

1 SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

This Environmental Health Criteria (EHC) monograph addresses the possible health effects of exposure to extremely low frequency (ELF) electric and magnetic fields. It reviews the physical characteristics of ELF fields as well as the sources of exposure and measurement. However, its main objectives are to review the scientific literature on the biological effects of exposure to ELF fields in order to assess any health risks from exposure to these fields and to use this health risk assessment to make recommendations to national authorities on health protection programs.

The frequencies under consideration range from above 0 Hz to 100 kHz. By far the majority of studies have been conducted on power-frequency (50 or 60 Hz) magnetic fields, with a few studies using power-frequency electric fields. In addition, there have been a number of studies concerning very low frequency (VLF, 3–30 kHz) fields, switched gradient magnetic fields used in magnetic resonance imaging, and the weaker VLF fields emitted by visual display units and televisions.

This chapter summarizes the main conclusions and recommendations from each section as well as the overall conclusions of the health risk assessment process. The terms used in this monograph to describe the strength of evidence for a given health outcome are as follows. Evidence is termed “limited” when it is restricted to a single study or when there are unresolved questions concerning the design, conduct or interpretation of a number of studies. “Inadequate” evidence is used when the studies cannot be interpreted as showing either the presence or absence of an effect because of major qualitative or quantitative limitations, or when no data are available.

Key gaps in knowledge were also identified and the research needed to fill these gaps has been summarized in the section entitled “Recommendations for research”.

1.1 Summary

1.1.1 Sources, measurements and exposures

Electric and magnetic fields exist wherever electricity is generated, transmitted or distributed in power lines or cables, or used in electrical appliances. Since the use of electricity is an integral part of our modern lifestyle, these fields are ubiquitous in our environment.

The unit of electric field strength is volts per metre (V m^{-1}) or kilovolts per metre (kV m^{-1}) and for magnetic fields the flux density is measured in tesla (T), or more commonly in millitesla (mT) or microtesla (μT) is used.

Residential exposure to power-frequency magnetic fields does not vary dramatically across the world. The geometric-mean magnetic field in homes ranges between 0.025 and 0.07 μT in Europe and 0.055 and 0.11 μT in the USA. The mean values of the electric field in the home are in the range of several tens of volts per metre. In the vicinity of certain appliances, the

instantaneous magnetic-field values can be as much as a few hundred microtesla. Near power lines, magnetic fields reach approximately 20 μT and electric fields up to several thousand volts per metre.

Few children have time-averaged exposures to residential 50 or 60 Hz magnetic fields in excess of the levels associated with an increased incidence of childhood leukaemia (see Section 1.1.10). Approximately 1% to 4% have mean exposures above 0.3 μT and only 1% to 2% have median exposures in excess of 0.4 μT .

Occupational exposure, although predominantly to power-frequency fields, may also include contributions from other frequencies. The average magnetic field exposures in the workplace have been found to be higher in “electrical occupations” than in other occupations such as office work, ranging from 0.4–0.6 μT for electricians and electrical engineers to approximately 1.0 μT for power line workers, with the highest exposures for welders, railway engine drivers and sewing machine operators (above 3 μT). The maximum magnetic field exposures in the workplace can reach approximately 10 mT and this is invariably associated with the presence of conductors carrying high currents. In the electrical supply industry, workers may be exposed to electric fields up to 30 kV m^{-1} .

1.1.2 *Electric and magnetic fields inside the body*

Exposure to external electric and magnetic fields at extremely low frequencies induces electric fields and currents inside the body. Dosimetry describes the relationship between the external fields and the induced electric field and current density in the body, or other parameters associated with exposure to these fields. The locally induced electric field and current density are of particular interest because they relate to the stimulation of excitable tissue such as nerve and muscle.

The bodies of humans and animals significantly perturb the spatial distribution of an ELF electric field. At low frequencies the body is a good conductor and the perturbed field lines outside the body are nearly perpendicular to the body surface. Oscillating charges are induced on the surface of the exposed body and these induce currents inside the body. The key features of dosimetry for the exposure of humans to ELF electric fields are as follows:

- The electric field inside the body is normally five to six orders of magnitude smaller than the external electric field.
- When exposure is mostly to the vertical field, the predominant direction of the induced fields is also vertical.
- For a given external electric field, the strongest induced fields are for the human body in perfect contact through the feet with ground (electrically grounded) and the weakest induced fields are for the body insulated from the ground (in “free space”).

- The total current flowing in a body in perfect contact with ground is determined by the body size and shape (including posture), rather than tissue conductivity.
- The distribution of induced currents across the various organs and tissues is determined by the conductivity of those tissues
- The distribution of an induced electric field is also affected by the conductivities, but less so than the induced current.
- There is also a separate phenomenon in which the current in the body is produced by means of contact with a conductive object located in an electric field.

