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 humans exposed to electric and magnetic fields in the low-frequency range of the electromagnetic spectrum. The general principles for the development of ICNIRP guidelines are published elsewhere (ICNIRP 2002). For the purpose of this document, the low-frequency range extends from 1 Hz to 100 kHz. Above 100 kHz, effects such as heating need to be considered, which are covered by other ICNIRP guidelines. However, in the frequency range from 100 kHz up to approximately 10 MHz protection from both, low frequency effects on the nervous system as well as high frequency effects need to be considered depending on exposure conditions. Therefore, some guidance in this document is extended to 10 MHz to cover the nervous system effects in this frequency range. Guidelines for static magnetic fields have been issued in a separate document (ICNIRP 2009). Guidelines applicable to movement-induced electric fields or time-varying magnetic fields up to 1 Hz will be published separately.

This publication replaces the low-frequency part of the 1998 guidelines (ICNIRP 1998). ICNIRP is currently revising the guidelines for the high-frequency portion of the spectrum (above 100 kHz).

SCOPE AND PURPOSE

The main objective of this publication is to establish guidelines for limiting exposure to electric and magnetic fields (EMF) that will provide protection against all 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.

The restrictions in these guidelines were based on established evidence regarding acute effects; currently available knowledge indicates that adherence to these restrictions protect workers and members of the public from adverse health effects from exposure to low frequency EMF. The epidemiological and biological data concerning chronic conditions were carefully reviewed and it was concluded that there is no compelling evidence that they are causally related to low-frequency EMF exposure.

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, 2005a; IEEE 1994, 2008).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and implanted 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 2005b).

These guidelines will be periodically revised and updated as advances are made in the scientific knowledge concerning any aspect relevant for limiting exposure of low frequency 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

* ICNIRP Secretariat, c/o Gunde Ziegelberger, c/o Bundesamt für Strahlenschutz, Ingolstaedter Landstrasse 1, 85764 Oberschleissheim, Germany.
For correspondence or reprints contact info@icnirp.org.
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of the physical movement of electric charge (electric current). An electric field, E, exerts a force on an electric charge and is expressed in volts per meter (V m^{-1}). Similarly, magnetic fields can exert physical forces on electric charges, if such charges are in motion and/or the magnetic field varies with time. 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 tesla (T), or as magnetic field strength, H, expressed in ampere per meter (A m^{-1}). The two quantities are related by the expression:

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{1}$$

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 E_i and current density J are related by Ohm's Law:

$$\boldsymbol{J} = \sigma \boldsymbol{E}_i \tag{2}$$

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

- electric field E_i; and
- Current I.

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

SCIENTIFIC BASIS FOR LIMITING EXPOSURE

These guidelines for limiting exposure have been developed following a thorough review of the 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 reliable scientific evidence were used as the basis for the exposure restrictions.

Biological effects of exposure to low frequency electromagnetic fields have been reviewed by the International Agency for Research on Cancer (IARC), ICNIRP, and the World Health Organization (WHO) (IARC 2002; ICNIRP 2003a; WHO 2007a) and national expert groups. Those publications provided the scientific basis for these guidelines.

As detailed below, the basis for the guidelines is two-fold: Exposure to low-frequency electric fields may cause well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects. In addition, the only well established effects in volunteers exposed to low frequency 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. For details see ICNIRP 2002.

Table 1. Quantities and corresponding SI units used in these guidelines.

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})

Coupling mechanisms between fields and the body

Human and animal bodies significantly perturb the spatial distribution of a low frequency 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 low frequency electric fields include:

- the electric field induced inside the body is considerably smaller than the external electric field, e.g., five to six orders of magnitude at 50–60 Hz;
- 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 is determined by the conductivity of those tissues; and

- there is also an indirect effect, 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 tissues. Electric fields may also be induced by movement in a static magnetic field. Key features of dosimetry for exposure of humans to low frequency magnetic fields include:

- for a given magnetic field strength and orientation, higher electric fields are induced in the bodies of larger people because the possible conduction loops are larger;
- the induced electric field and current depend on the orientation of the external magnetic 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 different field alignments;
- the weakest electric fields are induced by a magnetic field oriented along the principal body axis; 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. Exposure to low-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects (Reilly 1998, 1999). Thresholds for direct perception by the most sensitive 10% of volunteers at 50–60 Hz ranged between 2 and 5 kV m^{-1} and 5% found 15–20 kV m^{-1} annoying. 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. Thresholds for the spark discharge from a charged object through a grounded person depend on the size of the object and therefore require individual assessment.

