INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

ICNIRP GUIDELINES

FOR LIMITING EXPOSURE TO ELECTRIC FIELDS INDUCED BY MOVEMENT OF THE HUMAN BODY IN A STATIC MAGNETIC FIELD AND BY TIME-VARYING MAGNETIC FIELDS BELOW 1 HZ

PUBLISHED IN: **HEALTH PHYSICS 106(3):418-425; 2014**

ICNIRP PUBLICATION – 2014

GUIDELINES FOR LIMITING EXPOSURE TO ELECTRIC FIELDS INDUCED BY MOVEMENT OF THE HUMAN BODY IN A STATIC MAGNETIC FIELD AND BY TIME-VARYING MAGNETIC FIELDS BELOW 1 Hz

International Commission on Non-Ionizing Radiation Protection*

INTRODUCTION

In this document, guidelines are established for the protection of workers moving in static magnetic fields or being exposed to magnetic fields with frequencies below 1 Hz. This includes, but is not limited to workers engaged in activities related to magnetic resonance imaging (MRI). The general principles for the development of ICNIRP guidelines are published elsewhere (ICNIRP 2002).

SCOPE

The main objective of this publication is to provide guidelines for protection of workers against established adverse direct health effects arising from exposure to static magnetic fields and time-varying magnetic fields below 1 Hz and to avoid sensory effects which may be annoying and impair working ability. A two-tier approach is suggested, with a relaxation of the restrictions in conditions where the workers are made aware of the biological consequences of exposure and are trained to control their own behavior (ICNIRP 2009a; Jokela and Saunders 2011). The guidelines are not expected to be relevant for the general public because all exposures to intense magnetic fields below 1 Hz are currently found at workplaces.

The guidelines do not apply to the exposure of patients undergoing medical diagnosis or treatment. Detailed considerations of protection of patients undergoing MRI examinations are given in separate ICNIRP statements (ICNIRP 2009b, 2004). It is also recognized that, for research purposes, there might be a wish to investigate the effects of static magnetic fields exceeding the basic restrictions presented by these guidelines (ICNIRP 2009a); such experimental exposures, however, are a matter for the appropriate ethics committees (institutional review boards).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers, implanted defibrillators and cochlear implants. ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material and from dangers of objects unintentionally moving because of attraction by the magnetic force. Advice on avoiding these problems is not within the scope of the present document but is available elsewhere (IEC 2010; Shellock 2012).

These guidelines will be periodically revised and updated as advances are made in the scientific knowledge concerning any aspect relevant for limiting exposure of static and time-varying magnetic fields below 1 Hz.

PHYSICAL ASPECTS

The basic physical law associated with the induction of electric fields by a magnetic field is Faraday's law, which indicates that the induced electric field is directly related to the change of the magnetic flux through the body or part of it (e.g., the head). This can be presented as

$$\oint_l \mathbf{E}_i \times d\mathbf{l} = -\int_S \frac{d(\mathbf{B} \times d\mathbf{S})}{dt}, \tag{1}$$

where $\mathbf{E}_i$ is the local induced electric field vector, d**l** is the differential length vector along a closed pathway, *l,* within an individual exposed to the magnetic flux density **B,** and d**S** is the differential area vector directed normal to the differential area. The integrated area, *S*, is enclosed by the integration pathway. $\mathbf{E}_\text{i}$ is roughly perpendicular to **B**. The magnetic flux may change (1) due to the variation of the field as a function of time, (2) due to the movement of a body

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(*Manuscript accepted* 24 *May* 2013)
0017-9078/14/0

DOI: 10.1097/HP.0b013e31829e5580

in a space that results in a relative change to the magnitude or direction of the magnetic field or (3) both cases combined. The right-hand term of eqn (1) shows the time rate of the magnetic flux in terms of the surface integral of the time rate of magnetic flux density over the body area of interest.