For magnetic fields, the permeability of tissue is the same as that of air, so the field in tissue is the same as the external field. The bodies of humans and animals do not significantly perturb the field. The main interaction of magnetic fields is the Faraday induction of electric fields and associated current densities in the conductive tissues. The key features of dosimetry for the exposure of humans to ELF magnetic fields are as follows:

- The induced electric field and current depend on the orientation of the external field. Induced fields in the body as a whole are greatest when the field is aligned from the front to the back of the body, but for some individual organs the highest values are for the field aligned from side to side.
- The weakest electric fields are induced by a magnetic field oriented along the vertical body axis.
- For a given magnetic field strength and orientation, higher electric fields are induced in larger bodies.
- The distribution of the induced electric field is affected by the conductivity of the various organs and tissues. These have a limited effect on the distribution of induced current density.

1.1.3 Biophysical mechanisms

Various proposed direct and indirect interaction mechanisms for ELF electric and magnetic fields are examined for plausibility, in particular whether a “signal” generated in a biological process by exposure to a field can be discriminated from inherent random noise and whether the mechanism challenges scientific principles and current scientific knowledge. Many mechanisms become plausible only at fields above a certain strength. Nevertheless, the lack of identified plausible mechanisms does not rule out the possibility of health effects even at very low field levels, provided basic scientific principles are adhered to.

Of the numerous proposed mechanisms for the direct interaction of fields with the human body, three stand out as potentially operating at lower field levels than the others: induced electric fields in neural networks, radical pairs and magnetite.

Electric fields induced in tissue by exposure to ELF electric or magnetic fields will directly stimulate single myelinated nerve fibres in a biophysically plausible manner when the internal field strength exceeds a few volts per metre. Much weaker fields can affect synaptic transmission in neural networks as opposed to single cells. Such signal processing by nervous systems is commonly used by multicellular organisms to detect weak environmental signals. A lower bound on neural network discrimination of 1 mV m^{-1} has been suggested, but based on current evidence, threshold values around $10\text{--}100 \text{ mV m}^{-1}$ seem to be more likely.

The radical pair mechanism is an accepted way in which magnetic fields can affect specific types of chemical reactions, generally increasing concentrations of reactive free radicals in low fields and decreasing them in high fields. These increases have been seen in magnetic fields of less than 1 mT. There is some evidence linking this mechanism to navigation during bird migration. Both on theoretical grounds and because the changes produced by ELF and static magnetic fields are similar, it is suggested that power-frequency fields of much less than the geomagnetic field of around $50 \mu\text{T}$ are unlikely to be of much biological significance.

Magnetite crystals, small ferromagnetic crystals of various forms of iron oxide, are found in animal and human tissues, although in trace amounts. Like free radicals, they have been linked to orientation and navigation in migratory animals, although the presence of trace quantities of magnetite in the human brain does not confer an ability to detect the weak geomagnetic field. Calculations based on extreme assumptions suggest a lower bound for the effects on magnetite crystals of ELF fields of $5 \mu\text{T}$.

Other direct biophysical interactions of fields, such as the breaking of chemical bonds, the forces on charged particles and the various narrow bandwidth “resonance” mechanisms, are not considered to provide plausible explanations for the interactions at field levels encountered in public and occupational environments.

With regard to indirect effects, the surface electric charge induced by electric fields can be perceived, and it can result in painful microshocks when touching a conductive object. Contact currents can occur when young children touch, for example, a tap in the bathtub in some homes. This produces small electric fields, possibly above background noise levels, in bone marrow. However, whether these present a risk to health is unknown.

High-voltage power lines produce clouds of electrically charged ions as a consequence of corona discharge. It is suggested that they could increase the deposition of airborne pollutants on the skin and on airways inside the body, possibly adversely affecting health. However, it seems unlikely that corona ions will have more than a small effect, if any, on long-term health risks, even in the individuals who are most exposed.

None of the three direct mechanisms considered above seem plausible causes of increased disease incidence at the exposure levels generally encountered by people. In fact they only become plausible at levels orders of

magnitude higher and indirect mechanisms have not yet been sufficiently investigated. This absence of an identified plausible mechanism does not rule out the possibility of adverse health effects, but it does create a need for stronger evidence from biology and epidemiology.

1.1.4 Neurobehaviour

Exposure to power-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric charge effects. These responses depend on the field strength, the ambient environmental conditions and individual sensitivity. The thresholds for direct perception by 10% of volunteers varied between 2 and 20 kV m⁻¹, while 5% found 15–20 kV m⁻¹ annoying. The spark discharge from a person to ground is found to be painful by 7% of volunteers in a field of 5 kV m⁻¹. Thresholds for the discharge from a charged object through a grounded person depend on the size of the object and therefore require specific assessment.

High field strength, rapidly pulsed magnetic fields can stimulate peripheral or central nerve tissue; such effects can arise during magnetic resonance imaging (MRI) procedures, and are used in transcranial magnetic stimulation. Threshold induced electric field strengths for direct nerve stimulation could be as low as a few volts per metre. The threshold is likely to be constant over a frequency range between a few hertz and a few kilohertz. People suffering from or predisposed to epilepsy are likely to be more susceptible to induced ELF electric fields in the central nervous system (CNS). Furthermore, sensitivity to electrical stimulation of the CNS seems likely to be associated with a family history of seizure and the use of tricyclic antidepressants, neuroleptic agents and other drugs that lower the seizure threshold.