The responsiveness of electrically excitable nerve and muscle tissue to electric stimuli including those induced by exposure to low-frequency EMFs has been well established for many years (e.g., Reilly 2002; Saunders and Jefferys 2007). Myelinated nerve fibers of the human peripheral nervous system have been estimated to have a minimum threshold value of around 6 V_{peak} m^{-1} (Reilly 1998, 2002), based on theoretical calculation using a nerve model. However, peripheral nerve stimulation induced during volunteer exposure to the switched gradient magnetic fields of magnetic resonance (MR) systems suggested that the threshold for perception may be as low as about 2 V m^{-1} (Nyenhuis et al. 2001), based on calculations using a homogeneous human phantom model. A more accurate calculation of the electric fields induced in the tissues of a heterogeneous human model based on data from the above MR study has been carried out by So et al. (2004). These authors estimated the minimum threshold for peripheral nerve stimulation of between about 4–6 V m^{-1}, based on the assumption that stimulation took place in the skin or subcutaneous fat. With stronger stimuli, discomfort and then pain ensue; the lowest percentile for intolerable stimulation is approximately 20% above the median threshold for perception (ICNIRP 2004). Myelinated nerve fibers of the central nervous system (CNS) can be stimulated by electric fields induced during transcranial magnetic stimulation (TMS); the pulsed fields induced in cortical tissue during TMS are quite high (>100 V $m^{-1}{}_{peak}$), although theoretical calculation suggests that minimum stimulation threshold values may be as low as ~10 V $m^{-1}{}_{peak}$ (Reilly 1998, 2002). For both sets of nerves, thresholds rise above around 1–3 kHz due to the progressively shorter time available for the accumulation of electric charge on the nerve membrane and below about 10 Hz due to the accommodation of a nerve to a slowly depolarizing stimulus.[†]

Muscle cells are in general less sensitive to direct stimulation than nerve tissue (Reilly 1998). Cardiac muscle tissue deserves particular attention because aberrant function is potentially life-threatening: however, ventricular fibrillation thresholds exceed those for cardiac muscle stimulation by a factor of 50 or more (Reilly 2002), although this drops considerably if the heart is repeatedly excited during the vulnerable period of the cardiac cycle. Thresholds rise above about 120 Hz due to the much longer time-constant of muscle fibers compared with myelinated nerves.

The most robustly established effect of electric fields below the threshold for direct nerve or muscle excitation is the induction of magnetic phosphenes, the perception of faint flickering light in the periphery of the visual field, in the retinas of volunteers exposed to low frequency magnetic fields. The minimum threshold flux density is around 5 mT at 20 Hz, rising at higher and lower frequencies. In these studies, the phosphenes are thought to result from the interaction of the induced electric field with electrically excitable cells in the retina. This is formed as an outgrowth of the forebrain and can

[†] Accommodation does not occur for example in response to the low-frequency component of trapezoid or rectangular pulses with quick rise-times but low repetition frequencies such as those found in the switched gradient fields of MR systems.

be considered a good but conservative model of processes that occur in CNS tissue in general (Attwell 2003). The threshold for induced electric field strengths in the retina has been estimated to lie between about 50 and 100 mV m^{-1} at 20 Hz, rising at higher and lower frequencies (Saunders and Jefferys 2007) although there is considerable uncertainty attached to these values.

The integrative properties of the nervous tissue of the CNS may render it, and therefore functions such as cognitive processes like memory, sensitive to the effects of these physiologically weak electric fields. Saunders and Jefferys (2002) suggested that the electrical polarization of neurons in the CNS by such weak electric fields might enhance the synchronization of active groups of neurons and affect the recruitment of adjacent non-active neurons, thereby influencing overall nerve cell excitability and activity. I*n vitro* evidence from studies using brain slices suggests that minimum thresholds for these effects lie below frequencies of ~100 Hz and may be as low as 100 mV m^{-1} (Saunders and Jefferys 2007).

Two research groups have investigated the effects of weak electric fields applied directly to the head via electrodes[‡] on brain electrical activity and function in humans. One group (Kanai et al. 2008) reported that stimulation of the visual cortex induced the perception of cortical phosphenes (similar in appearance to phosphenes induced in the retina) when the stimulus frequency was characteristic for visual cortical activity either in dark conditions (around 10 Hz) or in light conditions (around 20 Hz) but not at higher or lower frequencies. The other group (Pogosyan et al. 2009) applied a 20 Hz signal to the motor cortex of volunteers during the performance of a visuo-motor task and found a small but statistically significant slowing of hand movement during task performance, which was consistent with an increased synchronization of 20 Hz motor cortex activity. No effect was seen at a lower stimulus frequency. In summary, both groups of authors found that 10–20 Hz electric fields, above the threshold for retinal phosphenes, can interact with ongoing rhythmic electrical activity in the visual and motor cortices and slightly affect visual processing and motor co-ordination, carrying the implication that 10–20 Hz EMF-induced electric fields of sufficient magnitude may have similar effects.