It is important to note that another fundamental source of the induced electric field is given by the electromotive electric field $\mathbf{E}_{vB} = \mathbf{v} \times \mathbf{B}$ where $\mathbf{v}$ is the velocity of a point in the tissue relative to the field. This field is associated with the magnetic force causing dielectric polarization, i.e., separating positive and negative charges in the tissue (Sanchez et al. 2012, 2009; Redzic 2004; Bringuier 2003). The dielectric polarization increases until the charges accumulated in tissue boundaries reach equilibrium, where their electric field partly counteracts the $\mathbf{E}_{vB}$ field (Redzic 2004). For some rotational movements the magnetic force manifested by the $\mathbf{E}_{vB}$ field also generates a space (bulk) charge inside a conducting body. The space and boundary charges may move during the motion. The currents associated with these movements are added to the currents generated by the rotational currents determined by Faraday's law, but in most cases of movements of biological bodies it can be assumed that rotational currents and electric fields dominate over the dielectric polarization phenomena.

The time constant for achieving the equilibrium of the polarization is given by $\tau = \epsilon/\sigma$, where ϵ is the permittivity and σ the conductivity of tissue (Redzic 2004). For human tissues the time constant may be in the order of milliseconds, which is relatively small compared to the time scale of human movements, which are in the range above 100 milliseconds. Therefore, the time constants of human tissue can be assumed to be short enough to enable the use of Faraday's law for the computation of the motion-induced electric field relevant to sensory effects below 1 Hz such as vertigo (Liu et al. 2003). It remains to be determined whether the assumption of charge equilibrium is valid for short acceleration or deceleration phases during the onset and ending of a head movement, in which case relatively short transient electric fields may arise in the frequency range relevant to sensory effects above 1 Hz (magnetophosphenes). Additionally, there is considerable lack of data of dielectric properties of human tissues below 10 Hz, which makes the precise calculation of the motion-induced electric field difficult (Gabriel et al. 1996a, b, c, 2009).

The electric field induced in the head can be approximated by a linear function of the time derivative of the average magnetic flux density dB/dt in that region:

$$E_i = C\frac{dB}{dt}, \tag{2}$$

where E_i is perpendicular to the magnetic field $\mathbf{B}$ given as an absolute value, t is time, and C is a conversion factor that depends on the location within the body, the size of the body, the shape of the body, electrical properties of the tissue as well as on the direction and distribution of the magnetic field . This conversion factor applies to a body rotating in a static magnetic field, moving in a field gradient, and staying stationary in a time-varying magnetic field. The conversion factor can be determined by computational simulation based on a realistic heterogeneous numerical model of the human body or body region of interest. By using two different human models placed in a static magnetic field, Ilvonen and Laakso (2009) have computed the conversion factor in the vestibular system located in the inner ear. In the case of a head nodding or shaking in a uniform magnetic field directed from left to right (shaking) and from top to down (nodding), the maximum conversion factor for different movements varied from 0.066–0.132 Vm^{-1} per Ts^{-1}. The mean of these (maximum) conversion factors was 0.095 Vm^{-1} per Ts^{-1}. This is close to 0.105 Vm^{-1} per Ts^{-1} computed by Dimbylow (2005) for a maximum conversion factor in the brain at 50 Hz (33 Vm^{-1} per T). These data imply that a reasonable estimate for C might be 0.1 Vm^{-1} per Ts^{-1}. For a detailed discussion of the conversion factors used for low-frequency guidelines, see ICNIRP (2010).

The change of the magnetic flux density (ΔB) is a relevant exposure parameter for limiting movements in a static magnetic field, as will be discussed later. The relation of ΔB with the induced electric field is given by

$$E_{i,ave} = \frac{\int_{t1}^{t2} E_i(t) \times dt}{t_2 - t_1} = \frac{C \times \Delta B}{t_2 - t_1}, \tag{3}$$

where $E_i(t)$ is the instantaneous induced electric field, ΔB is the magnetic flux density changed during the movement, C is the same conversion factor as in eqn (2) and $E_{i,\ ave}$ is the electric field corresponding to ΔB. The movement starts at time t_1 and the maximum ΔB is reached at t_2. For example, if ΔB would be 2 T during 1 s, the average induced electric field in the periphery of the brain would be approximately 0.2 Vm^{-1} when using 0.1 Vm^{-1} per Ts^{-1} for C.