The function of the retina, which is a part of the CNS, can be affected by exposure to much weaker ELF magnetic fields than those that cause direct nerve stimulation. A flickering light sensation, called magnetic phosphenes or magnetophosphenes, results from the interaction of the induced electric field with electrically excitable cells in the retina. Threshold induced electric field strengths in the extracellular fluid of the retina have been estimated to lie between about 10 and 100 mV m⁻¹ at 20 Hz. There is, however, considerable uncertainty attached to these values.

The evidence for other neurobehavioural effects in volunteer studies, such as the effects on brain electrical activity, cognition, sleep, hypersensitivity and mood, is less clear. Generally, such studies have been carried out at exposure levels below those required to induce the effects described above, and have produced evidence only of subtle and transitory effects at best. The conditions necessary to elicit such responses are not well-defined at present. There is some evidence suggesting the existence of field-dependent effects on reaction time and on reduced accuracy in the performance of some cognitive tasks, which is supported by the results of studies on the gross electrical activity of the brain. Studies investigating whether magnetic fields affect sleep quality have reported inconsistent results. It is possible that these

inconsistencies may be attributable in part to differences in the design of the studies.

Some people claim to be hypersensitive to EMFs in general. However, the evidence from double-blind provocation studies suggests that the reported symptoms are unrelated to EMF exposure.

There is only inconsistent and inconclusive evidence that exposure to ELF electric and magnetic fields causes depressive symptoms or suicide. Thus, the evidence is considered inadequate.

In animals, the possibility that exposure to ELF fields may affect neurobehavioural functions has been explored from a number of perspectives using a range of exposure conditions. Few robust effects have been established. There is convincing evidence that power-frequency electric fields can be detected by animals, most likely as a result of surface charge effects, and may elicit transient arousal or mild stress. In rats, the detection range is between 3 and 13 kV m⁻¹. Rodents have been shown to be aversive to field strengths greater than 50 kV m⁻¹. Other possible field-dependent changes are less well-defined; laboratory studies have only produced evidence of subtle and transitory effects. There is some evidence that exposure to magnetic fields may modulate the functions of the opioid and cholinergic neurotransmitter systems in the brain, and this is supported by the results of studies investigating the effects on analgesia and on the acquisition and performance of spatial memory tasks.

1.1.5 Neuroendocrine system

The results of volunteer studies as well as residential and occupational epidemiological studies suggest that the neuroendocrine system is not adversely affected by exposure to power-frequency electric or magnetic fields. This applies particularly to the circulating levels of specific hormones of the neuroendocrine system, including melatonin, released by the pineal gland, and to a number of hormones involved in the control of body metabolism and physiology, released by the pituitary gland. Subtle differences were sometimes observed in the timing of melatonin release associated with certain characteristics of exposure, but these results were not consistent. It is very difficult to eliminate possible confounding by a variety of environmental and lifestyle factors that might also affect hormone levels. Most laboratory studies of the effects of ELF exposure on night-time melatonin levels in volunteers found no effect when care was taken to control possible confounding.

From the large number of animal studies investigating the effects of power-frequency electric and magnetic fields on rat pineal and serum melatonin levels, some reported that exposure resulted in night-time suppression of melatonin. The changes in melatonin levels first observed in early studies of electric field exposures up to 100 kV m⁻¹ could not be replicated. The findings from a series of more recent studies, which showed that circularly-polarised magnetic fields suppressed night-time melatonin levels, were weakened by inappropriate comparisons between exposed animals and his-

torical controls. The data from other experiments in rodents, covering intensity levels from a few microtesla to 5 mT, were equivocal, with some results showing depression of melatonin, but others showing no changes. In seasonally breeding animals, the evidence for an effect of exposure to power-frequency fields on melatonin levels and melatonin-dependent reproductive status is predominantly negative. No convincing effect on melatonin levels has been seen in a study of non-human primates chronically exposed to power-frequency fields, although a preliminary study using two animals reported melatonin suppression in response to an irregular and intermittent exposure.

The effects of exposure to ELF fields on melatonin production or release in isolated pineal glands were variable, although relatively few in vitro studies have been undertaken. The evidence that ELF exposure interferes with the action of melatonin on breast cancer cells in vitro is intriguing. However this system suffers from the disadvantage that the cell lines frequently show genotypic and phenotypic drift in culture that can hinder transferability between laboratories.

No consistent effects have been seen in the stress-related hormones of the pituitary-adrenal axis in a variety of mammalian species, with the possible exception of short-lived stress following the onset of ELF electric field exposure at levels high enough to be perceived. Similarly, while few studies have been carried out, mostly negative or inconsistent effects have been observed in the levels of growth hormone and of hormones involved in controlling metabolic activity or associated with the control of reproduction and sexual development.

Overall, these data do not indicate that ELF electric and/or magnetic fields affect the neuroendocrine system in a way that would have an adverse impact on human health and the evidence is thus considered inadequate.

1.1.6 Neurodegenerative disorders

It has been hypothesized that exposure to ELF fields is associated with several neurodegenerative diseases. For Parkinson's disease and multiple sclerosis the number of studies has been small and there is no evidence for an association with these diseases. For Alzheimer's disease and amyotrophic lateral sclerosis (ALS) more studies have been published. Some of these reports suggest that people employed in electrical occupations might have an increased risk of ALS. So far, no biological mechanism has been established which can explain this association, although it could have arisen because of confounders related to electrical occupations, such as electric shocks. Overall, the evidence for the association between ELF exposure and ALS is considered to be inadequate.

