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Draft

ICNIRP Guidelines

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1 Hz TO 100 kHz)

International Commission on Non-Ionizing Radiation Protection

INTRODUCTION

In this document, guidelines are established for the protection of people exposed to electric and magnetic fields in the extremely-low-frequency (ELF) range of the electromagnetic spectrum. For the purpose of this document the ELF range extends from 1 Hz to 100 kHz. Guidelines for static fields have been issued in a separate document (ICNIRP 2009). Those guidelines should be applied to movement induced electric fields or time-varying magnetic fields up to 1 Hz.

This publication replaces the ELF part of the 1998 guidelines (ICNIRP 1998).

These guidelines are based on scientifically established adverse biological effects resulting from exposure to (ELF) electric and magnetic fields. All biological effects of such exposure have been reviewed by IARC, ICNIRP, HPA-NRPB, and WHO (IARC 2002, ICNIRP 2003, HPA-NRPB 2004, WHO 2007a). Those publications provided the scientific rationale for these guidelines.

These guidelines for limiting exposure have been developed following a thorough review of all published scientific literature. As detailed below, the basis for the guidelines is two-fold: Exposure to power-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects. In addition, the only well established effect in volunteers exposed to ELF magnetic fields are the stimulation of central and peripheral nervous tissues and the induction in the retina of phosphenes, a perception of faint flickering light in the periphery of the visual field. The retina is part of the CNS and is regarded as an appropriate, albeit conservative, model for induced electric field effects on CNS neuronal circuitry in general.

In view of the uncertainty inherent in the scientific data, reduction factors have been applied in establishing the exposure guidelines.

SCOPE AND PURPOSE

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against any established adverse health effects.

Studies on both direct and indirect effects of EMF have been assessed; direct effects result from direct interactions of fields with the body, indirect effects involve interactions with a conducting object where the electric potential of the object is different from that of the body. Results of laboratory and epidemiological studies, basic exposure assessment criteria and reference levels for practical hazard assessment are discussed and the guidelines presented here are applicable to both occupational and public exposure.

In establishing exposure limits, the Commission recognizes the need to reconcile a number of differing expert opinions. The validity of scientific reports has to be considered and extrapolations from animal experiments to effects on humans have to be made. The restrictions in these guidelines were based on scientific data alone; currently available knowledge indicates that these restrictions provide a high level of protection to workers and members of the public from exposure to time-varying ELF EMF.

These guidelines do not address product performance standards, which are intended to limit EMF emissions from specific devices under specified test conditions, nor does the document deal with the techniques used to measure any of the physical quantities that characterize electric, magnetic and electromagnetic fields. Comprehensive descriptions of instrumentation and measurement techniques for accurately determining such physical quantities may be found elsewhere (IEC 2004, IEC 2005, IEEE 1994, IEEE 2008).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document, but is available elsewhere (IEC 2005).

These guidelines will be periodically revised and updated as advances are made in identifying other adverse health effects, if any, of ELF time-varying electric and magnetic fields.

QUANTITIES AND UNITS

Whereas electric fields are associated only with the presence of electric charge, magnetic fields are the result of the physical movement of electric charge (electric current). An electric field, **E**, exerts forces on an electric charge and is expressed in volts per meter (V m^{-1}). Similarly, magnetic fields can exert physical forces on electric charges, but only when such charges are in motion. Electric and magnetic fields have both magnitude and direction (i.e., they are vectors). A magnetic field can be specified in two ways—as magnetic flux density, **B**, expressed in teslas (T), or as magnetic field strength, **H**, expressed in amperes per meter (A m^{-1}). The two quantities are related by the expression:

$$\mathbf{B} = \mu\mathbf{H} \quad (1)$$

where μ is the constant of proportionality (the magnetic permeability); in vacuum and air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi \times 10^{-7}$ when expressed in henry per meter ($H\ m^{-1}$). Thus, in describing a magnetic field for protection purposes, only one of the quantities **B** or **H** needs to be specified.

Exposure to time-varying EMF results in internal electric fields and in body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. The internal electric field and current density are related by Ohm's Law:

$$\mathbf{J} = \sigma\mathbf{E_i} \quad (2)$$

where σ is the electrical conductivity of the medium. The dosimetric quantities used in these guidelines, are as follows:

- In situ or internal electric field E_i;
- Current i;

A general summary of EMF and dosimetric quantities and units used in these guidelines is provided in Table 1.

Table 1. Electric, magnetic, electromagnetic and dosimetric quantities and corresponding SI units.

Quantity	**Symbol**	**Unit**
Conductivity	σ	siemens per meter ($S\ m^{-1}$)
Current	I	ampere (A)
Current density	**J**	ampere per square meter ($A\ m^{-2}$)
Frequency	*f*	hertz (Hz)
Electric field strength	**E**	volt per meter ($V\ m^{-1}$)
Magnetic field strength	**H**	ampere per meter ($A\ m^{-1}$)
Magnetic flux density	**B**	tesla (T)
Magnetic permeability	μ	henry per meter ($H\ m^{-1}$)
Permittivity	ε	farad per meter ($F\ m^{-1}$)

SCIENTIFIC BASIS FOR LIMITING EXPOSURE

These guidelines for limiting exposure have been developed following a thorough review of all published scientific literature. Well established criteria were used to evaluate the scientific validity of the methodology, results and conclusions of reported findings. Only effects for which there was good and reliable scientific evidence were used as the basis for the exposure restrictions.

Coupling mechanisms between fields and the body

Human and animal bodies significantly perturb the spatial distribution of an ELF electric field. At low frequencies, the body is a good conductor, and the perturbed field lines external to the body are nearly perpendicular to the body surface. Oscillating charges are induced on the surface of the exposed body and these produce currents inside the body. Key features of dosimetry for exposure of humans to ELF electric fields include:

- the electric field induced inside the body is normally five to six orders of magnitude smaller than the external electric field,
- since the exposure is usually to the vertical field, the predominant direction of the induced fields is also vertical,
- for a given external electric field, the strongest fields are induced when the human body is in perfect contact with the ground through the feet (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 are determined by the conductivity of those tissues,
- the distribution of the induced electric field is affected by the tissue conductivities; there is also a separate phenomenon of indirect induction, where the current in the body is produced by 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. Human and animal bodies do not significantly perturb the field. The main interaction of magnetic fields is the Faraday induction of electric fields and associated currents in the conductive tissues. Currents may also be induced by movement in a static magnetic field. Key features of dosimetry for exposure of humans to ELF magnetic fields include:

- the induced electric field and current depend on the orientation of the external field to the body. Generally induced fields in the body are greatest when the field is aligned from the front to the back of the body, but for some 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 and
- the distribution of the induced electric field is affected by the conductivity of the various organs and tissues.

Conclusions from the current scientific literature

Neurobehavior

The perception of surface electric charge and the acute neurophysiological studies that form the basis of the exposure guidelines are discussed in the rationale.

The evidence for other neurobehavioral effects in volunteers, such as effects on brain electrical activity, cognition, sleep, and mood, is less clear (see Cook et al 2002, 2006; Crasson 2003; ICNIRP 2003). Generally, such studies have been carried out at exposure levels below those required to induce the effects described in the rationale, and have produced evidence of only subtle and transitory effects at most. The conditions necessary to elicit such responses are not well defined at present.

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 (Rubin et al 2005; Röösli 2008).

There is only inconsistent and inconclusive evidence that exposure to ELF electric and magnetic fields causes depressive symptoms or suicide (WHO 2007a).

In animals, the possibility that exposure to ELF fields may affect neurobehavioral functions has been explored from a number of perspectives using a range of exposure conditions. Few 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. Other possible field-dependent changes are less well defined (WHO 2007a).