However, the evidence for other neurobehavioral effects on brain electrical activity, cognition, sleep, and mood in volunteers exposed to low frequency EMFs is much less clear (Cook et al. 2002, 2006; Crasson 2003; ICNIRP 2003a; Barth et al. 2010). Generally, such studies have been carried out at exposure levels at or below about 1–2 mT; i.e., below those required to induce the effects described above, and have produced evidence of 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; WHO 2007a).

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

In animals, the possibility that exposure to low frequency 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 low-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).

Thus, the perception of surface electric charge, the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes are well established and can serve as a basis for guidance. In addition, there is also indirect scientific evidence that brain functions such as visual processing and motor co-ordination can be transiently affected by induced electric fields. However, the evidence from other neurobehavioral research in volunteers exposed to low frequency electric and magnetic fields 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 suggest that the neuroendocrine system is not adversely affected by exposure to 50–60 Hz 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 50–60 Hz 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 50–60 Hz electric and magnetic fields on rat pineal and serum melatonin levels, some reported

[‡] Transcranial AC stimulation or tACS is applied at levels below local skin perception thresholds.

that exposure resulted in night-time suppression of melatonin, while other studies did not. In seasonally breeding animals, the evidence for an effect of exposure to 50–60 Hz fields on melatonin levels and melatonin-dependent reproductive status is predominantly negative (ICNIRP 2003a; WHO 2007a). No convincing effect on melatonin levels has been seen in a study of non-human primates chronically exposed to 50–60 Hz 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 low frequency electric-field exposure at levels high enough to be perceived (ICNIRP 2003a; 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 low frequency 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 low frequency 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 low frequency 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 (Kheifets et al. 2009). 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. Furthermore, studies using more sophisticated exposure assessment methods, e.g., job-exposure matrices, have generally not observed increased risks (Kheifets et al. 2009). For Alzheimer's disease, results are inconsistent. Strongest associations have been found in clinic based studies with a large potential for selection bias, but increased risks have also been observed in some, but not all, population based studies. Subgroup analyses within studies strengthen the impression of inconsistent data (Kheifets et al. 2009). Statistical heterogeneity between study results speaks against pooling of available results, although such attempts have been made (Garcia et al. 2008). In addition, there is some evidence for publication bias. Control of potential confounding from other occupational exposures has generally not been made. So far only one residential study is available, indicating an increased risk for Alzheimer's disease after long-term exposure, but based on very small numbers of cases (Huss et al. 2009).

The studies investigating the association between low frequency exposure and Alzheimer's disease are inconsistent. Overall, the evidence for the association between low frequency exposure and Alzheimer′s disease and ALS is inconclusive.

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 low frequency 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 or between studies (McNamee et al. 2009). 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 does not suggest an association between low frequency 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 low frequency 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 low frequency 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 (ICNIRP 2003a; WHO 2007a).

Low frequency 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). Overall, the evidence for an association between low frequency and developmental and reproductive effects is very weak.

Cancer. A considerable number of epidemiological reports, carried out particularly during the 1980's and 90's, indicated that long term exposure to 50–60 Hz magnetic fields, orders of magnitude below the limits of the 1998 ICNIRP exposure guidelines might be associated with cancer. While the first studies looked at childhood cancer in relation to magnetic fields, later research also investigated adult cancers. In general, the initially observed associations between 50–60 Hz magnetic fields and various cancers were not confirmed in studies designed to see whether the initial findings could be replicated. However, for childhood leukemia the situation is different. The research that followed the first study has suggested that there may be a weak association between the higher levels of exposure to residential 50–60 Hz magnetic fields and childhood leukemia risk, although it is unclear whether it is causal: a combination of selection bias, some degree of confounding and chance could explain the results (WHO 2007a). Two pooled analyses (Ahlbom et al. 2000; Greenland et al. 2000) indicate that an excess risk may exist for average exposures exceeding 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.

At the same time, no biophysical mechanism has been identified and the experimental results from the animal and cellular laboratory studies do not support the notion that exposure to 50–60 Hz 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 50–60 Hz magnetic fields on leukemia or lymphoma in rodent models (ICNIRP 2003a; 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 50–60 Hz magnetic fields on chemically-induced mammary tumors in rats (ICNIRP 2003a; 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. Most studies on the effects of 50–60 Hz 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 low frequency field exposure of cells have shown no induction of genotoxicity at fields below 50 mT (Crumpton and Collins 2004; WHO 2007a). 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 the animal studies, though more equivocal.

Rationale for these recommended low frequency 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 low-frequency EMFs on the nervous system: the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes. There is also indirect scientific evidence that brain functions such as visual processing and motor co-ordination can be transiently affected by induced electric fields. 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.