The few studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. However, the higher quality studies that focused on Alzheimer morbidity rather than mortality do not

indicate an association. Altogether, the evidence for an association between ELF exposure and Alzheimer's disease is inadequate.

1.1.7 Cardiovascular disorders

Experimental studies of both short-term and long-term exposure indicate that while electric shock is an obvious health hazard, other hazardous cardiovascular effects associated with ELF fields are unlikely to occur at exposure levels commonly encountered environmentally or occupationally. Although various cardiovascular changes have been reported in the literature, the majority of effects are small and the results have not been consistent within and between studies. With one exception, none of the studies of cardiovascular disease morbidity and mortality has shown an association with exposure. Whether a specific association exists between exposure and altered autonomic control of the heart remains speculative. Overall, the evidence does not support an association between ELF exposure and cardiovascular disease.

1.1.8 Immunology and haematology

Evidence for the effects of ELF electric or magnetic fields on components of the immune system is generally inconsistent. Many of the cell populations and functional markers were unaffected by exposure. However, in some human studies with fields from 10 μ T to 2 mT, changes were observed in natural killer cells, which showed both increased and decreased cell numbers, and in total white blood cell counts, which showed no change or decreased numbers. In animal studies, reduced natural killer cell activity was seen in female mice, but not in male mice or in rats of either sex. White blood cell counts also showed inconsistency, with decreases or no change reported in different studies. The animal exposures had an even broader range of 2 μ T to 30 mT. The difficulty in interpreting the potential health impact of these data is due to the large variations in exposure and environmental conditions, the relatively small numbers of subjects tested and the broad range of endpoints.

There have been few studies carried out on the effects of ELF magnetic fields on the haematological system. In experiments evaluating differential white blood cell counts, exposures ranged from 2 μ T to 2 mT. No consistent effects of acute exposure to ELF magnetic fields or to combined ELF electric and magnetic fields have been found in either human or animal studies.

Overall therefore, the evidence for effects of ELF electric or magnetic fields on the immune and haematological system is considered inadequate.

1.1.9 Reproduction and development

On the whole, epidemiological studies have not shown an association between adverse human reproductive outcomes and maternal or paternal exposure to ELF fields. There is some evidence for an increased risk of mis-

carriage associated with maternal magnetic field exposure, but this evidence is inadequate.

Exposures to ELF electric fields of up to 150 kV m⁻¹ have been evaluated in several mammalian species, including studies with large group sizes and exposure over several generations. The results consistently show no adverse developmental effects.

The exposure of mammals to ELF magnetic fields of up to 20 mT does not result in gross external, visceral or skeletal malformations. Some studies show an increase in minor skeletal anomalies, in both rats and mice. Skeletal variations are relatively common findings in teratological studies and are often considered biologically insignificant. However, subtle effects of magnetic fields on skeletal development cannot be ruled out. Very few studies have been published which address reproductive effects and no conclusions can be drawn from them.

Several studies on non-mammalian experimental models (chick embryos, fish, sea urchins and insects) have reported findings indicating that ELF magnetic fields at microtesla levels may disturb early development. However, the findings of non-mammalian experimental models carry less weight in the overall evaluation of developmental toxicity than those of corresponding mammalian studies.

Overall, the evidence for developmental and reproductive effects is inadequate.

1.1.10 Cancer

The IARC classification of ELF magnetic fields as “possibly carcinogenic to humans” (IARC, 2002) is based upon all of the available data prior to and including 2001. The review of literature in this EHC monograph focuses mainly on studies published after the IARC review.

Epidemiology

The IARC classification was heavily influenced by the associations observed in epidemiological studies on childhood leukaemia. The classification of this evidence as limited does not change with the addition of two childhood leukaemia studies published after 2002. Since the publication of the IARC monograph the evidence for other childhood cancers remains inadequate.

Subsequent to the IARC monograph a number of reports have been published concerning the risk of female breast cancer in adults associated with ELF magnetic field exposure. These studies are larger than the previous ones and less susceptible to bias, and overall are negative. With these studies, the evidence for an association between ELF magnetic field exposure and the risk of female breast cancer is weakened considerably and does not support an association of this kind.

In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF magnetic fields and the risk of these diseases remains inadequate.

For other diseases and all other cancers, the evidence remains inadequate.

Laboratory animal studies

There is currently no adequate animal model of the most common form of childhood leukaemia, acute lymphoblastic leukaemia. Three independent large-scale studies of rats provided no evidence of an effect of ELF magnetic fields on the incidence of spontaneous mammary tumours. Most studies report no effect of ELF magnetic fields on leukaemia or lymphoma in rodent models. Several large-scale long-term studies in rodents have not shown any consistent increase in any type of cancer, including haematopoietic, mammary, brain and skin tumours.