BIOLOGICAL EFFECTS

When the static magnetic field exceeds a threshold of approximately 2 T, the movement-induced electric field in the head may be high enough to evoke vertigo and other sensory perceptions such as nausea, visual sensations (magnetophosphenes) and a metallic taste in the mouth (WHO 2006; AGNIR 2008; ICNIRP 2009a; Heilmaier et al. 2011). There is also the possibility of acute neurocognitive effects, with subtle changes in attention, concentration and visuospatial orientation (van Nierop et al. 2012). All these effects are not considered to be hazardous *per se*, but they can be disturbing and may impair working ability. For normal movements, the threshold for peripheral nerve stimulation is unlikely to be reached with exposures below 8 T, although it is possible that the basic restrictions for peripheral nerve stimulation (ICNIRP 2010) may slightly be exceeded by very fast movements.

In addition to these movement-induced effects, static magnetic fields may cause direct effects arising from (1) induction of electrical ‘flow’ potentials across blood vessels due to the movement of electrolytes in the blood, (2) forces on paramagnetic and diamagnetic components of tissues, (3) changes in chemical reactions due to altered spin chemistry and (4) deflection of ionic currents due to magnetic (Lorentz) force. These direct interaction mechanisms are not considered to have a significant health effect when the magnetic flux density is below 7 T (WHO 2006; ICNIRP 2009a), above 7 T there is too little research for any firm conclusions.

Magnetophosphenes

The most established effect of induced electric fields below the threshold for nerve or muscle stimulation is the induction of magnetophosphenes, the perception of faint flickering visual sensations. Magnetophosphenes are evoked by the internal electric fields induced in the retina (and brain tissue) by a time-varying magnetic field. On the basis of human experiments, the threshold for the induction of retinal magnetophosphenes has been estimated to lie between about 50 and 100 mVm^{-1} (Root-Mean-Square) at 20 Hz, rising at higher and lower frequencies (Saunders and Jefferys 2007; Lövsund et al. 1980) although there is considerable uncertainty attached to these values. Available studies indicate that the threshold increases as 1/f at least down to 5 Hz and probably to lower frequencies (Adrian 1977; Lövsund et al. 1980). The threshold at 1 Hz would be at least 10 times higher than the minimum threshold at 20 Hz.

In the case of exposure to a static magnetic field, magnetophosphenes are most likely associated with the transient electric field peaks. As noted in Physical Aspects, these transient peaks arise due to sudden changes in the velocity of the head. The spectral components of a short transient extend into the frequency range of the magnetophosphenes.

The increase in the threshold of magnetophosphene induction below 10 Hz is the reason why the basic restriction for the induced electric field can be allowed to increase as a function of 1/f from 10 Hz down to 1 Hz (ICNIRP 2010). In the absence of experimental data, this relation is extrapolated to frequencies below 1 Hz until the basic restriction based on magnetophosphenes reaches the basic restriction for peripheral nerve stimulation at a frequency of 0.66 Hz.

Peripheral nerve stimulation

The responsiveness of electrically excitable nerve and muscle tissue to electric stimuli, including those induced by exposure to low-frequency electric and magnetic fields, has been well established for many years (e.g., Reilly 2002; Saunders and Jefferys 2007; ICNIRP 2010). Myelinated nerve fibers of the human peripheral nervous system have the lowest threshold for electrical nerve stimulation. The minimum threshold value of around 6 Vm^{-1} (peak) (Reilly 1998; 2002; Reilly and Diamant 2011) has been estimated 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 Vm^{-1} (Nyenhuis et al. 2001), based on calculations using a homogeneous human simulation 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 to lie between 3.8 and 5.8 Vm^{-1}, based on the assumption that stimulation takes place in the skin or subcutaneous fat. With stronger stimuli, discomfort and then pain ensue. Below 10 Hz the threshold rises due to the accommodation of a nerve to a slowly depolarizing stimulus.