Overall, this research is not sufficiently reliable to provide a basis for human exposure limits.

Neuroendocrine system

The results of volunteer studies as well as residential and occupational epidemiological studies have not suggested that the neuroendocrine system is adversely affected by exposure to power frequency electric or magnetic fields. This applies particularly to circulating levels of specific hormones, 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. 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 (WHO 2007a).

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. 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 (ICNIRP 2003; WHO 2007a). No convincing effect on melatonin levels has been seen in a study of non-human primates chronically exposed to power-frequency fields.

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 (ICNIRP 2003; WHO 2007a). Similarly, while few studies have been carried out, mostly negative or inconsistent effects have been seen in the levels of growth hormone and 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.

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 between ELF exposure and 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 for 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 (Kheifets et al 2009).

The studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. Overall, the evidence for the association between ELF exposure and Alzheimer´s disease and ALS is weak.

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 (WHO 2007a). Though 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. Most of the studies of cardiovascular disease morbidity and mortality have shown no association with exposure (Kheifets et al 2007). Whether a specific association exists between exposure and altered autonomic control of the heart remains speculative. Overall, the evidence suggests that there is no association between ELF exposure and cardiovascular diseases.

Reproduction and development

Overall, epidemiological studies have not shown an association between human adverse reproductive outcomes and maternal or paternal exposure to ELF fields. There is some limited evidence for increased risk of miscarriage associated with maternal magnetic field exposure, but this reported association has not been found in other studies and overall the evidence for such an association is poor.

Exposures to ELF electric fields up of 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 (ICNIRP 2003; WHO 2007a).

ELF magnetic field exposure of mammals does not result in gross external, visceral or skeletal malformations using fields up to 20 mT (Juutilainen 2003, 2005; WHO 2007a). Some studies show an increase of minor skeletal anomalies, in both rats and mice but skeletal variations are relatively common findings in teratological studies and are often considered biologically insignificant.

Overall, the evidence for an association between ELF and developmental and reproductive effects is very weak.

Cancer

A considerable number of epidemiological reports, carried out particularly during the 1980s and 90s, indicated that long term exposure to ELF magnetic fields, orders of magnitude below the limits of the current guidelines might be associated with adverse health effects. While the first studies looked at childhood cancer in relation to magnetic fields, later research also investigated different adult cancers. In general, the initially observed associations between ELF magnetic fields and various cancers were not consistently confirmed in studies designed to see whether the initial findings could be replicated. However, for childhood leukemia the situation is different. Research that followed the first study has suggested that there may be an association between residential ELF magnetic fields and childhood leukemia risk, although it cannot be excluded that a combination of selection bias, some degree of confounding and chance could explain the results (WHO 2007a). Two pooled analyses indicate that an excess risk may exist around 0.3-0.4 µT, although the authors of those analyses cautioned strongly that their results cannot be interpreted as showing a causal relationship between magnetic fields and childhood leukemia (Ahlbom et al 2000; Greenland et al 2000).

In principle, there are several alternative explanations for these findings, such as causation, bias, chance and confounding (ICNIRP SCI 2004). Epidemiologists have made extensive efforts to assess the findings and have evaluated bias, confounding and chance as possible explanations, but concluded that, at most, some of the observed association might be due to bias and that chance is an unlikely explanation. At the same time, no biophysical mechanism has been identified and the experimental results don't support the notion that exposure to ELF magnetic fields is a cause of childhood leukemia.

It should be noted that there is currently no adequate animal model of the most common form of childhood leukemia, acute lymphoblastic leukemia. Most studies report no effect of ELF magnetic fields on leukemia or lymphoma in rodent models (ICNIRP 2003; WHO 2007a). Several large-scale long-term studies in rodents have not shown any consistent increase in any type of cancer, including hematopoietic, mammary, brain and skin tumors.

A substantial number of studies have examined the effects of ELF magnetic fields on chemically-induced mammary tumors in rats (ICNIRP 2003; WHO 2007a). 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 (Anderson et al 2000). Most studies on the effects of ELF magnetic field exposure on chemically-induced or radiation-induced leukemia/lymphoma models were negative. Studies of pre-neoplastic liver lesions, chemically-induced skin tumors and brain tumors reported predominantly negative results.

Generally, studies of the effects of ELF field exposure of cells have shown no induction of genotoxicity at fields below 50 mT (Crumpton and Collins 2004; WHO 2007a). A notable exception is evidence from one group reporting DNA damage from intermittent exposures at field strengths as low as 35 µT (Ivancsits et al 2003a,b). However, these effects have not been replicated (Scarfi et al 2005).

Overall, in contrast to the epidemiological evidence of an association between childhood leukemia and prolonged exposure to power frequency magnetic fields, the animal cancer data, particularly those from large-scale lifetime studies, are almost universally negative. The data from cellular studies are generally supportive of this view, though more equivocal.

Rationale for these recommended ELF guidelines

ICNIRP addresses acute and chronic health effects and considers recent dosimetric developments in this guidance.

Acute effects

There are a number of well established acute effects of exposure to ELF EMFs on the nervous system: the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes. There is also strong indirect scientific evidence that CNS functions such as cognitive processing can be affected by induced electric fields below the threshold for direct stimulation. In addition, painful currents can occur when a person makes contact with a conducting object at a different electrical potential. All these effects have thresholds, below which they do not occur and can be avoided by meeting appropriate basic restrictions on electric fields induced in the body and on contact current.

Prevention of perception and painful effects of surface electric charge induced on the body by exposure to ELF electric fields is addressed through a series of protective measures.

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 an individual’s response sensitivity. Thresholds for direct perception by 10% of volunteers ranged between 2 and 20 kV m^{-1} and 5% found 15–20 kV m^{-1} annoying (Reilly 1998, 1999). The spark discharge from a person to ground is found to be painful to 7% of volunteers in a field of 5 kV m^{-1}, whereas it would be painful to about 50% in a 10 kV m^{-1} field (Reilly, 1998, 1999). Thresholds for the spark discharge from a charged object through a grounded person depend on the size of the object and therefore requires individual assessment.

The responsiveness of electrically excitable nerve and muscle tissue to electric stimuli including induced electric fields has been well established for many years (eg Reilly 1998 2002; Saunders and Jefferys 2002, 2007; Wood 2008; Kavet et al 2008). It is known to depend very much on the properties of the nerve or muscle cell membrane, particularly the membrane time-constant, which results from the structure of biological membranes: the thin lipid membrane behaves as a capacitance while the ion channels provide a parallel resistance. An electric field will stimulate the peripheral nerve if the induced membrane depolarization is above a threshold value sufficient for the opening of the voltage-gated sodium channels to become self-sustaining. Myelinated nerve axons (nerve fibers) are more sensitive to electric field stimulation than non-myelinated fibres: the fatty myelin sheath increases the nerve fiber length-constant, a measure of the resistance of the cell membrane compared to the intracellular and extracellular resistances, so increasing the transmembrane potential that will result from an extracellular electric field gradient. In addition, the myelin sheath results in membrane time-constants of only about 120-150 µs, rendering myelinated fibers more sensitive to higher frequencies than non-myelinated fibers; for myelinated fibers, the thresholds begin to rise above around 1-3 kHz due to the progressively shorter time available for the accumulation of electric charge on the nerve membrane. Thresholds will also rise below about 10 Hz due to the slow inactivation of the voltage-gated sodium ion channels and/or the activation of slow potassium channels, termed accommodation (Baker and Bostock 1989; Benzanilla 2000).