Following the recommendations made concerning guidelines on limits of exposure to static magnetic fields (ICNIRP 2009), ICNIRP considers that there are occupational circumstances where, with appropriate advice and training, it is reasonable for workers voluntarily and knowingly to experience transient effects such as retinal phosphenes and possible minor changes in some brain functions, since they are not believed to result in long-term or pathological health effects. Exposure of all parts of the body in these circumstances should be limited in order to avoid peripheral and central myelinated nerve stimulation. ICNIRP notes the relatively narrow margin between peripheral nerve perception and pain thresholds; see above. For both types of nerves, thresholds rise above around 1–3 kHz due to the very short membrane time-constants resulting from myelination, and below about 10 Hz due to the accommodation to a slowly depolarizing stimulus.

Avoiding retinal phosphenes should protect against any possible effects on brain function. Phosphene thresholds are a minimum around 20 Hz and rise rapidly at higher and lower frequencies, intersecting with the thresholds for peripheral and central nerve stimulation at which point limits on peripheral nerve stimulation should apply. For workers who are not trained and who may be unaware and not in control of their exposure status the basic restriction is set at the phosphene threshold in order to avoid these transient but potentially disturbing effects of exposure. For members of the public, a reduction factor of 5 is applied to the phosphene threshold.

Exposure to low-frequency electric fields causes well-defined biological responses through surface electric-charge effects. Prevention of the painful effects of surface electric charge induced on the body by such exposure are addressed by the reference levels.

Chronic effects. The literature on chronic effects of low frequency 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 low frequency 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 prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure.

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 ellipsoid models. In recent years, more realistic calculations based on anatomically and electrically refined heterogeneous models (Xi and Stuchly 1994; Dimbylow 2005, 2006; Bahr et al. 2007) resulted in a much better knowledge of internal 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; Nagaoka et al. 2004). 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 those calculations, the maximum local peak electric field induced by a 50 Hz magnetic field in the brain is approximately 23–33 mV m^{-1} per mT, depending on field orientation and body model. There is no conversion factor for peripheral nerve tissue available at present. Therefore, the skin, which contains peripheral nerve endings, was chosen as a worst-case target tissue. The electric field induced in the skin by such a field is approximately 20–60 mV m^{-1} per mT. The maximum local electric field induced by a 50 Hz electric field in the brain is approximately 1.7–2.6 mV m^{-1} per kV m^{-1}, while in the skin it is approximately 12–33 mV m^{-1} per kV m^{-1}.

In view of the uncertainties in the available dosimetry as well as the influence of body parameters in the derivation of reference levels, ICNIRP is taking a conservative approach in deriving reference levels from the basic restrictions.

GUIDELINES FOR LIMITING EMF EXPOSURE

Separate guidance is given for occupational exposures and exposure of the general public. Occupational exposure in these guidelines refers to adults exposed to time-varying electric, and magnetic fields from 1 Hz to 10 MHz at their workplaces, generally under known conditions, and as a result of performing their regular or assigned job activities. By contrast, the term general population refers to individuals of all ages and of varying health status which might increase the variability of the individual susceptibilities. In many cases, members of the public are unaware of their exposure to EMF. These considerations underlie the adoption of more stringent exposure restrictions for the public than for workers while they are occupationally exposed.

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 extent 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 internal electric field strength E_i, as it is the electric field that affects nerve cells and other electrically sensitive cells.

The internal electric field strength is difficult to assess. Therefore, for practical exposure assessment purposes, reference levels of exposure are provided. 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 (PNS) and central nerve stimulation (CNS), the induction of retinal phosphenes and possible effects on some aspects of brain function.

In view of the considerations above for frequencies in the range 10 Hz to 25 Hz, occupational exposure should be limited to fields that induce electric field strengths in CNS tissue of the head (i.e., the brain and retina) of less than 50 mV m^{-1} in order to avoid the induction of retinal phosphenes. These restrictions should also prevent any possible transient effects on brain function. These effects are not considered to be adverse health effects; however, ICNIRP recognizes that they may be disturbing in some occupational circumstances and should be avoided but no additional reduction factor is applied. Phosphene thresholds rise rapidly at higher and lower frequencies, intersecting with the thresholds for peripheral and central myelinated nerve stimulation at 400 Hz. At frequencies above 400 Hz, limits on peripheral nerve stimulation apply in all parts of the body.

Exposure in controlled environments, where workers are informed about the possible transient effects of such exposure, should be limited to fields that induce electric fields in the head and body of less than 800 mV m^{-1} in order to avoid peripheral and central myelinated nerve stimulation. A reduction factor of 5 has been applied to a stimulation threshold of 4 V m^{-1} in order to account for the uncertainties described above. Such restrictions rise above 3 kHz.