Vertigo

Movement of the head within a static magnetic field above 2 T frequently gives rise to sensations of vertigo and nausea (Glover et al. 2007). These sensations are predominantly due to the induced electric field which affects the neural output of the vestibular system that is involved in maintaining balance. Volunteer studies have shown that vertigo can also be evoked by applying the electric field by means of galvanic AC or DC currents of the order of 1 mA fed to the electrodes attached behind the ears in the vicinity of the vestibular system (Fitzpatrick and Day 2004).

Movement-induced vertigo seems not only to be determined by the dB/dt, but also by the time integral of dB/dt, i.e., ΔB, the change of magnetic flux density during the movement, as reported by Glover et al. (2007). They examined the threshold of vertigo sensations in volunteers inside a 7 T MR scanner. The volunteers were positioned at the iso-center of the magnetic field where they nodded and shook their heads. The movements were cyclically repeated to enhance the sensation of vertigo. All of the subjects reported mild or severe vertigo sensations and some even experienced nausea with rapid movements. The datapoints in Fig. 1 show the threshold of vertigo in terms of ΔB and duration of the movement. The peak dB/dt values recorded during the experiment ranged from 1.5 to 6 Ts^{-1}, the duration of each shake or nod ranged from 0.5 to 6 s, and the change in magnetic flux density ΔB varied from 2 to 6 T. The dB/dt values recorded during nodding were higher than those recorded during shaking. This is in agreement with a simple circulating current model which indicates that for axial shaking (rotation axis parallel to the magnetic field) the induced electric field is a minimum, while for nodding (rotation axis perpendicular to the magnetic field) a maximum electric field is found near the inner ear where the circulating currents intersect (Jokela and Saunders 2011). Overall, these results indicated that the threshold of vertigo correlated somewhat better with ΔB than with the peak dB/dt and that the most effective frequency range was below 1 Hz.

It is a common experience from working with clinical MR imaging that vertigo sensations disappear when movement is slowed down. This indicates that there is a finite time during which the sensation of vertigo develops. In the experiment of Glover et al. (2007) vertigo sensations were reported by most volunteers when the duration of a single movement was less than 4 s even though there was one vertigo observation for longer duration of movement (Fig. 1). As a conservative approach ICNIRP decided to set the basic restriction so that the basic restriction curve remains below that single observation. There remains, however, a clear need to obtain more data on vertigo thresholds, particularly for relatively slow movements.

In addition to the effects of electric fields induced by a movement, a direct interaction of the magnetic field with the vestibular system cannot be excluded. An altered sense of balance has been observed in volunteers standing stationary in proximity to a 7 T MR scanner (Glover et al. 2007). This effect was ascribed to a difference in the diamagnetic susceptibility between the linear-movement sensors of the vestibular system and the surrounding endolymph fluid. A recent study (Roberts et al. 2011) suggests that the Lorentz force resulting from interaction between the magnetic field and naturally occurring ionic currents in the endolymph fluid might explain the direct effect.

