INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

ICNIRP GUIDELINES

ON LIMITS OF EXPOSURE TO STATIC MAGNETIC FIELDS

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GUIDELINES ON LIMITS OF EXPOSURE TO STATIC MAGNETIC FIELDS

International Commission on Non-Ionizing Radiation Protection*

PREFACE

In recent years, the development of new technologies using static magnetic fields has increased the possibility of human exposure to these fields and raised some concern as to their possible health effects. In several countries, governmental or other competent authorities have issued exposure limits that are mainly intended for specific uses, i.e., magnetic resonance imaging (MRI) and particle accelerators for high-energy physics. Since applications of magnetic fields in industry and medicine are likely to grow in the future, thus increasing the possibility of occupational and general public exposure, and since the number of people with ferromagnetic implants and implanted electronic devices that can be affected by the fields is growing, there is a need for international guidelines.

The International Non-Ionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC), in cooperation with the Environmental Health Division of the World Health Organization (WHO), developed a health criteria document on magnetic fields within the Environmental Health Criteria Programme sponsored by the United Nations Environment Programme (UNEP/WHO/IRPA 1987). This document contains a review of biological effects reported from exposure to static magnetic fields and, together with more recent publications, serves as the scientific data base for the development of the rationale for these guidelines.

At the 8th International Congress of the International Radiation Protection Association (Montreal, 18–22 May 1992), the IRPA established a new independent scientific organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), as a continuation of the former IRPA/INIRC. The functions of the Commission are to investigate the hazards that may result from the different forms of non-ionizing radiation (NIR) and to deal with all aspects of the NIR protection.

A first draft of these guidelines was prepared by the IRPA/INIRC and distributed by the IRPA Executive Officer on 20 December 1991 to the IRPA Executive Council and Associate Societies for comments. The comments received were discussed during the last meeting of the IRPA/INIRC held in Vancouver, Canada, on 7–10 May 1992; thereafter, the text was revised and subject to substantial changes. The present guidelines were approved during the meeting of the ICNIRP in Neuherberg, Germany, on 7–12 May 1993.

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The IRPA Associate Societies and a number of competent institutions and individual experts helped by giving comments during the preparation of these guidelines. Their cooperation is gratefully acknowledged.

SCOPE AND PURPOSE

These guidelines apply to occupational and general public exposure to static magnetic fields. The guidelines do not apply to deliberate exposure of patients undergoing medical diagnosis or treatment. Readers are referred to the IRPA/INIRC document on protection of patients undergoing a magnetic resonance (MR) examination (IRPA/INIRC 1991b).

QUANTITIES AND UNITS

Whereas electric fields are associated with the presence of electric charge, magnetic fields result from the

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physical movement of electric charge (electric current). Similarly, magnetic fields can exert physical forces on electric charges but only when such charges are in motion. A magnetic field can be represented as a vector and may be specified in one of two ways: as magnetic flux density B or as magnetic field strength H. B and H are expressed in teslas (T) and amperes per meter (A m^{-1}), respectively. In a vacuum and in air, B and H are related by the expression

$$B = \mu_0 H. \qquad (1)$$

The constant of proportionality μ_0 in eqn (1) is termed the permeability of free space (or any nonmagnetic material) and has the numerical value $4\pi \times 10^{-7}$ expressed in henrys per meter (H m^{-1}). Thus, to describe a magnetic field in air or nonmagnetic materials (including biological materials) with an adequate approximation, only one of the quantities B or H needs to be specified.

In the present document, the limits of exposure are given in terms of magnetic flux density (B).

The magnitude of the force F acting on an electric charge q moving with a speed v in a direction perpendicular to a magnetic flux density B is given by the expression

$$F = \mathrm{q}\, v\, B. \qquad (2)$$

The direction of the force (the Lorentz force) is determined from the vector product of the charge, velocity and the magnetic flux density and is therefore always perpendicular to the direction of the flow of electric charge. As a result, the interaction of a magnetic field with electric charge will result in a change of direction of the flow of the charge but never a change in speed. Magnetic fields therefore do not do work but can facilitate the transformation of one form of energy into another.

The magnetic flux density is accepted as the most relevant quantity for relating magnetic field effects. The magnetic flux within a given area of surface is the product of the area and the component of the magnetic flux density normal to its surface. The weber (Wb) is the unit of magnetic flux, Φ, and 1 Wb = 1 T m^2.

A general summary of magnetic field quantities and units is provided in Table 1.

SI units are the internationally accepted units for expressing quantities in the scientific literature (Williamson et al. 1981). Unfortunately, researchers in magnetism have been slow to adopt this system, therefore the factors that allow a conversion of values from the older centimeter-gram-second system are given in Table 2.