For the general public for CNS tissue of the head a reduction factor of 5 is applied, giving a basic restriction of 10 mV m^{-1} between 10 and 25 Hz. Above and below these values, the basic restrictions rise. At 1,000 Hz it intersects with basic restrictions that protect against peripheral and central myelinated nerve stimulation. Here, the reduction factor of 10 results in a basic restriction of 400 mV m^{-1}, which should be applied to the tissues of all parts of the body.

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

Time averaging

ICNIRP recommends that the restrictions on internal 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 (see also section on non-sinusoidal exposure).

Spatial averaging of induced electric field

When restricting adverse effects of induced electric fields to nerve cells and networks, it is important to define the distance or volume over which the local induced electric field must be averaged. As a practical compromise, satisfying requirements for a sound biological basis and computational constraints, ICNIRP recommends determining the induced electric field as a vector average of the electric field in a small contiguous tissue volume of $2 \times 2 \times 2$ mm^3. For a specific tissue, the 99[th] percentile value of the electric field is the relevant value to be compared with the basic restriction.

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

Exposure characteristic	Frequency range	Internal electric field (V m^{-1})
Occupational exposure		
CNS tissue of the head	1–10 Hz	0.5/f
	10 Hz–25 Hz	0.05
	25 Hz–400 Hz	2×10^{-3}f
	400 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
General public exposure		
CNS tissue of the head	1–10 Hz	0.1/f
	10 Hz–25 Hz	0.01
	25 Hz–1000 Hz	4×10^{-4}f
	1000 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f

Notes:
- f is the frequency in Hz.
- All values are rms.
- In the frequency range above 100 kHz, RF specific basic restrictions need to be considered additionally.

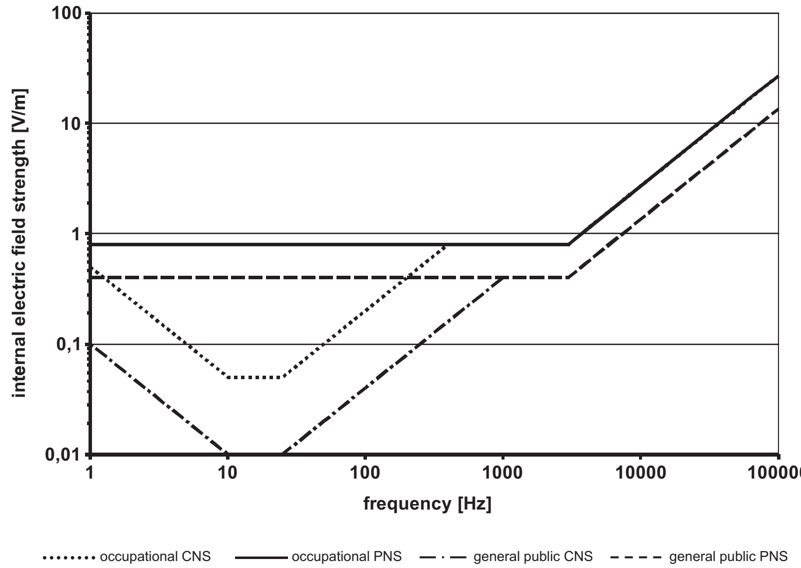

Fig. 1. Basic restrictions for general public and occupational exposure in terms of internal electric field strength concerning CNS and PNS effects.

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 electrotonic distance varying from 2 to 7 millimeters for invertebrate nerves (Reilly 1998; Reilly and Diamant 2003). 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 1,000 interacting cells, which is approximately 1 mm^3 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 measure 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. Another option for the spatial averaging is to define the local electric field as an average in a small volume or along a line segment (Reilly and Diamant 2003).

As a general rule the averaging volume should not extend beyond the boundary of the tissue except for tissues such as the retina and skin, which are too thin to cover the whole averaging cube. For the skin the same averaging volume of $2 \times 2 \times 2$ mm^3 can be assumed, and it may extend to the subcutaneous tissue. For the retina the averaging volume may extend to the tissues in front and behind it.

REFERENCE LEVELS

The reference levels are obtained from the basic restrictions by mathematical modeling using published data (Dimbylow 2005, 2006). They are calculated for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. Frequency dependence and dosimetric uncertainties were taken into account. The reference levels presented consider two distinct effects and approximate a combination of the induced electric fields in the brain, relevant for CNS effects, and the induced electric fields in non-CNS tissues anywhere in the body, relevant for PNS effects (i.e., at 50 Hz, the factor used to convert the basic restriction for CNS effects to an external magnetic field exposure is 33 V m^{-1} per T, and for PNS effect 60 V m^{-1} per T. An additional reduction factor of 3 was applied to these calculated values to allow for dosimetric uncertainty).