A substantial number of studies have examined the effects of ELF magnetic fields on chemically-induced mammary tumours in rats. Inconsistent results were obtained that may be due in whole or in part to differences in experimental protocols, such as the use of specific sub-strains. Most studies on the effects of ELF magnetic field exposure on chemically-induced or radiation-induced leukaemia/lymphoma models were negative. Studies of pre-neoplastic liver lesions, chemically-induced skin tumours and brain tumours reported predominantly negative results. One study reported an acceleration of UV-induced skin tumourigenesis upon exposure to ELF magnetic fields.

Two groups have reported increased levels of DNA strand breaks in brain tissue following in vivo exposure to ELF magnetic fields. However, other groups, using a variety of different rodent genotoxicity models, found no evidence of genotoxic effects. The results of studies investigating non-genotoxic effects relevant to cancer are inconclusive.

Overall there is no evidence that exposure to ELF magnetic fields alone causes tumours. The evidence that ELF magnetic field exposure can enhance tumour development in combination with carcinogens is inadequate.

In vitro studies

Generally, studies of the effects of ELF field exposure of cells have shown no induction of genotoxicity at fields below 50 mT. The notable exception is evidence from recent studies reporting DNA damage at field strengths as low as 35 μ T; however, these studies are still being evaluated and our understanding of these findings is incomplete. There is also increasing evidence that ELF magnetic fields may interact with DNA-damaging agents.

There is no clear evidence of the activation by ELF magnetic fields of genes associated with the control of the cell cycle. However, systematic studies analysing the response of the whole genome have yet to be performed.

Many other cellular studies, for example on cell proliferation, apoptosis, calcium signalling and malignant transformation, have produced inconsistent or inconclusive results.

Overall conclusion

New human, animal and in vitro studies, published since the 2002 IARC monograph, do not change the overall classification of ELF magnetic fields as a possible human carcinogen.

1.1.11 Health risk assessment

According to the WHO Constitution, health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. A risk assessment is a conceptual framework for a structured review of information relevant to estimating health or environmental outcomes. The health risk assessment can be used as an input to risk management that encompasses all the activities needed to reach decisions on whether an exposure requires any specific action(s) and the undertaking of these actions.

In the evaluation of human health risks, sound human data, whenever available, are generally more informative than animal data. Animal and in vitro studies can support evidence from human studies, fill data gaps left in the evidence from human studies or be used to make a decision about risks when human studies are inadequate or absent.

All studies, with either positive or negative effects, need to be evaluated and judged on their own merit and then all together in a weight-of-evidence approach. It is important to determine to what extent a set of evidence changes the probability that exposure causes an outcome. The evidence for an effect is generally strengthened if the results from different types of studies (epidemiology and laboratory) point to the same conclusion and/or when multiple studies of the same type show the same result.

Acute effects

Acute biological effects have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection for acute effects.

Chronic effects

Scientific evidence suggesting that everyday, chronic low-intensity (above 0.3–0.4 μ T) power-frequency magnetic field exposure poses a health

risk is based on epidemiological studies demonstrating a consistent pattern of increased risk for childhood leukaemia. Uncertainties in the hazard assessment include the role that control selection bias and exposure misclassification might have on the observed relationship between magnetic fields and childhood leukaemia. In addition, virtually all of the laboratory evidence and the mechanistic evidence fail to support a relationship between low-level ELF magnetic fields and changes in biological function or disease status. Thus, on balance, the evidence is not strong enough to be considered causal, but sufficiently strong to remain a concern.

Although a causal relationship between magnetic field exposure and childhood leukaemia has not been established, the possible public health impact has been calculated assuming causality in order to provide a potentially useful input into policy. However, these calculations are highly dependent on the exposure distributions and other assumptions, and are therefore very imprecise. Assuming that the association is causal, the number of cases of childhood leukaemia worldwide that might be attributable to exposure can be estimated to range from 100 to 2400 cases per year. However, this represents 0.2 to 4.9% of the total annual incidence of leukaemia cases, estimated to be 49 000 worldwide in 2000. Thus, in a global context, the impact on public health, if any, would be limited and uncertain.

A number of other diseases have been investigated for possible association with ELF magnetic field exposure. These include cancers in both children and adults, depression, suicide, reproductive dysfunction, developmental disorders, immunological modifications and neurological disease. The scientific evidence supporting a linkage between ELF magnetic fields and any of these diseases is much weaker than for childhood leukaemia and in some cases (for example, for cardiovascular disease or breast cancer) the evidence is sufficient to give confidence that magnetic fields do not cause the disease.

1.1.12 Protective measures

It is essential that exposure limits be implemented in order to protect against the established adverse effects of exposure to ELF electric and magnetic fields. These exposure limits should be based on a thorough examination of all the relevant scientific evidence.

Only the acute effects have been established and there are two international exposure limit guidelines (ICNIRP, 1998a; IEEE, 2002) designed to protect against these effects.

As well as these established acute effects, there are uncertainties about the existence of chronic effects, because of the limited evidence for a link between exposure to ELF magnetic fields and childhood leukaemia. Therefore the use of precautionary approaches is warranted. However, it is not recommended that the limit values in exposure guidelines be reduced to some arbitrary level in the name of precaution. Such practice undermines the scientific foundation on which the limits are based and is likely to be an expensive and not necessarily effective way of providing protection.