Myelinated nerve fibers exist in both the peripheral nervous system (PNS) and in the white matter of the central nervous system (CNS). Myelinated nerve fibers of the PNS have been stimulated by pulsed electric fields induced during volunteer exposure to the switched gradient magnetic fields of MR (Bourland et al 1999; Schaefer et al 2000; Nyenhuis et al 2001). These studies investigated thresholds for perception, uncomfortable and intolerable sensation in 84 volunteers exposed to switched gradient fields for the y-gradient field (anterior-posterior or coronal gradient) and z-gradient field (head-to-toe or axial gradient) in which dB/dt pulses (gradient field ramps) of between 50 and 1000 µs, separated by 300 µs intervals, were applied at various intensities. Significant motor contraction of either abdominal or thoracic skeletal muscle was observed for gradient field strengths approximately 50% greater than the sensation threshold. Experimentally, minimum threshold (peak) values for perception have been reported to range between 2 and 6 V m^{-1} (Nyenhuis et al 2001; So et al 2004), similar to calculations by Reilly (1998) of the median electric stimulation threshold for large diameter (20 µm) myelinated peripheral nerves (around 6 V m^{-1}pk) in response to sinusoidal stimuli. With regard to nerve tissue in the CNS, small volumes of cortical tissue are deliberately stimulated during transcranial magnetic stimulation (TMS) in order to produce a transient change in brain function for diagnostic, therapeutic or research purposes. TMS typically utilizes short pulses inducing large (>100 V m^{-1}pk) electric fields in brain tissue (Walsh and Cowey 1998). However, minimum threshold values for the stimulation of the slightly smaller myelinated nerve fibers in the CNS (compared to those in the peripheral nervous system) have been estimated to be as low as ~10 V m^{-1}pk (Reilly 1998).

Muscle cells also show electrical excitability and can respond to direct electrical stimulation but in general are less sensitive to direct electrical stimulation than myelinated nerve fibers (Reilly 1998). Nevertheless, cardiac muscle tissue deserves particular attention because it depends on the synchronized behavior of electrically interconnected muscle cells whose aberrant function could be fatal. Reilly (1998; 2002) conservatively estimated the one-percentile threshold for cardiac muscle stimulation (the induction of ectopic beats) in a population to be similar to the median peripheral nerve stimulation threshold of around 6 V m^{-1}pk. This would apply for durations of induced electric field much greater than cardiac muscle membrane time-constant (~ 3 ms), i.e. at stimulation frequencies below about 120 Hz. Cardiac stimulation is not necessarily hazardous, although it may render the heart more sensitive to ventricular fibrillation (Reilly 1998). Ventricular fibrillation however, in which the asynchronous contraction of ventricular muscle causes the ventricle to fail to pump blood effectively around the body, is life-threatening but minimum thresholds for fibrillation exceed those for excitation by a factor of 50 or more. However, this drops to a factor of only 2 if the heart is repeatedly excited during the vulnerable period of the cardiac cycle (Reilly 1998; 2002).

The integrative properties of the synapses and neural networks of the CNS should in theory render it and therefore cognitive function sensitive to the effects of physiologically weaker electric fields, below the threshold for direct nerve or muscle excitation. The non-myelinated regions of the CNS, which form the grey matter, include these synaptic regions and cell bodies. Here, the shorter length constants and longer time constants render this tissue less sensitive to electric fields than myelinated nerve fibers, above about 200 Hz, but, on the other hand, their integrative function means that transmembrane voltages are variable and therefore potentially sensitive to much smaller additional changes in voltage. In addition, much of normal cognitive function of the brain depends on the collective activity of very large numbers of neurons; neural networks are thought to have complex non-linear dynamics that can be very sensitive to small voltages applied diffusely across the elements of the network (Adair 2001; Jefferys et al 2003). Interacting groups or networks of nerve cells exposed to weak spatially and temporally coherent electrical signals would be expected on theoretical grounds to show increased sensitivity through improved signal-to-noise ratios compared with the response of individual cells (Adair 2001; Saunders and Jefferys 2007). Recent *in vitro* neurophysiological evidence suggests that minimum thresholds for these effects may be as low as 100 mV m^{-1} at frequencies of less than ~100 Hz (Saunders and Jefferys 2007). However, the experimental evidence for effects of ELF induced electric fields (mostly at 50/60 Hz) on brain function in volunteers is less clear (see above). Generally, such studies have been carried out at exposure levels below those required to induce the effects described above; further studies are required to clarify the uncertainties regarding this possibility.

The most robustly established effect of physiologically weak induced electric fields is the induction in volunteers of magnetic phosphenes, the perception of faint flickering light in the periphery of the visual field. They result from the interaction of the induced electric field with electrically excitable cells in the retina, which is an outgrowth of the forebrain and therefore part of the CNS (Attwell 2003; Reilly 2002). Indeed, Attwell (2003) notes that the retina is a good but conservative model of the neurophysiological processes that occur in CNS tissue in general. The minimum threshold flux density for phosphenes is around 5 mT at 20 Hz, rising at higher and lower frequencies (eg. Lövsund et al 1980a, 1980b). Threshold induced electric field strengths in the retina have been estimated to lie between about 50 and 100 mV m^{-1} at 20 Hz (Saunders and Jefferys 2007) although there is considerable uncertainty attached to these values. Reilly (2002) indicated that the rise in phosphene threshold above 20 Hz is the result of relatively long membrane time-constants of around 25 ms identified in electrophysiological studies of the neural tissue of the retina.

Other electrically excitable tissues with the potential to show network behavior include glial cells located within the CNS and the autonomic and enteric nervous systems, which comprise interconnected non-myelinated nerve cells and are distributed throughout the body and gut, respectively. These latter systems are involved in regulating the visceral or ‘housekeeping’ functions of the body; however, non-myelinated nerve cells are less sensitive to direct electrical stimulation than myelinated nerve cells (Reilly 1998). Tissues regarded as non-excitable, such as the kidney or liver, also possess voltage-gated ion channels, but these show slow electric potentials and their sensitivity is likely to be lower than those of nerve and muscle cells specialized for rapid electrical signaling (Saunders and Jefferys 2007). In addition, these tissues also lack the integrative properties of synapses and neuronal networks that render the central nervous system potentially more vulnerable.

Chronic effects

The literature on chronic effects of ELF fields has been evaluated in detail by individual scientists and scientific panels. WHO's cancer research institute, IARC (International Agency for Research on Cancer) evaluated ELF magnetic fields in 2002 and classified them in category 2 B, which translates to "possibly carcinogenic to humans". The basis for this classification was the epidemiologic results on childhood leukemia.

It is the view of ICNIRP that the currently existing scientific evidence that ELF magnetic fields is causally associated with childhood leukemia is too weak to form the basis for exposure guidelines.

Dosimetry

Historically, magnetic field models assumed that the body has a homogeneous and isotropic conductivity and applied simple circular conductive loop models to estimate induced currents in different organs and body regions. Electric fields induced by time varying electric and magnetic fields were computed by using simple homogeneous prolate ellipsoid models. In recent years, more realistic calculations based on anatomically and electrically refined heterogeneous models (Xi and Stuchly 1994, Dimbylow 2005 and 2006, Bahr et al 2007) resulted in a much better knowledge of *in situ* electric fields in the body from exposure to electric and magnetic fields.

The most useful dosimetric results for the purpose of these guidelines have been obtained from high resolution calculations of induced electric field with voxel sizes below 4 mm (Dimbylow 2005; Bahr et al 2007; Hirata et al 2009). The maximum electric field is induced in the body when the external fields are homogeneous and directed parallel to the body axis (E-field) or perpendicular (H-field). According to the calculations of Dimbylow (2005) and Bahr (2007), the maximal local peak electric field induced by a 50 Hz magnetic field (1 µT) in CNS tissue is 0.05-0.08 mV m^{-1}, while for a corresponding electric field (1 kV m^{-1}) it is 3-4 mV m^{-1}. Table 5 shows some representative data from dosimetric studies for estimating the maximum electric field induced by the time derivative of a homogeneous magnetic field.