In addition, the electric field reference level for occupational exposure up to 25 Hz includes a sufficient margin to prevent stimulation effects from contact currents under most practical conditions. Between 25 Hz and 10 MHz the reference levels are based on the basic restriction on induced electric fields only and might 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 10 MHz prevent adverse indirect effects (shocks and burns) for more than 90% of exposed individuals. In addition, the electric field reference levels for general public exposure up to 50 Hz include a sufficient margin to prevent surface electric-charge effects such as perception in most people.

Tables 3 and 4 summarize the reference levels for occupational and general public exposure, respectively, and the reference levels are illustrated in Figs. 2 and 3. The reference levels assume an exposure by a uniform (homogeneous) field with respect to the spatial extension of the human body.

Spatial averaging of external electric and magnetic fields

Reference levels have been determined for the exposure conditions where the variation of the electric or magnetic field over the space occupied by the body is relatively small. In most cases, however, the distance to the source of the field is so close that the distribution of the field is non-uniform or localized to a small part of the body. In these cases the measurement of the maximum field strength in the position of space occupied by the body always results in a safe, albeit very conservative exposure assessment.

For a very localized source with a distance of a few centimeters from the body, the only realistic option for the exposure assessment is to determine dosimetrically the induced electric field, case by case. When the distance exceeds 20 cm, the distribution of the field becomes less localized but is still non-uniform, in which case it is possible to determine the spatial average along the body or part of it (Stuchly and Dawson 2002; Jokela 2007). The spatial average should not exceed the reference level. The local exposure may exceed the reference level but with an important provision that the basic restriction shall not be exceeded. It is the task of standardization bodies to give further guidance on the specific exposure situations where the spatial averaging can be applied. This guidance shall be based on well established dosimetry. The standardization bodies also may derive new reference levels for special types of non-uniform exposure.

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

Frequency range	E-field strength E (kV m^{-1})	Magnetic field strength H (A m^{-1})	Magnetic flux density B (T)
1 Hz–8 Hz	20	$1.63 \times 10^5/f^2$	$0.2/f^2$
8 Hz–25 Hz	20	$2 \times 10^4/f$	$2.5 \times 10^{-2}/f$
25 Hz–300 Hz	$5 \times 10^2/f$	8×10^2	1×10^{-3}
300 Hz–3 kHz	$5 \times 10^2/f$	$2.4 \times 10^5/f$	$0.3/f$
3 kHz–10 MHz	1.7×10^{-1}	80	1×10^{-4}

Notes:
- f in Hz.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure.
- To prevent indirect effects especially in high electric fields see chapter on "Protective measures."
- In the frequency range above 100 kHz, RF specific reference levels need to be considered additionally.

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

Frequency range	E-field strength E (kV m^{-1})	Magnetic field strength H (A m^{-1})	Magnetic flux density B (T)
1 Hz–8 Hz	5	$3.2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8 Hz–25 Hz	5	$4 \times 10^3/f$	$5 \times 10^{-3}/f$
25 Hz–50 Hz	5	1.6×10^2	2×10^{-4}
50 Hz–400 Hz	$2.5 \times 10^2/f$	1.6×10^2	2×10^{-4}
400 Hz–3 kHz	$2.5 \times 10^2/f$	$6.4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz–10 MHz	8.3×10^{-2}	21	2.7×10^{-5}

Notes:
- f in Hz.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure.
- In the frequency range above 100 kHz, RF specific reference levels need to be considered additionally.

Additivity of exposure to electric and magnetic fields

Each of the external electric and magnetic field induces an electric field component, which add vectorially in the tissue. 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 at the same phase. This would imply that the exposures to the external electric and magnetic fields are additive (Cech et al. 2008). Such situations, however, are judged to be very

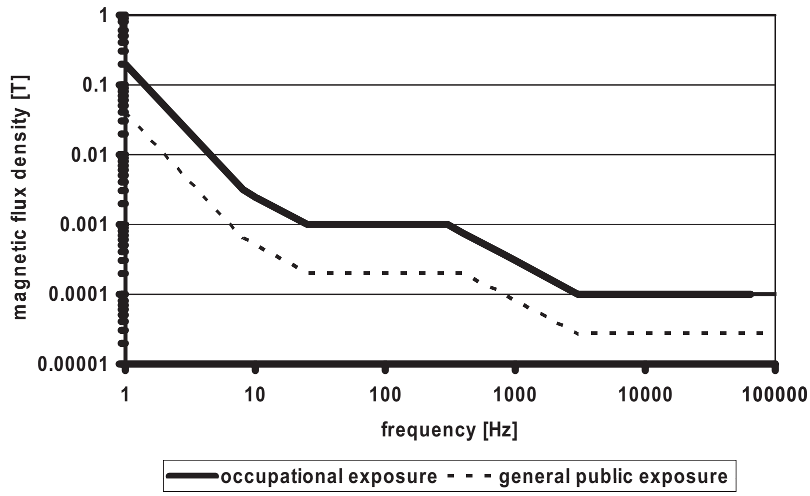

Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 3 and 4).