Table 1. Static magnetic field quantities and corresponding SI units.

Quantity	Symbol	Unit
Current	I	ampere (A)
Current density	J	ampere per square meter (A m^{-2})
Magnetic field strength	H	ampere per meter (A m^{-1})
Magnetic flux	Φ	weber (Wb) = volt s = tesla m^2
Magnetic flux density	B	tesla (T) = Wb m^{-2}
Permeability	μ	henry per meter (H m^{-1})
Permeability of free space	μ_0	$\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}

For a more complete inventory and discussion of concepts, quantities, units, and terminology for nonionizing radiation protection, the reader is referred to the relevant IRPA/INIRC publication (IRPA/INIRC 1991c).

SOURCES AND LEVELS

The natural static magnetic field of the earth is ~50 μT and, depending on the geographic location, varies from ~30 to 70 μT. An average person rarely experiences strong static magnetic fields (Grandolfo and Vecchia 1985; Krause 1986; Stuchly 1986). Magnetic flux densities on the order of 20 μT are produced under high direct current (DC) transmission lines. At present there are few high-voltage direct current (HVDC) transmission lines in operation anywhere in the world. In the future there is a potential for exposure to greater magnetic flux densities due to new means of transportation. Fast passenger trains based on magnetic levitation may produce magnetic flux densities on the order of 10–100 mT for some designs (Chadwick and Lowes 1992; Nakagawa 1992).

The highest exposure for members of the general public occurs in patients undergoing a diagnostic examination by MRI or spectroscopy (MRS). In MRI procedures, magnetic flux densities range from 0.15–2 T and the exposure is usually limited to <0.5 h. Systems using higher magnetic fields are being considered for MRS and future uses. Exposures can also occur during other medical applications, such as holding various prostheses in place (e.g., dental, neck, head), and in the colonic stoma; these devices produce only localized fields.

In addition to staff involved in the use of MR equipment, a few other occupations are associated with exposure to strong magnetic fields. Strong fields are produced in high-energy technologies such as thermonuclear reactors, magnetohydrodynamic systems, superconducting generators, and DC power generation and distribution. Research facilities that use bubble chambers, particle accelerators, superconducting spectrometers, and isotope separation units also have areas of high magnetic flux density around these devices. Other industries where exposure to strong magnetic fields occurs are those involving electrolytic processes such as aluminium production, and manufacture of magnets and magnetic materials.

RATIONALE FOR EXPOSURE LIMITS

Interaction mechanisms

The three established physical mechanisms through which static magnetic fields interact with living matter are magnetic induction and magnetomechanical

Table 2. Conversion factors for units.[a]

From \ To	T	G	γ	A m^{-1}	Oe
T	1	10^4	10^9	7.96 10^5	10^4
G	10^{-4}	1	10^5	79.6	1
γ	10^{-9}	10^{-5}	1	7.96 10^{-4}	10^{-5}
A m^{-1}	1.257×10^{-6}	1.257×10^{-2}	1,257	1	1.257×10^{-2}
Oe	10^{-4}	1	10^5	79.6	1

[a] Symbols: T = tesla (1 T = 1 Wb m^{-2}), G = gauss, γ = gamma, A = ampere, m = meter, Oe = oersted.

and electronic interactions (Tenforde 1985; Bernhardt 1986a; UNEP/WHO/IRPA 1987).

Magnetic induction. This mechanism originates through the following types of interaction:

Electrodynamic interactions with moving electrolytes. Static fields exert Lorentz forces on moving ionic charge carriers and thereby give rise to induced electric fields and currents. This interaction is the basis of magnetically induced potentials in flowing blood that have been studied with both static and time-varying ELF fields.

Faraday currents. Time-varying magnetic fields induce currents in living tissues in accordance with the Faraday law of induction. This mechanism can be active also in the case of static fields due to the movements of human beings in areas in which this kind of field is present.

Magnetomechanical effects. The two types of mechanical effects that a static magnetic field can exert on biological objects are as follows:

Magnetoorientation. In a uniform static field, both diamagnetic and paramagnetic molecules experience a torque that tends to orientate them in a configuration that minimizes their free energy within the field. This effect has been well studied for assemblies of diamagnetic macromolecules with differing magnetic susceptibilities along the principal axes of symmetry. Included among this class of macromolecules are the arrays of photopigments in retinal rod disc membranes and sickle-shape erythrocytes in a deoxygenated state. In particular, risks for people affected by sickle-cell anemia deserve consideration because of the relatively high incidence of this pathology (Wintrobe 1981).