Implementing other suitable precautionary procedures to reduce exposure is reasonable and warranted. However, electric power brings obvious health, social and economic benefits, and precautionary approaches should not compromise these benefits. Furthermore, given both the weakness of the evidence for a link between exposure to ELF magnetic fields and childhood leukaemia, and the limited impact on public health if there is a link, the benefits of exposure reduction on health are unclear. Thus the costs of precautionary measures should be very low. The costs of implementing exposure reductions will vary from one country to another, making it very difficult to provide a general recommendation for balancing the costs against the potential risk from ELF fields.

In view of the above, the following recommendations are given.

- Policy-makers should establish guidelines for ELF field exposure for both the general public and workers. The best source of guidance for both exposure levels and the principles of scientific review are the international guidelines.
- Policy-makers should establish an ELF EMF protection programme that includes measurements of fields from all sources to ensure that the exposure limits are not exceeded either for the general public or workers.
- Provided that the health, social and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposure is reasonable and warranted.
- Policy-makers, community planners and manufacturers should implement very low-cost measures when constructing new facilities and designing new equipment including appliances.
- Changes to engineering practice to reduce ELF exposure from equipment or devices should be considered, provided that they yield other additional benefits, such as greater safety, or little or no cost.
- When changes to existing ELF sources are contemplated, ELF field reduction should be considered alongside safety, reliability and economic aspects.
- Local authorities should enforce wiring regulations to reduce unintentional ground currents when building new or rewiring existing facilities, while maintaining safety. Proactive measures to identify violations or existing problems in wiring would be expensive and unlikely to be justified.
- National authorities should implement an effective and open communication strategy to enable informed decision-making by all stakeholders; this should include information on how individuals can reduce their own exposure.

- Local authorities should improve planning of ELF EMF-emitting facilities, including better consultation between industry, local government, and citizens when siting major ELF EMF-emitting sources.
- Government and industry should promote research programmes to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.

1.2 Recommendations for research

Identifying the gaps in the knowledge concerning the possible health effects of exposure to ELF fields is an essential part of this health risk assessment. This has resulted in the following recommendations for further research (summarized in Table 1).

As an overarching need, further research on intermediate frequencies (IF), usually taken as frequencies between 300 Hz and 100 kHz, is required, given the present lack of data in this area. Very little of the required knowledge base for a health risk assessment has been gathered and most existing studies have contributed inconsistent results, which need to be further substantiated. General requirements for constituting a sufficient IF database for health risk assessment include exposure assessment, epidemiological and human laboratory studies, and animal and cellular (in vitro) studies (ICNIRP, 2003; ICNIRP, 2004; Litvak, Foster & Repacholi, 2002).

For all volunteer studies, it is mandatory that research on human subjects is conducted in full accord with ethical principles, including the provisions of the Helsinki Declaration (WMA, 2004).

For laboratory studies, priority should be given to reported responses (i) for which there is at least some evidence of replication or confirmation, (ii) that are potentially relevant to carcinogenesis (for example, genotoxicity), (iii) that are strong enough to allow mechanistic analysis and (iv) that occur in mammalian or human systems.

1.2.1 Sources, measurements and exposures

The further characterization of homes with high ELF exposure in different countries to identify relative contributions of internal and external sources, the influence of wiring/grounding practices and other characteristics of the home could give insights into identifying a relevant exposure metric for epidemiological assessment. An important component of this is a better understanding of foetal and childhood exposure to ELF fields, especially from residential exposure to underfloor electrical heating and from transformers in apartment buildings.

It is suspected that in some cases of occupational exposure the present ELF guideline limits are exceeded. More information is needed on exposure (including to non-power frequencies) related to work on, for example, live-line maintenance, work within or near the bore of MRI magnets

(and hence to gradient-switching ELF fields) and work on transportation systems. Similarly, additional knowledge is needed about general public exposure which could come close to guideline limits, including sources such as security systems, library degaussing systems, induction cooking and water heating appliances.

Exposure to contact currents has been proposed as a possible explanation for the association of ELF magnetic fields with childhood leukaemia. Research is needed in countries other than the USA to assess the capability of residential electrical grounding and plumbing practices to give rise to contact currents in the home. Such studies would have priority in countries with important epidemiological results with respect to ELF and childhood leukaemia.

1.2.2 Dosimetry

In the past, most laboratory research was based on induced electric currents in the body as a basic metric and thus dosimetry was focused on this quantity. Only recently has work begun on exploring the relationship between external exposure and induced electric fields. For a better understanding of biological effects, more data on internal electric fields for different exposure conditions are needed.

Computation should be carried out of internal electric fields due to the combined influence of external electric and magnetic fields in different configurations. The vectorial addition of out-of-phase and spatially varying contributions of electric and magnetic fields is necessary to assess basic restriction compliance issues.

Very little computation has been carried out on advanced models of the pregnant woman and the foetus with appropriate anatomical modelling. It is important to assess possible enhanced induction of electric fields in the foetus in relation to the childhood leukaemia issue. Both maternal occupational and residential exposures are relevant here.

