphenes and alterations of visual evoked potentials (VEPs). These effects occur at relatively high levels of exposure. Phosphenesis a biological effect, while alterations of the VEP "are not necessarily harmful"[64].

Exposure guidance, based on the current understanding of ELF-induced biological effects, has been developed by a number of countries and organizations[64,65]. This chapter will focus on guidelines published by the American Conference of Governmental Industrial Hygienists (ACGIH)[66] and the International Commission on Non-Ionizing Radiation Protection (ICNIRP)[67,68].

The rationale for these exposure limits is based on induced body currents. For occupational exposures, both the ACGIH and ICNIRP recommend limiting induced current densities in the body to those levels that occur normally, that is, up to about 10 mA/m^2. (Higher current densities can also occur naturally in the heart.) They acknowledged that biological effects have been demonstrated in laboratory studies at field strengths below those permitted by the exposure guidelines; however, both concluded that there was no convincing evidence that occupational exposure to these field levels leads to adverse health effects.

The ACGIH guideline extends into part of the RF spectral region, which that organization calls sub-radio frequency (sub-RF)[66]. The ACGIH threshold limit value (TLV) for occupational exposure to ELF electric fields states that exposure should not exceed 25 kV/m for frequencies from 0 (DC) to 220 Hz. For frequencies in the range of 220 Hz to 3 kHz, the TLV is given by

$$E_{TLV} = 5.525 \times 10^6/f \text{ (V/m)}$$

where E has units of V/m (rms value) and f is frequency in Hz. From 3 to 30 kHz, the ETLV is 1842V/m. A proviso is added for workers with cardiac pacemakers, limiting power-frequency exposures to 1 kV/m. Electromagnetic interference with pacemaker function may occur in some models at power-frequency electric fields as low as 2 kV/m.

The TLV for magnetic fields from 1 to 300 Hz limits routine occupational (rms) exposure to ceiling values determined by

$$B_{TLV} = 60 / f \text{ (mT)}$$

where f is the frequency in Hz. At frequencies below 1 Hz, the TLV is 60 mT. From 300 Hz to 30 kHz the ceiling value is a limit of 0.2 mT. For workers with cardiac pacemakers, the limit is 0.1 mT at power frequencies.

Because of ambiguities in the scientific understanding of the mechanism of biological interaction, the sub-RF TLVs are ceiling limits; that is, they are values not to be exceeded[66].

ICNIRP makes recommendations for exposure limits of both workers and members of the general public to electric and magnetic fields[67]. Basic restrictions are mandatory limitations on quantities that closely match all known biophysical mechanisms with tissue that may lead to adverse health effects. In the ICNIRP 2010 guideline, it is expressed as internal electric fields (V/m). However, since the internal electric field is difficult to measure, reference levels are provided in the guideline that can be measured.

For untrained workers, the basic restriction is set at the phosphene threshold, and for the general public, a reduction factor of 5 is applied to the phosphene threshold. ICNIRP does not recommend an averaging time for the ELF spectral region "because the known effects of induced and contact currents at those frequencies are acute phenomena involving a rapid response of the nervous system"[68,69].

Frequency-dependent reference levels are recommended for both E and B. The allowable E-field strength reaches a maximum in the band between 1 and 25 Hz at values of 20 and 5 kV/m for occupational and general public exposure, respectively. Field strength then decreases with frequency before reaching another plateau. Exposure limits at 60 Hz are 83.3 kV/m for workers and 41.67 kV/m for members of the general public.

For B fields, the maximum flux density occurs at 1 Hz, then decreases in a frequency-dependent manner. Exposure limits at 60 Hz are 1 mT and 0.2 mT for workers and the general public, respectively.

EXPOSURE ASSESSMENT

Although not addressed in this report, information on evaluating exposures to ELF fields is available in two AIHA publications: *The Occupational Environment — Its Evaluation and Control*[70] and the Nonionizing Radiation Guide Series, *Extremely Low Frequency (ELF) Electric and Magnetic Fields*[71]. In addition to information on instruments and measurements, these two publications include reviews of key issues dealing with ELF exposure. Also, the National Institute for Occupational Safety and Health (NIOSH) has published a useful guide, *Manual for Measuring Occupational Electric and Magnetic Field Exposures*[72].

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