Table 2. Conversion factors for maximum E-field induced by magnetic field in biological bodies.

Biological body model	**Conversion Factor [(mV/m)/(T/s)]**	**B-field, direction**	**Reference**
Brain, NORMAN	97.4	homog., AP[1]	Dimbylow 2005
Homog. sphere of 15 cm (diam.).	37.5	-	-
Retina, NORMAN	22.6	homog., AP	Dimbylow 2005
Homog. ellipsoid a=40 cm cm, b= 20 cm	140	homog., AP (perpendicular to b-axis)	IEC 60601

Heterogeneous body	340	MRI-gradient, LR[2)]	Brand and Heid 2002
Heterogeneous body	200-250	MRI-gradient, AP	So et al 2004
Heterogeneous body	650[3)]	MRI-gradient, AP	Bencsik et al 2007
-	650	homog.	ICNIRP 1998[4)]

Note
1) Anterior to Posterior (front to back)
2) Left to Right
3) 3.3 (V/m)/(T/s) with clasped hands
4) Adopted for the relation between the basic restriction and reference level

GUIDELINES FOR LIMITING EMF EXPOSURE

Separate guidance is given for occupational exposures and exposure of the general public. It is recommended that the limits for occupational exposure in these guidelines be applied to those individuals who are exposed to time-varying electric, and magnetic fields from 1 Hz to 100 kHz as a result of performing their regular or assigned job activities. The term “general public” refers to the entire population.

Addressing scientific uncertainty

All scientific data and their interpretation are subject to some degree of uncertainty. Examples are methodological variability and inter-individual, inter-species, and inter-strain differences. Such uncertainties in knowledge are compensated for by reduction factors.

There is however insufficient information on all sources of uncertainty to provide a rigorous basis for establishing reduction factors over the whole frequency range and for all modulation patterns. Therefore, the degree to which caution is applied in the interpretation of the available database and in defining reduction factors is to a large degree a matter of expert judgment.

Basic restrictions and reference levels

Limitations of exposure that are based on the physical quantity or quantities directly related to the established health effects are termed basic restrictions. In this guideline, the physical quantity used to specify the basic restrictions on exposure to EMF is the *in situ* electric field strength **E**, as it is the electric field that affects nerve cells and other electrically sensitive cells. Because of relatively large uncertainties in the conductivity of the tissue, induced electric field appears to be a more stable dose quantity than the induced current density.

The *in situ* electric field strength is difficult to assess. Therefore, for practical exposure assessment purposes, reference levels of exposure are provided to determine whether the basic restrictions are likely to be met or exceeded. Most reference levels are derived from relevant basic restrictions using measurement and/or computational techniques but some address perception (electric field) and adverse indirect effects of exposure to EMF. The derived quantities are electric field strength (**E**), magnetic field strength (**H**), magnetic flux density (**B**) and currents flowing through the limbs (I_L). The quantity that addresses indirect effects is the contact current (I_C). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

BASIC RESTRICTIONS

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against adverse health effects. As noted above, the risks come from transient nervous system responses including peripheral nerve stimulation and possible effects on central nervous system (CNS) function.

Central nervous system

In view of the considerations above for frequencies in the range 10 Hz to 100 Hz, occupational exposure should be limited to fields that induce electric field strengths in CNS tissue of less than 100 mV m^{-1}. This value represents the lower estimate of possible effects on CNS function. The phosphene threshold will be exceeded around 20 Hz. Myelinated nerves are more sensitive than non-myelinated neural tissue such as the grey matter of the CNS to induced electric fields at frequencies above 200 Hz.

For the general public a reduction factor of 5 is applied, giving a basic exposure restriction of 20 mV m^{-1}. This will also protect against the occurrence of phosphenes. The lower basic restriction for exposure of the general public takes into account the fact that their age, health status and knowledge of exposure may differ from that of workers.

Below 10 Hz and above 100 Hz, the basic restriction on induced electric fields in the CNS increases progressively, corresponding to the increase in the threshold for the effects considered in these frequency ranges.

The basic restrictions are presented in Table 2 and Figure 1.

Time averaging

ICNIRP recommends that the restrictions on *in situ* electric fields induced by electric or magnetic fields including transient or very short-term peak fields be regarded as instantaneous values which should not be time averaged.

Spatial averaging

When restricting adverse effects of induced electric fields to nerve cells and networks in the CNS, it is important to define the distance or volume over which the local induced electric field must be averaged. Basically the electric field effects on neurons and other electrically excitable cells are local effects, but there are electrophysiological and practical dosimetric factors that constrain the minimum volume or distance. The major physical factor disturbing the function of neurons and neuronal networks is the voltage produced by the induced electric field over the membrane of the cell. For isolated nerve fibers aligned along the direction of the electric field (maximum coupling) this voltage is integrated from the electric field over the electro tonic distance varying from 2 to 7 millimeters for invertebrate nerves (Reilly 1998). For myelinated nerve cells a good assumption for the integration distance is approximately 2 mm, which is the maximum inter-nodal distance between the nodes of Ranvier. These distances are relevant when considering stimulation thresholds to isolated nerve cells. In the case of sub-threshold weak electric field effects, such as retinal phosphenes, the collective “network” effect of numerous interacting nerve cells must be taken into account. The threshold of the effect is considerably lower than the stimulation threshold of isolated nerve cells, which is due to summation and integration of small, induced voltages in the synapses. It has been suggested that the averaging volume for the induced electric field should be based on minimum of 1000 interacting cells, which is approximately 1 mm^2 in most nerve tissue (Jefferys 1994). Hence a biologically reasonable averaging distance might extend from 1 to 7 mm. From a practical point of view it is difficult to achieve satisfactory accuracy in the millimeter resolution computation of the induced electric field, and even more difficult to measuring it. Maximal values in one voxel in a specific tissue are prone to large stair-casing errors associated with sharp corners of the cubical voxel. A solution to obtain more stable peak approximations is based on choosing for the peak value a value representing the 99^{th} percentile value of the induced field in a specific tissue. From the biological point of view however, this is a somewhat arbitrary choice because the peak value depends on the resolution. A preferred method for the spatial averaging is to define the local electric field as an average in a small volume. To clarify further the issue of spatial integration it would be important to carry out studies on the fine details of the distribution of the induced electric field particularly in the brain, spinal cord and retina.

As a practical compromise, satisfying requirements for a sound biological basis and computational constraints, ICNIRP recommends to determine the induced electric field as an average of the magnitude of the electric field in a cubical volume of 5x5x5 mm^3 (Bahr et al 2007).