Magnetomechanical translation. Static magnetic fields produce a net force on paramagnetic and ferromagnetic materials that leads to translational motion. Because of the limited amount of magnetic material in most living objects, the influence of this effect on biological functions is negligible; however, fields as weak as the geomagnetic field can exert significant forces on chains of biogenic magnetite particles found in certain species of organisms (Kirschvink et al. 1985).

Electronic interactions. Certain chemical reactions involve radical electron intermediate states in which the Zeeman interaction with a low-intensity static magnetic field produces an effect on electronic spin states. It is probable that the usual lifetime of biologically relevant electron intermediate states is sufficiently short so that magnetic field interactions exert only a small, and perhaps negligible, influence on the yield of chemical reaction products.

Biological studies

Due to special receptors, a number of lower organisms and aquatic mammals possess sensitivity to static magnetic fields with low intensities comparable to that of the geomagnetic field (Grandolfo et al. 1985; Bernhardt 1986b; UNEP/WHO/IRPA 1987; Saunders 1989).

In addition, a number of *in vitro* studies have shown changes in magnetic orientation in assemblies of macromolecules including retinal rod outer segments, muscle fibers, photosynthetic systems, halobacteria purple membranes, and various synthetic liquid crystals and gels. Certain chemical reactions which involve a radical electron intermediate state may also be sensitive to static magnetic fields of moderate intensity (e.g., 10 mT) (Schulten 1982; UNEP/WHO/IRPA 1987).

Studies on mice have not demonstrated any harm to the fetus from exposure to magnetic fields up to 1 T (Mahlum et al. 1979; Sikov et al. 1979; Konermann and Mönig 1986).

The existing evidence from experiments with laboratory animals indicates an absence of significant effects on the many developmental, behavioral, and physiological parameters evaluated at static magnetic flux densities up to 2 T (Tenforde 1985; Miller 1987; UNEP/WHO/IRPA 1987; Kowalczuk et al. 1991).

According to theoretical considerations, magnetohydrodynamic effects could retard blood flowing in a strong magnetic field and produce a rise in blood pressure (Tenforde et al. 1983). This effect is predicted to cause a flow reduction of at most a few percent at 5 T, but was not observed at 1.5 T in humans (Shellock and Crues 1987) or at 4.7 T in a phantom model (Budinger 1992).

Human studies

Some studies on workers involved in the manufacture of permanent magnets indicated various subjective symptoms and functional disturbances including irritability, fatigue, headache, loss of appetite, bradycardia, tachycardia, decreased blood pressure, altered electroencephalogram, itching, burning, and numbness

(Vyalov 1967, 1974; Roshchin 1985; Paltsev 1989; Syromyatnikov et al. 1989). Lack of any statistical analysis or assessment of the impact of physical or chemical hazards in the working environment significantly reduces the value of these reports and makes them difficult to evaluate. Although the studies are inconclusive they suggest that, if long-term effects occur, they are very subtle since no cumulative gross effects were reported.

It has been reported that individuals exposed to a 4 T magnetic flux density could experience sensory effects associated with motion in the field, such as vertigo, nausea, a metallic taste, and magnetic phosphenes when moving the eyes or head (Schenck et al. 1992).

Two epidemiological surveys of general health data in workers chronically exposed to static magnetic fields failed to reveal any significant health effects. Marsh et al. (1982) studied the health data of 320 workers in plants using large electrolytic cells for chemical separation processes where the average static field level in the work environment was 7.6 mT and the maximum field was 14.6 mT. Slight changes in white blood cell picture (still within the normal range) were detected in the exposed group compared to the 186 controls. None of the observed transient changes in blood pressure or blood parameters was considered indicative of a significant adverse effect associated with magnetic field exposure. Budinger et al. (1984) studied the prevalence of disease among 792 workers at U.S. National Laboratories who were exposed occupationally to static magnetic fields. The control group consisted of 792 unexposed workers matched for age, race, and socioeconomic status. The range of magnetic field exposures was from 0.5 mT for long durations to 2 T for periods of several hours. No statistically significant change in the prevalence of 19 categories of disease was observed in the exposed group relative to the controls. No difference in the prevalence of disease was found between a subgroup of 198, who had experienced exposures of 0.3 T or higher for periods ≥ 1 h, and the remainder of the exposed population or the matched controls.