There is a need to further refine micro-dosimetric models in order to take into account the cellular architecture of neural networks and other complex suborgan systems identified as being more sensitive to induced electric field effects. This modelling process also needs to consider influences in cell membrane electrical potentials and on the release of neurotransmitters.

1.2.3 Biophysical mechanisms

There are three main areas where there are obvious limits to the current understanding of mechanisms: the radical pair mechanism, magnetic particles in the body and signal-to-noise ratios in multicell systems, such as neuronal networks.

The radical pair mechanism is one of the more plausible low-level interaction mechanisms, but it has yet to be shown that it is able to mediate significant effects in cell metabolism and function. It is particularly impor-

tant to understand the lower limit of exposure at which it acts, so as to judge whether this could or could not be a relevant mechanism for carcinogenesis. Given recent studies in which reactive oxygen species were increased in immune cells exposed to ELF fields, it is recommended that cells from the immune system that generate reactive oxygen species as part of their immune response be used as cellular models for investigating the potential of the radical pair mechanism.

Although the presence of magnetic particles (magnetite crystals) in the human brain does not, on present evidence, appear to confer a sensitivity to environmental ELF magnetic fields, further theoretical and experimental approaches should explore whether such sensitivity could exist under certain conditions. Moreover, any modification that the presence of magnetite might have on the radical pair mechanism discussed above should be pursued.

The extent to which multicell mechanisms operate in the brain so as to improve signal-to-noise ratios should be further investigated in order to develop a theoretical framework for quantifying this or for determining any limits on it. Further investigation of the threshold and frequency response of the neuronal networks in the hippocampus and other parts of the brain should be carried out using *in vitro* approaches.

1.2.4 Neurobehaviour

It is recommended that laboratory-based volunteer studies on the possible effects on sleep and on the performance of mentally demanding tasks be carried out using harmonized methodological procedures. There is a need to identify dose-response relationships at higher magnetic flux densities than used previously and a wide range of frequencies (i.e. in the kilohertz range).

Studies of adult volunteers and animals suggest that acute cognitive effects may occur with short-term exposures to intense electric or magnetic fields. The characterization of such effects is very important for the development of exposure guidance, but there is a lack of specific data concerning field-dependent effects in children. The implementation of laboratory-based studies of cognition and changes in electroencephalograms (EEGs) in people exposed to ELF fields is recommended, including adults regularly subjected to occupational exposure and children.

Behavioural studies on immature animals provide a useful indicator of the possible cognitive effects on children. The possible effects of pre- and postnatal exposure to ELF magnetic fields on the development of the nervous system and cognitive function should be studied. These studies could be usefully supplemented by investigations into the effects of exposure to ELF magnetic fields and induced electric fields on nerve cell growth using brain slices or cultured neurons.

There is a need to further investigate potential health consequences suggested by experimental data showing opioid and cholinergic responses in animals. Studies examining the modulation of opioid and cholinergic

responses in animals should be extended and the exposure parameters and the biological basis for these behavioural responses should be defined.

1.2.5 Neuroendocrine system

The existing database of neuroendocrine response does not indicate that ELF exposure would have adverse impacts on human health. Therefore no recommendations for additional research are given.

1.2.6 Neurodegenerative disorders

Several studies have observed an increased risk of amyotrophic lateral sclerosis in “electrical occupations”. It is considered important to investigate this association further in order to discover whether ELF magnetic fields are involved in the causation of this rare neurodegenerative disease. This research requires large prospective cohort studies with information on ELF magnetic field exposure, electric shock exposure as well as exposure to other potential risk factors.

It remains questionable whether ELF magnetic fields constitute a risk factor for Alzheimer’s disease. The data currently available are not sufficient and this association should be further investigated. Of particular importance is the use of morbidity rather than mortality data.

1.2.7 Cardiovascular disorders

Further research into the association between ELF magnetic fields and the risk of cardiovascular disease is not considered a priority.

1.2.8 Immunology and haematology

Changes observed in immune and haematological parameters in adults exposed to ELF magnetic fields showed inconsistencies, and there are essentially no research data available for children. Therefore, the recommendation is to conduct studies on the effects of ELF exposure on the development of the immune and haematopoietic systems in juvenile animals.

1.2.9 Reproduction and development

There is some evidence of an increased risk of miscarriage associated with ELF magnetic field exposure. Taking into account the potentially high public health impact of such an association, further epidemiological research is recommended.

1.2.10 Cancer

Resolving the conflict between epidemiological data (which show an association between ELF magnetic field exposure and an increased risk of childhood leukaemia) and experimental and mechanistic data (which do not support this association) is the highest research priority in this field. It is recommended that epidemiologists and experimental scientists collaborate on this. For new epidemiological studies to be informative they must focus on new aspects of exposure, potential interaction with other factors or on high exposure groups, or otherwise be innovative in this area of research. In addi-

tion, it is also recommended that the existing pooled analyses be updated, by adding data from recent studies and by applying new insights into the analysis.

Childhood brain cancer studies have shown inconsistent results. As with childhood leukaemia, a pooled analysis of childhood brain cancer studies should be very informative and is therefore recommended. A pooled analysis of this kind can inexpensively provide a greater and improved insight into the existing data, including the possibility of selection bias and, if the studies are sufficiently homogeneous, can offer the best estimate of risk.