Table 2. Basic restrictions for human exposure to time-varying electric and magnetic fields

Exposure characteristic	Frequency range	*In situ* electric field V m^{-1}
Occupational exposure		
	1 – 10 Hz	1 / f
	10 Hz – 100 Hz	0.1
	100 Hz – 200 Hz	$1{\cdot}10^{-3}$ f
	200 Hz – 1000 Hz	0.2
	1 kHz – 100 kHz	$2{\cdot}10^{-4}$ f
General public exposure		
	1 – 10 Hz	0.2 / f
	10 Hz – 100 Hz	0.02
	100 Hz – 200 Hz 200 Hz – 1000 Hz 1 kHz – 100 kHz	$0.2{\cdot}10^{-3}$ f 0.04 $4{\cdot}10^{-5}$ f

Notes:
- f is the frequency in Hz
- All values are rms

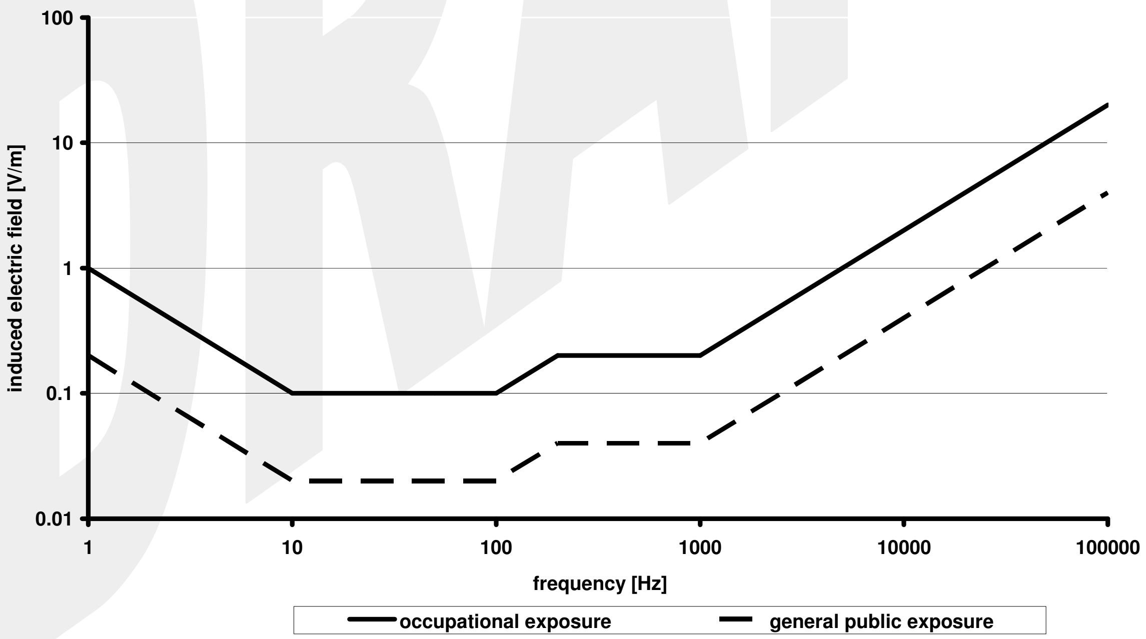

Figure 1 Basic restrictions for general public and occupational exposure in terms of in situ electric field strength concerning CNS tissue.

REFERENCE LEVELS

The reference levels are obtained from the basic restrictions by mathematical modeling (ICNIRP 2003, Bahr et al 2006, Dimbylow 2005 and 2006). They are calculated for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection.

In addition, the electric field reference levels for occupational exposure up to 100 Hz includes a sufficient margin to prevent stimulation effects from contact currents under all possible conditions. Between 100 Hz and 100 kHz the reference levels are based on the basic restriction on induced electric fields only and may thus not provide a sufficient margin to prevent stimulation effects from contact currents under all possible conditions in that frequency band.

The electric field reference levels for general public exposure up to 100 kHz prevent from adverse indirect effects (shocks and burns) for more than 90 % of exposed individuals.

Tables 3 and 4 summarize the reference levels for occupational and general public exposure, respectively, and the reference levels are illustrated in Figures 2 and 3. The reference levels assume an exposure by a uniform (homogeneous) field with respect to the spatial extension of the human body. The frequency dependence of the reference field levels is consistent with data on both biological effects and coupling of the field.

Table 3. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values)

Frequency range	**E-field strength ($V m^{-1}$)**	**H-field strength ($A m^{-1}$)**	**B-field (µT)**
1 – 10 Hz	20 000	$2 \times 10^5 / f^2$	$2.5 \times 10^5 / f^2$
10 - 25 Hz	20 000	$2 \times 10^4 / f$	$2.5 \times 10^4 / f$
0.025 -0.1 kHz	500/f	20/f	25/f
0.1 – 0.4 kHz	5 000	200	250
0.4 – 1 kHz	2000/f	80/f	100/f
1 – 100 kHz	2000	80	100

Note:
- *f in Hz or kHz,* as indicated in the frequency range column.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure
- For purposes of demonstrating compliance with the basic restrictions, the reference levels for the electric and magnetic fields should be considered additively.
- To prevent indirect effects especially in high electric fields see chapter on "Protective measures"

Table 4. Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values)

Frequency range	E-field strength (V m^{-1})	H-field strength (A m^{-1})	B-field (µT)
1 – 10 Hz	10 000	4 x 10^4 / f²	5 x 10^4 / f²
0.01 – 0.025	10 000	4/f	5/f
0.025 – 0.1 kHz	250/f	4/f	5/f
0.1 – 0. kHz	250/f	40	50
0.4 – 1 kHz	250/f	16/f	2/f
1-3 kHz	250/f	16	20
3 – 100 kHz	87	16	20

Note:
- *f in Hz or kHz,* as indicated in the frequency range column.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure
- For purposes of demonstrating compliance with the basic restrictions, the reference levels for the electric and magnetic fields should be considered additively.

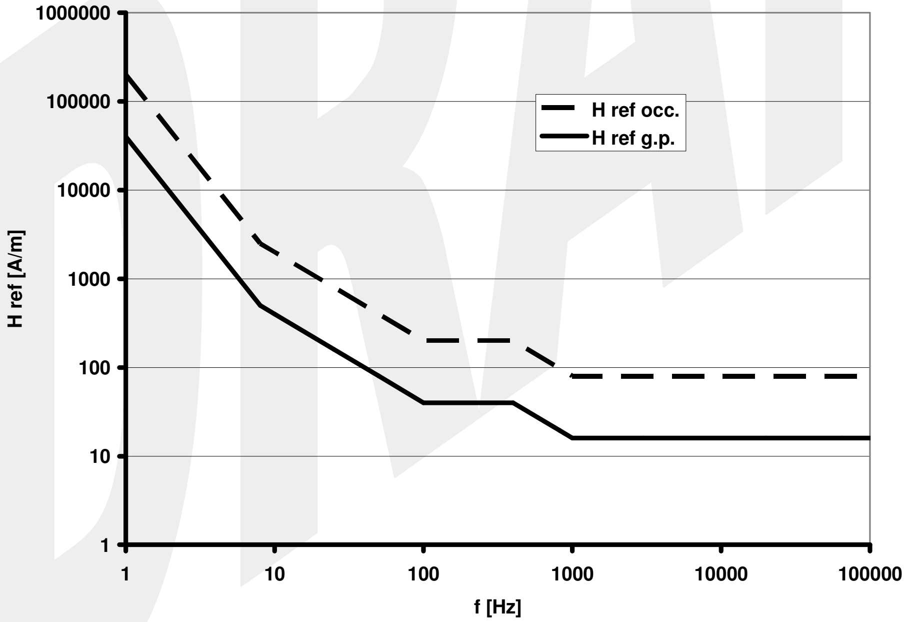

Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 3 and 4).