Rockette and Arena (1983) reported that workers in the aluminium industry have an elevated leukemia mortality rate. Although this epidemiological study reported an increased cancer risk for persons directly involved in aluminium production where workers are exposed to large static magnetic fields, there is at present no clear evidence to indicate the responsible carcinogenic factors within the work environment. The process used for aluminium reduction creates coal tar, pitch volatiles, fluoride fumes, sulphur oxides, and carbon dioxide. The presence of hydrocarbon particulates, and perhaps other environmental contaminants, must be considered in any attempt to relate magnetic field exposure and increased cancer risk among persons working in the aluminium industry. In a more recent study on French aluminium workers, conducted by Mur et al. (1987), cancer mortality and mortality from all causes were found not to differ significantly from that observed for the general male population of France. Barregärd et al. (1985) conducted a study of a cohort of workers at a chloroalkali plant where the 100-kA DC currents used for the electrolytic production of chlorine gave rise to static magnetic flux densities at worker locations ranging from 4–29 mT. The observed vs. expected incidence of cancer among these workers over a 25-y period was not significantly different.

Population exposure considerations

A distinction is made in the exposure limits for workers and the general public for the following reasons. The occupationally exposed population consists of adults exposed under controlled conditions who should be trained to be aware of potential risks and to take appropriate precautions. Occupational exposure is limited to the duration of the working day and the working lifetime. The general public is comprised of individuals of all ages and different health statuses. Individuals or groups of particular susceptibility may be included in the general population. In many instances, members of the general public are not aware that exposure occurs or may be unwilling to accept any risks (however slight) associated with exposure. The general public can be exposed for up to 24 h d^{-1}, and over the whole lifetime.

Derivation of exposure limits

Current scientific knowledge does not suggest any detrimental effect on major developmental, behavioral, and physiological parameters in higher organisms for transient exposure to static magnetic flux densities up to 2 T.

From the analysis of established mechanisms of interaction, long-term exposure to magnetic flux densities of 200 mT should not have adverse consequences on health.

The movement of a person in a field of 200 mT will result in an induced current density of between 10 and 100 mA m^{-2} (assuming a 30-cm-radius-conducting loop of tissue and a tissue conductivity of 0.2 S m^{-1}). These values of current density are considered not to create adverse effects on the function of the central nervous system for fields of frequencies <10 Hz; they are consistent with the IRPA/INIRC basic limit on exposure to 50/60-Hz magnetic fields, 10 mA m^{-2}, and with the expected frequency response of such effects <10 Hz (IRPA/INIRC 1990a).

A calculation can be made of the electric fields and current densities that will be induced in the aorta and other large blood vessels of human subjects exposed to a 200-mT field. The maximum magnitude of the induced electric field in a blood vessel is equal to vB when the blood flow velocity, v, is orthogonal to the magnetic flux density, B. Assuming a cardiac output of 5,100 cm^3 min^{-1} and an aortic diameter of 1.6 cm, the average aortic blood velocity is 42 cm s^{-1} in an adult human. With this value of the blood flow velocity, an orthogonal 200-mT field will induce a maximum electric field of 84 mV m^{-1} across the lumen of the vessel. The induced current density within the aorta can be calculated by forming the product of the electrical conductivity of blood and the induced electric field. Taking the conductivity of human blood to be 0.52 S m^{-1} (Tenforde et al. 1983), the maximum induced current density is 44 mA m^{-2} in a 200-mT field. This value of induced current density is below that which would be expected to produce adverse hemodynamic or cardiovascular effects (Tenforde et al. 1985).

Thus it is recommended that the occupational exposure limit is a time-weighted average value of 200 mT during the working day with a ceiling value of 2 T. Because the extremities do not contain large blood vessels or critical organs, a limit of 5 T can be allowed.

The restriction to 200 mT is a conservative one based on the present lack of any knowledge of long-term effects of exposure. For the reasons just given, the exposure limit for the general public incorporates an additional safety factor of 5 resulting in a continuous exposure limit of 40 mT.

Interference with implanted medical devices

Irnich and Batz (1989) investigated magnetostatic interference of >1,200 pacemakers from 18 manufacturers. They found that 87% of all implanted pacemakers were influenced (reverted to a fixed pacing mode) when exposed to magnetic flux densities up to 2 mT, 19.6% were influenced when exposed up to 1 mT, and 1.7% were influenced when exposed up to 0.5 mT, with a minimum interference level occurring at 0.31 mT. Similar results have also been described by Barbaro et al. (1991).

Considerations of potential hazards due to interference of magnetic fields with electronic devices lead to the recommendation that locations with magnetic flux densities >0.5 mT should be posted with appropriate warning signs. Persons with cardiac pacemakers should be discouraged from inadvertently entering areas with fields large enough in dimension to include most of a person's trunk at magnetic flux densities >0.5 mT.