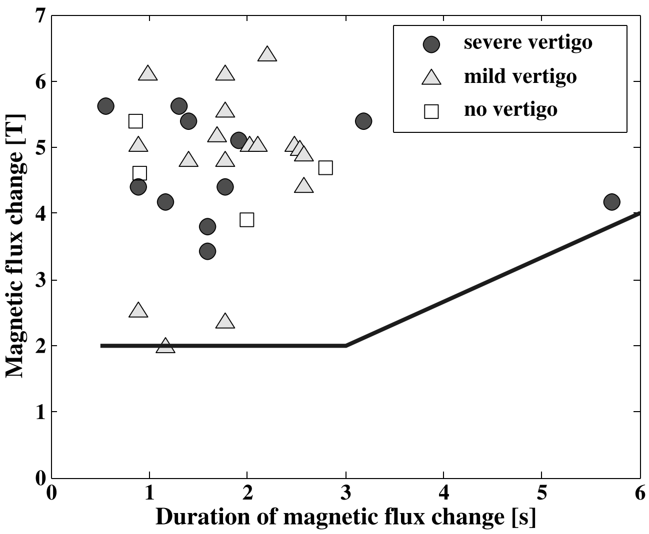

Fig. 1. The vertigo threshold in terms of magnetic flux density change, Δ*B*, plotted as a function of duration of a head shake or nod inside a 7 T MR scanner (Glover et al. 2007). The two line segments show the basic restriction for magnetic flux change during any 3 s period during the movement (see Recommendations).

Therefore, since the sensory effects appear to depend on the product of time and dB/dt and given the possibility of direct magnetic field effects on the body, it is important to restrict both the static magnetic flux density (B) and the maximum change of the magnetic flux density (ΔB) experienced by the body during movement.

RECOMMENDATIONS

The objective of this guideline is to prevent peripheral nerve stimulation and to minimize the possibility of transient sensory effects as a consequence of electric fields induced in the human body by movements in static magnetic fields within occupational settings. The basic restrictions and reference levels shown in Table 1 have been determined to achieve this objective. The basic restrictions have been defined for the change in external magnetic flux density and for the induced internal electric field. ICNIRP recommends limiting exposure to below both sets of restrictions. Since internal electric fields cannot be readily determined, reference levels have been derived to assess compliance with these basic restrictions. Since the motion-induced electric field is a non-sinusoidal field, where the spectrum extends above 1 Hz up to 25 Hz, it is necessary also to apply the basic restrictions and reference levels in the ICNIRP (2010) guidelines. The restrictions for the exposure to static magnetic field have been specified in ICNIRP (2009a).

A distinction is made between controlled and uncontrolled exposures. Basic restrictions for controlled exposure are intended to be used in work environments where access is restricted to workers who have been trained to understand the biological effects that may result from exposure, and where the workers are able to control their movements in order to prevent annoying and disturbing sensory effects. Restrictions for uncontrolled exposure apply to all other occupational situations.

Basic restrictions for ΔB

In order to prevent transient sensory effects such as vertigo and nausea arising from motion-induced electric field below a few Hz, ICNIRP recommends that the change of the magnetic flux density ΔB should not exceed 2 T during any 3-s period. Note that the maximum value for the measured ΔB may not always occur at the end of the 3-s period because the direction of dB/dt may change during the period. The basic restriction for ΔB has been plotted in Fig. 1

Table 1. Exposure restrictions for controlling movement in a static magnetic field and exposure to a time-varying magnetic field below 1 Hz. Above 1 Hz the basic restrictions and the reference levels are presented in the ICNIRP (2010) guidelines. For uncontrolled exposure the reference levels for a magnetic flux density may be converted to dB/dt by using (eqn 5).

	Basic restrictions				Reference levels	
Frequency *f* (Hz)	ΔB (T)[a]	$B_{\text{peak to peak}}$ (T)	Internal electric field strength [Vm^{-1} ($_{\text{peak}}$)]		dB/dt [Ts^{-1} ($_{\text{peak}}$))]	
Critical effect	Vertigo due to movement in static B field	Vertigo due to time-varying B field	PNS effects due to movement in static B field and due to time-varying B field	Phosphenes due to movement in static B field and due to time-varying B field	PNS effects due to movement in static B field and due to time-varying B field	Phosphenes due to movement in static B field and due to time-varying B field
Exposure condition[b]	Uncontrolled	Uncontrolled	Controlled	Uncontrolled	Controlled	Uncontrolled
0	2					
0–1		2				
0–0.66			1.1	1.1	2.7	2.7
0.66–1[c]			1.1	0.7/f	2.7	1.8/f

[a] The maximum change of magnetic flux density ΔB is determined over any 3 s period.