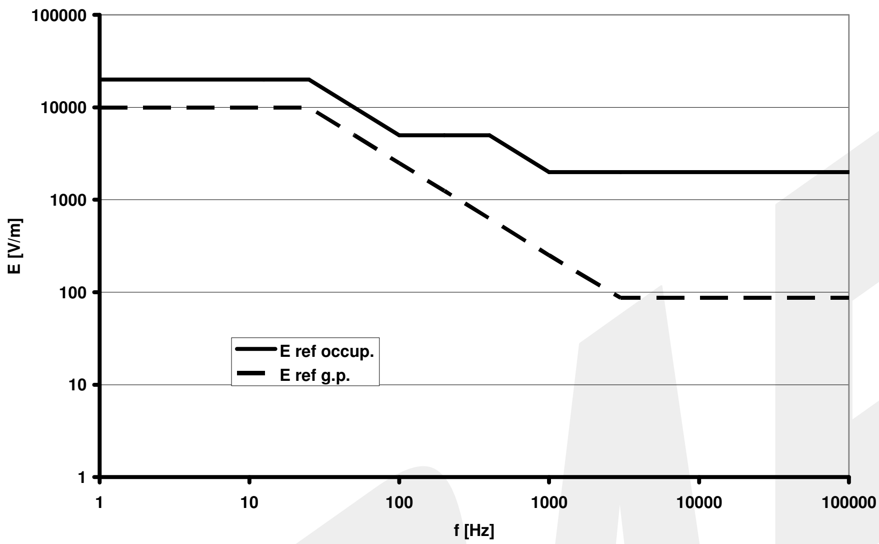

Fig. 3. Reference levels for exposure to time varying electric fields (compare Tables 3 and 4).

REFERENCE LEVELS FOR CONTACT CURRENTS

Up to 100 kHz reference levels for contact current are given for which caution must be exercised to avoid shock and burn hazards. The point contact reference levels are presented in Table 5. Since the threshold contact currents that elicit biological responses in children and adult women are approximately one-half and two-thirds, respectively, of those for adult men, the reference levels for contact current for the general public are set lower by a factor of 2 than the values for occupational exposure. It should be noted, that the reference levels are not intended to prevent perception but to avoid painful shocks. Perception of contact current is not *per se* hazardous but could be considered an annoyance. Prevention of excess contact currents is possible by technical means.

Table 5. Reference levels for time varying contact currents from conductive objects.

Exposure characteristics	**Frequency range**	**Maximum contact current (mA)**
Occupational exposure	up to 2.5 kHz	1.0
	2.5–100 kHz	0.4*f*
General public exposure	up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*

f is the frequency in kHz.

SIMULTANEOUS EXPOSURE TO MULTIPLE FREQUENCY FIELDS

It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. The formulae below apply to relevant frequencies under practical exposure situations. For electrical stimulation, relevant for frequencies up to 100 kHz, *in situ* electric fields should be added according to

$$\sum_{j=1Hz}^{100kHz} \frac{E_{i,j}}{E_{L,j}} \le 1 \qquad (3)$$

where

$E_{i,j}$ is the *in situ* electric field strength induced at frequency j;

$E_{L,j}$ is the induced electric field strength restriction at frequency j as given in Table 2;

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied.

$$\sum_{j=1Hz}^{100kHz} \frac{E_{j}}{E_{L,j}} \le 1 \qquad (4)$$

and

$$\sum_{j=1Hz}^{100kHz} \frac{H_{j}}{H_{L,j}} \le 1 \qquad (5)$$

where

E_j is the electric field strength at frequency j;

$E_{L,j}$ is the electric field strength reference level at frequency j as given in Tables 3 and 4 ;

H_j is the magnetic field strength at frequency j;

$H_{L,j}$ is the magnetic field strength reference level at frequency j as given in Tables 3 and 4;

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{j=1Hz}^{100kHz} \frac{I_{j}}{I_{L,j}} \le 1 \qquad (6)$$

I_j is the contact current component at frequency j;

$I_{L,j}$ is the reference level of the contact current at frequency j as given in Table 5;

NON SINUSOIDAL EXPOSURE

At low frequencies below 100 kHz most the electric and magnetic fields are more or less distorted by harmonic components distributed over a large frequency band. Consequently the waveforms of the fields show complex, often pulsed, patterns. It is always possible to decompose such a field to discrete spectral components by using e.g. FFT (Fast Fourier Transformation) techniques and applying the multiple frequency rule described above. This procedure is based on the assumption that the spectral components add in phase i.e. all maxima coincide at the same time and results in a sharp peak. This is a realistic assumption when the number of spectral components is limited and their phases are not coherent, i.e. they vary randomly. For fixed coherent phases the assumption may be unnecessarily conservative. Additionally, sampling and windowing in FFT spectral analysis may create spurious frequencies, which may artificially increase the linearly summed exposure ratio.

An alternative option to the spectral method is to weight the external electric and magnetic fields and induced electric field or current with a filter function, where attenuation (input/output ratio) is proportional to the basic restriction and reference level (ICNIRP 2003; Jokela 2000). In the case of a broadband field consisting of harmonic components the restriction imposed by the filtering can be presented mathematically as:

$$\left| \sum_i \frac{A_i}{C_i} \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1 \qquad (7)$$

where t is time and C_i is the basic restriction or reference level at i:th harmonic frequency f_i A_i and θ_i φ are the amplitudes, phase angles of the field and phase angles of the filter at the harmonic frequencies.

Each change of the slope of an exposure limit creates a change in the phase angle, which should, approximate within 90 degrees the phase change of a simple filter block consisting of a resistor (R) and a capacitor (C). See ICNIRP (2003) for further details.

Eq. 7 looks similar to Eqs. 3 - 6 except that it takes into account the effect of varying phases of harmonic components. Table 6 gives the guidance values for the peak value of the filtered peak electric and magnetic field. The limit for the peak value is derived from the ICNIRP basic restrictions and reference levels with the following procedure:

At first determine the reference frequency at the plateau region where the attenuation of the filter is set to a minimum value of 1 (see Table 6 for the definition of a plateau region). Then obtain the corresponding ICNIRP reference level valid over the plateau region (rms value). Finally convert it to the peak value (amplitude) by multiplying with 1.41 ($\sqrt{2}$).

In the measurement instruments the weighting filter can be an electronic or digital filter where the attenuation should not deviate more than 3 dB from the exact piecewise linear frequency response.

The weighted peak approach can be used both for coherent and non-coherent fields. In the latter case the measurement time must be long enough to detect the worst case peak value with a reasonable probability. In the case of non-coherent fields, consisting of a few frequencies, the weighted peak approach is identical to the spectral summation.

Table 6. Guidance values for non-sinusoidal fields expressed as weighted (filtered) peak values.

	$E_{induced}$	f	$E_{external}$	f	B	f
	mV m^{-1}	Hz	V m^{-1}	kHz	µT	kHz
occupational	$\sqrt{2} \times 50$	10-100	$\sqrt{2} \times 2000$	1-100	$\sqrt{2} \times 100$	1-100
general public	$\sqrt{2} \times 10$	10-100	$\sqrt{2} \times 500$	1-100	$\sqrt{2} \times 20$	1-100

PROTECTIVE MEASURES

ICNIRP notes that protection of people exposed to electric and magnetic fields could be ensured by compliance with all aspects of these guidelines.

Measures for the protection of workers include engineering and administrative controls, and personal protection programs. Appropriate protective measures must be implemented when exposure in the workplace results in the basic restrictions being exceeded. As a first step, engineering controls should be undertaken wherever possible to reduce device emissions of fields to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar health protection mechanisms.

Administrative controls, such as limitations on access and the use of audible and visible warnings, should be used in conjunction with engineering controls. Personal protection measures, such as protective clothing, though useful in certain circumstances, should be regarded as a last resort to ensure the safety of the worker, and priority should be given to engineering and administrative controls wherever possible. Furthermore, when such items as insulated gloves are used to protect individuals from shock, the basic restrictions must not be exceeded, since the insulation protects only against indirect effects of the fields.