It is difficult to give precise guidance as to the effect of static magnetic fields on implanted ferromagnetic devices or materials. Movements or dislodgements, possibly caused by magnetic fields, depend on a number of factors; these include the strength and the gradient of the field, the degree of ferromagnetism of the implant or material, its size, its orientation with respect to the field (Shellock 1989; Shellock and Curtis 1991). Depending on these factors, some ferromagnetic materials may be influenced by static fields as small as a few milliteslas.

Considerations of potential hazards due to movement or dislodgement of ferromagnetic implants or materials (particularly if the object is in a potentially dangerous area of the body such as near a vital neural, vascular, or soft-tissue structure, or the eye) or hazards from flying metallic objects, lead to the recommendation that areas with magnetic flux densities >3 mT should be indicated by specific warning signs.

EXPOSURE LIMITS

Occupational

Whole-body continuous occupational exposure during the work day should be limited to a time-weighted average magnetic flux density not >200 mT. Occupational whole-body exposure should not exceed a magnetic flux density ceiling value of 2 T. When restricted to the limbs, exposures up to 5 T can be permitted.

General public

Continuous exposure of members of the general public should not exceed a magnetic flux density of 40 mT.

Occasional access to special facilities where magnetic flux densities exceed 40 mT can be allowed under appropriately controlled conditions, provided that the appropriate occupational exposure limit is not exceeded.

Additional considerations

People with cardiac pacemakers, ferromagnetic implants, and implanted electronic devices may not be protected by the limits given in Table 3.

The majority of cardiac pacemakers are unlikely to be affected in fields <0.5 mT; therefore, cardiac pacemaker and implantable defibrillator bearers should avoid locations where the magnetic flux density is >0.5 mT. There are also other vital electronic aids in increas-

Table 3. Limits of exposure to static magnetic field.[a,b,c,d]

Exposure characteristics	Magnetic flux density
Occupational	
Whole working day (time-weighted average)	200 mT
Ceiling value	2 T
Limbs	5 T
General public	
Continuous exposure	40 mT

[a] Caution: People with cardiac pacemakers and other implanted electrically activated devices, or with ferromagnetic implants, may not be adequately protected by the limits given here. The majority of cardiac pacemakers are unlikely to be affected from exposure to fields below 0.5 mT. People with some ferromagnetic implants or electrically activated devices (other than cardiac pacemakers) may be affected by fields above a few mT.

[b] When magnetic flux densities exceed 3 mT, precautions should be taken to prevent hazards from flying metallic objects.

[c] Analog watches, credit cards, magnetic tapes, computer disks, etc. may be adversely affected by exposures to 1 mT but this is not a safety concern for humans.

[d] General public. Occasional access of members of the public to special facilities where magnetic flux densities exceed 40 mT can be allowed under appropriately controlled conditions provided that the appropriate occupational exposure limit is not exceeded.

ing use [i.e., electronic inner ear prostheses, insulin pumps, electronically guided active prostheses (e.g., hand, arm, and leg) and muscle stimulation devices (e.g., sphincter muscle of the bladder)] that may be susceptible to static magnetic flux densities above a few milliteslas, particularly if the person is moving within the field.

People with ferromagnetic implants should ask their physician for advice and, in particular, people with aneurysm clips that are not definitely known to be nonmagnetic should not be exposed to magnetic fields above a few mT because of the danger of twisting or dislodgement.

The limits recommended for occupational and general public exposures to static magnetic fields are summarized in Table 3.

MEASUREMENT

The most commonly used method in field mapping is the Hall probe method (UNEP/WHO/IRPA 1987). The Hall effect can be explained as the result of the action exerted on the charge carriers by the magnetic field that forces them sideways in a strip. Electric charges thus appear on the sides of the strip and, as a result, a transverse Hall electric field is created. Several factors set limits on the obtainable accuracy, the most serious being the temperature coefficient of the Hall voltage.

Fluxmeters and ballistic galvanometers directly measure the variation of the magnetic flux using a search coil, thereby providing a measurement of the magnetic field value averaged over the volume of the coil. Measurements are performed by moving the coils in a static field. The coil geometry is often chosen to suit a particular measurement (Henrichsen 1984).

Methods for measuring magnetic fields show that by selecting the correct method magnetic fields can be measured with good accuracy in most normal situations. Both point-measurements and space-integrated values of static magnetic fields can be obtained by the methods described.

The exposure limit values have been set for a homogeneous field. For inhomogeneous fields, the average magnetic flux density must be measured over an area of 100 cm^2.

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