[b] For controlled exposure conditions, a ΔB of 2 T may be exceeded.

where the constant ΔB restriction changes to a constant dB/dt restriction at 3-s duration of the movement.

For specific work applications, exposure to static magnetic fields up to 8 T can be justified if the environment is controlled and appropriate work practices are implemented to control movement-induced sensory effects (ICNIRP 2009a). The probability of vertigo and nausea will be low if it is possible to move so slowly that the maximum ΔB does not exceed 2 T during any 3-s period.

In the case of a stationary body in a time-varying magnetic field, the peak-to-peak value of the magnetic flux density is equivalent to ΔB and consequently should be limited to 2 T.

In this context, vertigo and nausea may be annoying and disturbing, but they are not considered to indicate a serious long-term health effect. Therefore, no additional reduction factor has been applied to their threshold.

Basic restrictions for induced electric field

In order to prevent stimulation of peripheral nerves in controlled exposure, ICNIRP recommends that the induced electric field should not exceed the basic restriction of 1.1 Vm^{-1} (peak) over the frequency range of motion-induced field. This restriction was obtained by converting the basic restriction of 0.8 Vm^{-1} (Root-Mean-Square) to the peak value that applies to all tissues in the frequency range below 3 kHz (ICNIRP 2010).

Because the stimulation of peripheral nerves is regarded as an adverse health effect, a reduction factor of 5 has been applied to the threshold to account for biological uncertainties.

In order to avoid the induction of magnetophosphenes, the strength of the induced electric field should not exceed the basic restrictions for occupational exposure defined by ICNIRP (2010) for time-varying magnetic fields, with an extension to frequencies below 1 Hz. The linear increase of the basic restriction for magnetophosphenes as a function of $1/f$ ceases at 0.66 Hz where it reaches the level of 1.1 Vm^{-1} (peak), which is the basic restriction for peripheral nerve stimulation (Fig. 2). Basic restrictions for magnetophosphenes apply only to uncontrolled exposures, since workers in controlled exposure situations are considered to be able to avoid this effect by limiting their motion speed. Basic restrictions for peripheral nerve stimulation apply to both conditions.

Like vertigo and nausea, magnetophosphenes may be annoying and disturbing, but they are not considered to

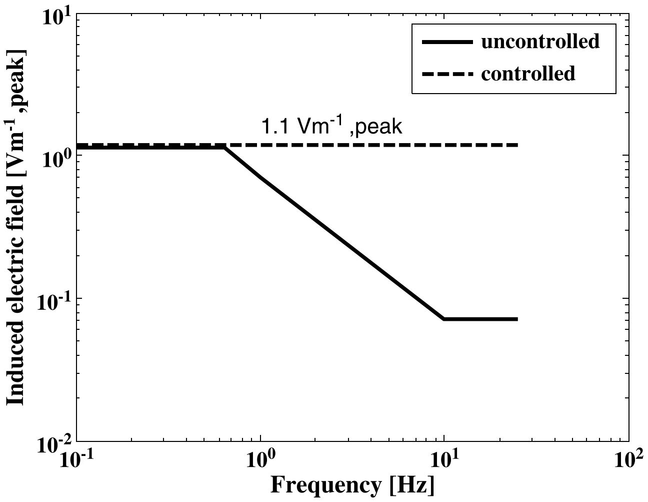

Fig. 2. Basic restrictions for the induced electric field for uncontrolled and controlled exposure conditions. The basic restrictions for uncontrolled exposures are based on protection against magnetophosphenes and peripheral nerve stimulation. The basic restrictions for controlled exposures are based on protection against peripheral nerve stimulation only. Above 1 Hz, the basic restrictions are equal to the occupational basic restrictions in ICNIRP (2010).

cause serious long-term health effects. Therefore, no additional reduction factor has been applied to their thresholds.