For adult breast cancer more recent studies have convincingly shown no association with exposure to ELF magnetic fields. Therefore further research into this association should be given very low priority.

For adult leukaemia and brain cancer the recommendation is to update the existing large cohorts of occupationally exposed individuals. Occupational studies, pooled analyses and meta-analyses for leukaemia and brain cancer have been inconsistent and inconclusive. However, new data have subsequently been published and should be used to update these analyses.

The priority is to address the epidemiological evidence by establishing appropriate *in vitro* and animal models for responses to low-level ELF magnetic fields that are widely transferable between laboratories.

Transgenic rodent models for childhood leukaemia should be developed in order to provide appropriate experimental animal models to study the effect of ELF magnetic field exposure. Otherwise, for existing animal studies, the weight of evidence is that there are no carcinogenic effects of ELF magnetic fields alone. Therefore high priority should be given to *in vitro* and animal studies in which ELF magnetic fields are rigorously evaluated as a co-carcinogen.

With regard to other *in vitro* studies, experiments reporting the genotoxic effects of intermittent ELF magnetic field exposure should be replicated.

1.2.11 Protective measures

Research on the development of health protection policies and policy implementation in areas of scientific uncertainty is recommended, specifically on the use of precaution, the interpretation of precaution and the evaluation of the impact of precautionary measures for ELF magnetic fields and other agents classified as “possible human carcinogens”. Where there are uncertainties about the potential health risk an agent poses for society, precautionary measures may be warranted in order to ensure the appropriate protection of the public and workers. Only limited research has been performed on this issue for ELF magnetic fields and because of its importance, more research is needed. This may help countries to integrate precaution into their health protection policies.

Further research on risk perception and communication which is specifically focused on electromagnetic fields is advised. Psychological and sociological factors that influence risk perception in general have been widely investigated. However, limited research has been carried out to analyse the relative importance of these factors in the case of electromagnetic fields or to identify other factors that are specific to electromagnetic fields. Recent studies have suggested that precautionary measures which convey implicit risk messages can modify risk perception by either increasing or reducing concerns. Deeper investigation in this area is therefore warranted.

Research on the development of a cost–benefit/cost-effectiveness analysis for the mitigation of ELF magnetic fields should be carried out. The use of cost–benefit and cost-effectiveness analyses for evaluating whether a policy option is beneficial to society has been researched in many areas of public policy. The development of a framework that will identify which parameters are necessary in order to perform this analysis for ELF magnetic fields is needed. Due to uncertainties in the evaluation, quantifiable and unquantifiable parameters will need to be incorporated.

Table 1. Recommendations for further research

Sources, measurements and exposures	Priority
Further characterization of homes with high ELF magnetic field exposure in different countries	Medium
Identify gaps in knowledge about occupational ELF exposure, such as in MRI	High
Assess the ability of residential wiring outside the USA to induce contact currents in children	Medium
Dosimetry	
Further computational dosimetry relating external electric and magnetic fields to internal electric fields, particularly concerning exposure to combined electric and magnetic fields in different orientations	Medium
Calculation of induced electric fields and currents in pregnant women and in the foetus	Medium
Further refinement of microdosimetric models taking into account the cellular architecture of neural networks and other complex suborgan systems	Medium
Biophysical mechanisms	
Further study of radical pair mechanisms in immune cells that generate reactive oxygen species as part of their phenotypic function	Medium
Further theoretical and experimental study of the possible role of magnetite in ELF magnetic field sensitivity	Low
Determination of threshold responses to internal electric fields induced by ELF on multicell systems, such as neural networks, using theoretical and in vitro approaches	High

Table 1. Continued

Neurobehaviour

Cognitive, sleep and EEG studies in volunteers, including children and occupationally exposed subjects, using a wide range of ELF frequencies at high flux densities	Medium
Studies of pre- and post-natal exposure on subsequent cognitive function in animals	Medium
Further study of opioid and cholinergic responses in animals	Low

Neurodegenerative disorders

Further studies of the risk of amyotrophic lateral sclerosis in “electric” occupations and in relation to ELF magnetic field exposure and of Alzheimer’s disease in relation to ELF magnetic field exposure	High
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Immunology and haematology

Studies of the consequences of ELF magnetic field exposure on immune and haematopoietic system development in juvenile animals.	Low
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Reproduction and development

Further study of the possible link between miscarriage and ELF magnetic field exposure	Low
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Cancer

Update existing pooled analyses of childhood leukaemia with new information	High
Pooled analyses of existing studies of childhood brain tumour studies	High
Update existing pooled and meta-analyses of adult leukaemia and brain tumour studies and of cohorts of occupationally exposed individuals	Medium
Development of transgenic rodent models of childhood leukaemia for use in ELF studies	High
Evaluation of co-carcinogenic effects using in vitro and animal studies	High
Attempted replication of in vitro genotoxicity studies	Medium

Protective measures

Research on the development of health protection policies and policy implementation in areas of scientific uncertainty	Medium
Further research on risk perception and communication focused on electromagnetic fields	Medium
Development of a cost–benefit/cost-effectiveness analysis for the mitigation of ELF fields	Medium