With the exception of protective clothing and other personal protection, the same measures can be applied to the general public whenever there is a possibility that the general public reference levels might be exceeded. It is also essential to establish and implement rules that will prevent:

- interference with medical electronic equipment and devices (including cardiac pacemakers);
- detonation of electro-explosive devices (detonators); and
- fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents, or spark discharges.

Managing Risk in Occupational Exposure

Within a workplace people should be designated to ensure that the hazards associated with exposure to ELF fields are managed. This is usually done through a risk management process the details of which should include:

- Identification of the hazards. This step should include identification of all ELF source(s).

- Assessment of the risk. This step includes assessment of exposure levels, comparison with the relevant limits and consideration of both the likelihood and severity of the consequence(s) of the hazard.
- Choice of the most appropriate control measures to prevent or minimize the level of risk. The control/s chosen must not cause other hazards.
- Implementation of the chosen control measures. This step must include maintenance requirements to ensure the ongoing effectiveness of the control/s and training on the control measures for workers potentially exposed to ELF fields.
- Monitoring and reviewing the effectiveness of the control measures. The monitoring and review process must assess whether the chosen controls have been implemented as planned, that the control measures are effective and that the control measures have not introduced new hazards or worsened existing hazards.
- Review of the risk management process if changes to the way work is performed have the potential to change the exposure to the hazard.

General Public Exposure

Measures for the protection of members of the general public who may be exposed to fields due to their proximity to ELF sources with the capacity for producing fields exceeding the limits must include the following:

- Determination of the boundaries of areas where general public exposure limits appropriate to the circumstance may be exceeded,
- Restriction of public access to those areas where the general public exposure limits appropriate to the circumstance may be exceeded, and
- Appropriate provision of warning signs or notices.

CONSIDERATIONS REGARDING POSSIBLE LONG-TERM EFFECTS

As noted above, epidemiological studies have consistently found that everyday chronic low-intensity (above 0.3-0.4 µT) power frequency magnetic field exposure is associated with an increased risk of childhood leukemia. IARC has classified such fields as possibly carcinogenic. However, a causal relationship between magnetic fields and childhood leukemia has not been established nor have any other long term effects been established. The absence of established causality means that this effect cannot be addressed in the basic restrictions. However, risk management advice, including considerations on precautionary measures, has been given by WHO (WHO 2007a, WHO 2007b) and other bodies.

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Informative Annex

Spatial averaging

Reference levels are used for practical exposure assessment where most realistic results are obtained when the variation of the fields over the space occupied by the body is relatively small. In most exposure situations, however, the distance to the source of field is so close that the distribution of the fields is non-uniform or localized to the small part of the body. For a very localized source with a distance of a few centimeters from the body, the only choice for a realistic exposure assessment is numerical dosimetry. In the non-uniform distribution case, where the distance to the source is not less than 20 to 30 cm, it is always safe to measure the maximum electric or magnetic field strength in the position of the body. This, however, often results in a too conservative exposure assessment. A more realistic approach is to measure the spatial average over a defined volume that would be occupied by a person (Jokela 2007). The integration volume must be based on well established dosimetry which also gives specifications for the distances to the source and spatial characteristics of the fields which must be satisfied when using spatial integration. A good example of this approach is presented by Stuchly and Dawson (2002) who have shown on the basis of numerical calculations that magnetic flux density averaged over an exposed organ is a conservative estimate of the equivalent uniform magnetic field for that organ. Because the brain is the organ most critical to the effects of the induced current and electric field, this result strongly suggest that the average magnetic field over the head is the most important indicator of the exposure to low-frequency magnetic field. The average over the length of the torso may protect the spinal cord.

Each of the external electric and magnetic field induce in the body an electric field component which add in the tissue as vectors. In the case of the exposure analysis based on the external electric and magnetic fields a conservative approach would be to assume that both the electrically and magnetically induced field components attain the maximum value in the same critical point in the same phase. If this conservative approach does not prove compliance with the reference values in a given exposure situation, compliance with the basic restrictions need to be considered. Such situations are judged to be infrequent because of great difference in the distribution of the electrically and magnetically induced electric fields and phase difference of the corresponding induced electric field.

GLOSSARY

Adverse effect

An effect detrimental to the health of an individual due to exposure to an electric or magnetic field, or a contact current.

Averaging distance

The distance over which the *in situ* electric field is averaged when determining compliance with Basic Restrictions.

Basic Restrictions

Mandatory limitations on the quantities that closely match all known biophysical interaction mechanisms with tissue that may lead to adverse health effects.

Cancer

Diseases characterized by the uncontrolled and abnormal division of eukaryotic cells and by the spread of the disease (metastasis) to disparate sites in the organism.

Carcinogens

Several natural and artificial agents, mostly chemicals and types of radiation, that increase the frequency with which cells become cancerous.

Cell cycle

The cyclical process of growth and cellular reproduction in unicellular and multicellular organisms. The cycle includes nuclear division, or mitosis, and cell division, or cytokinesis.

Central nervous system (CNS)

The portion of the vertebrate nervous system consisting of the brain and spinal cord, but not including the peripheral nerves.

Characteristics

Detailed physical properties of electric or magnetic fields such as the magnitude, frequency spectrum, polarization, modulation etc.

Conductivity

A property of materials that determines the magnitude of the electric current density when an electric field is impressed on the material, expressed in units of siemens per meter (S/m); the inverse of resistivity.

Contact current

Current passed into a biological medium via a contacting electrode or other source of current.

Current density

A vector of which the integral over a given surface is equal to the current flowing through the surface; the mean density in a linear conductor is equal to the current divided by the cross-sectional area of the conductor. Expressed in ampere per square meter (A/m^2).

DC

Abbreviation for ‘direct current,’ but also used for to indicate constancy of fields, see ‘Static field.’

Depolarization (cellular)

The reduction of the resting potential across a cellular membrane.

Direct effect

A biological effect resulting from direct interaction of EMF with biological structures.

Direct electro stimulation

Stimulation via the electric field within the biological medium induced by an external electric or magnetic field without direct contact with other conductors or spark discharges.

DNA (deoxyribonucleic acid)

A polymeric molecule consisting of deoxyribonucleotide building blocks that in a double-stranded, double-helical form is the genetic material of most organisms.

Dosimetry

Measurement, or determination by calculation, of internal electric field strength or induced current density or specific absorption (SA), or specific absorption rate (SAR), in humans or animals exposed to electromagnetic fields.

Electric field

A vector field E measured in volts per meter.

Electric field strength *(E)*

Force exerted by an electric field on an electric point charge, divided by the electric charge. Electric field strength is expressed in newton per coulomb or volts per meter (N/C =V/m).

Electromagnetic energy

The energy stored in an electromagnetic field. Expressed in joule (J).

Electromagnetic fields

The combination of electric and magnetic fields in the environment. This term is often confused with 'electromagnetic radiation' and can therefore be misleading when used with extremely low frequencies for which the radiation is barely detectable.

Electro stimulation

Induction of a propagating action potential in excitable tissue by an applied electrical stimulus; electrical polarization of presynaptic processes leading to a change in post synaptic cell activity.

ELF

Extremely low frequency; frequency in the range of 1- 300 Hz.

EMF

Electric and magnetic fields.

Established mechanism

A bioelectric mechanism having the following characteristics: (a) can be used to predict a biological effect in humans; (b) an explicit model can be made using equations or parametric relationships; (c) has been verified in humans, or animal data can be confidently extrapolated to humans; (d) is supported by strong evidence; and (e) is widely accepted among experts in the scientific community.

Exposure

That which occurs whenever a person is subject to the influence of an ELF field or contact current.

Exposure, long-term

This term indicates exposure during a major part of the lifetime of the biological system involved; it may, therefore, vary from a few weeks to many years in duration.