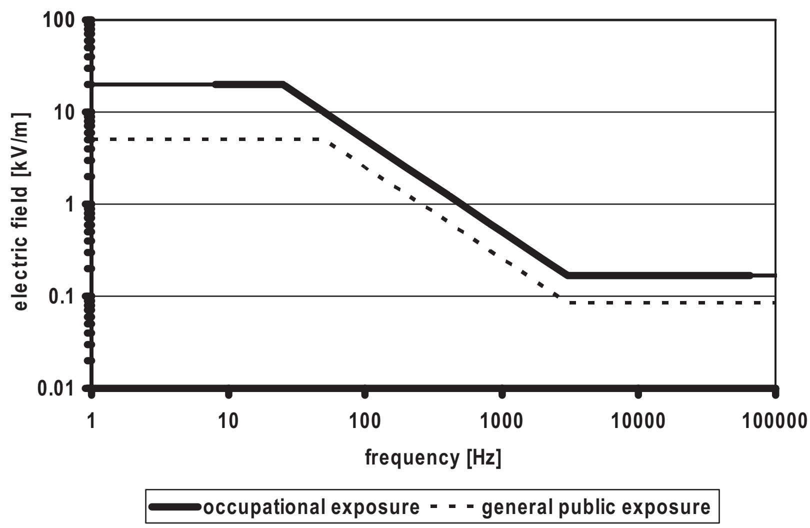

Fig. 3. Reference levels for exposure to time varying electric fields (compare Tables 3 and 4).

infrequent taking into account the great difference in the distribution of the electrically and magnetically induced electric fields.

REFERENCE LEVELS FOR CONTACT CURRENTS

Up to 10 MHz 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 are approximately one-half 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 as 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*
	100 kHz–10 MHz	40
General public exposure	Up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*
	100 kHz–10 MHz	20

Note: *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 10 MHz, internal electric fields should be added according to

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{E_{i,j}}{E_{L,j}} \leq 1 \tag{3}$$

where $E_{i,j}$ is the internal electric field strength induced at frequency j, and $E_{L,\,j}$ 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:

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{E_{j}}{E_{R,j}} \leq 1 \tag{4}$$

and

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{H_{j}}{H_{R,j}} \leq 1 \tag{5}$$

where

E_j = the electric field strength at frequency j;
$E_{R,\,j}$ = 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;
$H_{R,\,j}$ = 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:

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{I_{j}}{I_{L,j}} \leq 1 \tag{6}$$

where I_j is the contact current component at frequency j, and $I_{L,j}$ 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 the electric and particularly magnetic fields are in most cases 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., Fourier Transformation techniques (FT) 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 FT 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, induced electric field and induced current with a filter function which is related to the basic restriction or reference level (ICNIRP 2003b; Jokela 2000). In the case of a broadband field consisting of harmonic components the restriction imposed by the filtering can be presented mathematically as

$$\left| \sum_{i} \frac{A_i}{EL_i} \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1, \tag{7}$$

where t is time and EL_i is the exposure limit at the ith harmonic frequency f_i, where A_i, θ_i, φ_i, are the amplitudes of the field, phase angles of the field and phase angles of the filter at the harmonic frequencies. Except the phase angles, the equation is similar to the summation eqns (3), (4), and (5). More guidance on the practical implementation of the weighting (determination of the weighted peak exposure) is given in the informative annex (Appendix).

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.

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 (2007a and b) and other entities.

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ICNIRP
P. Vecchia, Chairperson (Italy)
M. Hietanen, Vice-Chairperson until 2008 (Finland)
R. Matthes, Vice-Chairperson since 2008 (Germany)
A. Ahlbom until 2008 (Sweden)
E. Breitbart until 2008 (Germany)
F. R. de Gruijl until 2008 (The Netherlands)
M. Feychting (Sweden)
A. Green (Australia)
K. Jokela (Finland)
J. Lin (USA)
R. Saunders (United Kingdom)
K. Schulmeister (Austria)
P. Söderberg (Sweden)
B. Stuck (USA)
A. Swerdlow (United Kingdom)
M. Taki until 2008 (Japan)
B. Veyret (France)
G. Ziegelberger, Scientific Secretary (Austria)
M. H. Repacholi, Chairman Emeritus (Switzerland)
ICNIRP ELF Task Group
R. Matthes (Germany), ELF Task Group Chairman
A. Ahlbom (Sweden)
K. Jokela (Finland)
C. Roy (Australia)
R. Saunders (United Kingdom)

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APPENDIX

Informative annex

Determination of the weighted peak exposure. The weighting may be implemented by computing first the spectrum of the waveform and then applying eqn (7). In many applications, however, it is more convenient to use analog or digital filtering of the waveform in the time domain. The gain of the filter (ratio of the output to the input signal) should vary as a function of frequency in direct proportion to the exposure limit $G = EL(f_{ref})/EL(f)$, where EL is the limit at frequency f and f_{ref} is an arbitrary reference frequency from 1 Hz to 100 kHz. The peak value of the filtered waveform should not exceed the exposure limit (basic restriction or reference level) converted to the peak (amplitude) value at the reference frequency. Table 6 shows an example of the derived peak limits. In addition to the amplitude physical filters always influence on the phase of the field, which changes the peak value of the filtered field. As shown in Figs. 1, 2, and 3 the limits are divided to the frequency ranges where the limit varies directly proportional to $1/f^2$, $1/f$, f^0 (constant), or f. On the $1/f^2$, $1/f$, f^0, and f ranges the phase angle of the filter φ_i (see eqn 7) is 180, 90, 0, and $-90°$, respectively. The weighting filter can be approximated with an electronic or digital filter where the attenuation should not deviate more than 3 dB and phase more than 90° from the exact piecewise linear frequency response. As an example, Fig. A1 shows the attenuation and phase as a function of frequency for the filter used for the weighting of the induced electric field. The approximate curves are based on a simple approximation with RC (resistor/capacitor) type filter function. 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. Derived peak limits for non-sinusoidal electric and magnetic fields. The reference frequency is 50 Hz.

	$E_{induced}$ (mV m^{-1}) Brain	body tissue	$E_{external}$ (V m^{-1})	B μT
Occupational	$\sqrt{2} \times 100$	$\sqrt{2} \times 800$	$\sqrt{2} \times 10{,}000$	$\sqrt{2} \times 1{,}000$
General public	$\sqrt{2} \times 20$	$\sqrt{2} \times 400$	$\sqrt{2} \times 5{,}000$	$\sqrt{2} \times 200$

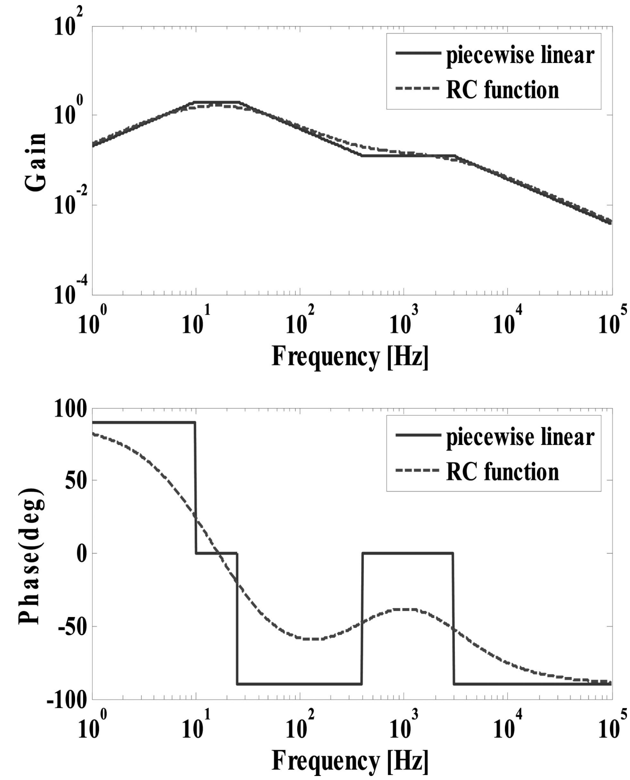

Fig. A1. Amplitude and phase response for the weighting of the induced electric field.

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 *internal* 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.

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 ($S\ m^{-1}$); 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.

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 a low frequency 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 low frequency 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.

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 = 1,000 Hz, 1 MHz = 1,000 kHz, 1 GHz = 1,000 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.

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 ampere 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 tesla (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 low frequency 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 as a result of performing their regular or assigned job activities.

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^{-1}).

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 non-photic 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. Some examples of sources of uncertainty about exposure-effect threshold levels include the extrapolation of animal data to effects on humans, differences in the physiological reserves of different people with corresponding differences in tolerance, and statistical uncertainties (confidence limits) in the dose-response function. In ICNIRP's view, uncertainty in measurements used to implement the guidelines is a problem more appropriate to the functions of organizations responsible for the development of compliance methods. It is not considered in the setting of reduction factors by ICNIRP.

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.,

$$F_{\mathrm{rms}} = \sqrt{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} [F(t)]^2 dt}. \qquad \text{(A1)}$$

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 = 10,000 gauss (q.v.).

Threshold

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

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.*