Exposure assessment

The evaluation of a person's exposure by measurements, modeling, information about sources or other means.

Exposure metric

A single number that summarizes exposure to an electric and/or magnetic field. The metric is usually determined by a combination of the instrument's signal processing and the data analysis performed after the measurement.

Frequency

The number of sinusoidal cycles completed by electromagnetic waves in 1 second; usually expressed in hertz (Hz).

General public

The term General public refers to the entire population. It includes individuals of all ages, and of varying health status, and this will include particularly vulnerable groups or individuals such as the frail, elderly, pregnant workers, babies and young children.

General public exposure

All exposure to ELF fields received by members of the general public. This definition excludes occupational exposure, and medical exposure.

Harmonic (frequency)

Frequencies that are integral multiples of the power frequency or some other reference frequency. Should be sub harmonics included?

Heart rate

The measurement of the number of heartbeats per minute.

Hertz (Hz)

The unit for expressing frequency, (f). One hertz equals one cycle per second. 1 kHz = 1000 Hz, 1 MHz = 1000 kHz, 1 GHz = 1000 MHz.

Induction

An electric or magnetic field in a conducting medium caused by the action of a time-varying external (environmental) electric or magnetic field.

In situ

Within biological tissue.

Instantaneous

Adjective used to describe particular parameters that must be measured or evaluated over a very short time interval (typically 100 microseconds or less).

Let-go current

The threshold current level at which involuntary muscular contraction prevents release of a grip on an energized conductor.

Magnetic field

A vector quantity, **H**, specifies a magnetic field at any point in space, and is expressed in ampere per meter (A m^{-1}). See also magnetic flux density.

Magnetic field strength (*H*)

The magnitude of the magnetic field vector; expressed in units of amperes per meter (A/m).

Magnetic flux density (*B*)

A vector quantity that determines the force on a moving charge or charges (electric current). Magnetic flux density is expressed in teslas (T). One gauss (deprecated unit) equals 10^{-4} T.

Magnetophosphenes

The sensation of flashes of light caused by induced electric currents stimulating the retina.

Mean

The arithmetic average of a series of measurements or other data.

Median threshold

The threshold value within a statistical distribution at which 50% of subjects have greater thresholds and 50% have lesser thresholds.

Medical exposure

Exposure of a person to ELF fields received as a patient undergoing medical diagnosis or recognized medical treatment, or as a volunteer in medical research.

Mutagen

A substance that is able to cause a mutation.

Mutation

Any detectable and heritable change in the genetic material not caused by genetic recombination.

Nerve

A bundle of axons.

Nerve fiber

A single nerve axon.

Neuron

A single cellular unit usually consisting of an axon, cell body, and dendritic tree.

Non-ionizing radiation (NIR)

Includes all radiations and fields of the electromagnetic spectrum that do not normally have sufficient energy to produce ionization in matter; characterized by energy per photon less than about 12 eV, which is equivalent to wavelengths greater than 100 nm, or frequencies lower than 3×10^{15} Hz.

No uniform field

A field that is not constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

Occupational exposure

All exposure to EMF experienced by individuals in the course of performing their work.

Peripheral nerve

Nerve found outside the central nervous system and leading to and from the central nervous system.

Permeability

The scalar or tensor quantity whose product by the magnetic field strength is the magnetic flux density. Note: For isotropic media, the permeability is a scalar; for anisotropic media, a matrix. Synonym: absolute permeability. If the permeability of a material or medium is divided by the permeability of vacuum (magnetic constant) μ_0, the result is termed relative permeability (μ). Unit: henrys per meter (H/m).

Permittivity

A constant defining the influence of an isotropic medium on the forces of attraction or repulsion between electrified bodies, and expressed in farad per meter (F/m); *relative permittivity* is the permittivity of a material or medium divided by the permittivity of vacuum.

Phase duration (t_p)

The time between zero crossings of a waveform having zero mean. For a sine wave of frequency f, $t_p = 1/(2f)$. For an exponential waveform, t_p is interpreted as the duration measured from the waveform peak to a point at which it decays to 0.37 (e^{-1}) of its peak value.

Phosphene

Visual sensation caused by nonphotic stimuli. Electro-phosphenes are induced by electric currents; magneto-phosphenes are induced magnetically.

Plasma membrane

Lipid bilayer that surrounds the cytoplasm of both animal and plant cells.

Polarization (cellular)

The electric potential formed across a cell membrane.

Power frequency

The frequency at which AC electricity is generated. For electric utilities, the power frequency is 60 Hz in North America, Brazil and parts of Japan, and 50 Hz in much of the rest of the world.

Protein

One of a group of high-molecular weight, nitrogen-containing organic compounds of complex shape and composition.

Public exposure

All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures.

Radiofrequency (RF)

Electromagnetic energy with frequencies in the range 3 kHz to 300 GHz.

Reduction factor

Reduction of the effect threshold to compensate for various sources of uncertainty in the guideline setting process.

Reference Levels

The rms and peak electric and magnetic fields and contact currents to which a person may be exposed without an adverse effect and with acceptable safety factors. The Reference Levels for electric and magnetic field exposure in this document may be exceeded if it can be demonstrated that the Basic Restrictions are not exceeded.

Thus, it is a practical or ‘surrogate’ parameters that may be used for determining compliance with the Basic Restrictions.

Relative permeability

(Absolute) permeability (q.v.) divided by the permeability in vacuum. A value near one signifies that the material is only weakly magnetized by an external field.

Relative phase

The phase angle of a sinusoidal waveform relative to the phase angle of another waveform measured at a different point within the conductive medium or with respect to a stated reference waveform.

Relative risk (RR)

The ratio of the disease rate in the group under study to that in a comparison group, with adjustments for confounding factors such as age, if necessary. For rare diseases, the relative risk is practically the same as the odds ratio.

Root mean square (rms)

The square root of the mean of the square of a time variant function, F(t), over a specified time period from t_1 to t_2. It is derived by first squaring the function and then determining the mean value of the squares obtained, and taking the square root of that mean value, i.e.

$$F_{rms} = \sqrt{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[F(t)]^2\,dt}$$

Safety factor

A factor used in deriving Basic Restrictions and Reference Levels which provides for the protection of exceptionally sensitive individuals, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in reaction thresholds, and uncertainties in induction models.

S.I.

Abbreviation for the International system of units.

Spatial Peak

Term used to describe the highest level of a particular quantity averaged over a small mass or area in the human body.

Spark discharge

The transfer of current through an air gap requiring a voltage high enough to ionize the air, as opposed to direct contact with a source.

Static field

A field that does not vary with time. In most environments, electric and magnetic fields change with time, but their frequency spectrum has a component at 0 Hz. This 'quasi-static' component of the field can be measured by averaging the oscillating signal over the sample time.

Tesla (T)

S.I. unit of magnetic flux density. 1 tesla = 10000 gauss (q.v.)

Threshold

The level of a stimulus marking the boundary between a response and a no response.

Transients

A brief bursts of high-frequency fields, usually resulting from mechanical switching of AC electricity.

Uniform field

A field that is constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

Unperturbed field

The electric or magnetic field, generated by a source, that is uninfluenced by the presence of conducting objects, including the human body, or sections of it.

Ventricular fibrillation

Arrhythmia of the ventricles of the heart characterized by rapid uncoordinated contractions.

Voxel

A three-dimensional computational element. In this standard used to represent animal and human tissues in dosimetry models.

Waveform

The variation of an electrical amplitude with time. Unless otherwise stated, in this standard the term *waveform* refers to values (or measurements) at sites within the biological medium.

Workers

See glossary term *Occupational exposure*.