Because the waveform of the motion-induced electric field is a non-sinusoidal transient, the restriction of the induced electric field should be based on the weighted peak approach:

$$\left|\sum \frac{A_i}{EL_i}\cos(2\pi f_i t + \theta_i + \varphi_i)\right| \le 1, \tag{4}$$

where t is time and EL_i is the exposure restriction (peak value) at the i^{th} harmonic frequency f_i, where A_i, θ_i, φ_i, are the amplitude of the field, the phase angle of the field and the phase angle of the filter at f_i . More explanations on the weighted peak method may be found in ICNIRP (2003, 2010).

Reference levels

A practical way for determining compliance with the basic restrictions for the induced internal electric field is to ensure that the magnetic flux density does not exceed the reference levels derived conservatively from the basic restrictions. The recommended reference levels in Table 1 join with the ICNIRP (2010) reference levels for magnetic flux density at 1 Hz when the magnetic flux density is converted to the peak (amplitude) dB/dt by

$$\frac{dB_0}{dt} = 2\pi f\sqrt{2}B_{RMS}, \tag{5}$$

where B_0 is the peak value of the sinusoidal magnetic flux density and B_{RMS} is the Root-Mean-Square value (Fig. 3). Note that the reference levels are approximately directly proportional to the basic restrictions except for a small difference in corner frequencies. As in the case of compliance with the basic restrictions for the induced electric field, compliance with the reference levels for dB/dt should be determined by the weighted peak approach.

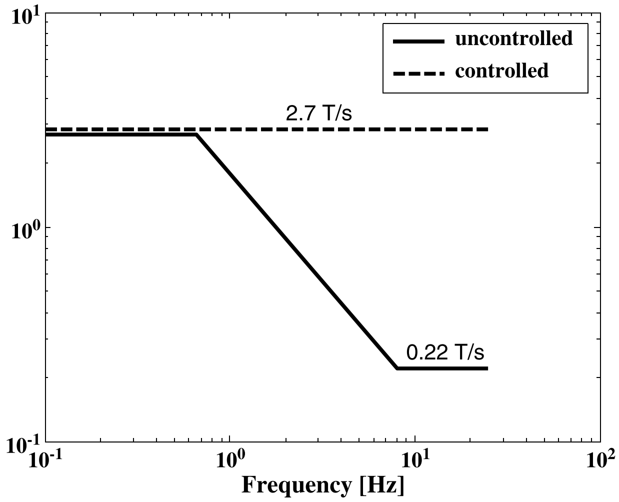

Fig. 3. Reference levels for dB/d**t** for uncontrolled and controlled exposure conditions. Above 1 Hz the reference levels are equal to the occupational reference levels for magnetic flux density (ICNIRP 2010) converted to the peak dB/dt by using (eqn 5).

In order to avoid electrical stimulation of peripheral nerves, the reference level for peak dB/dt has been set to 2.7 Ts^{-1} for controlled exposure conditions. Note that to account for uncertainties arising from the conversion of the basic restriction to the reference level a reduction factor of approximately 3 is included in this reference level (ICNIRP 2010). There is no need for spectral weighting because the reference level limiting the stimulation of peripheral nerves is constant over a large frequency range (Fig. 3).

Acknowledgments—During the preparation of this document, ICNIRP was composed of the following members: R. Matthes, Chairman (since 2012), Germany; M. Feychting, Vice-Chairperson (since 2012), Sweden; R. Croft, Australia; A. Green, Australia; K. Jokela, Finland; J.C. Lin, United States of America; C. Marino, Italy; A.P. Peralta, The Philippines; R. Saunders, United Kingdom (until 2010); K. Schulmeister, Austria (until 2012); P. Söderberg, Sweden; B.E. Stuck, United States of America; A.J. Swerdlow, United Kingdom (until 2012); Z. Sienkiewicz, United Kingdom; E. van Rongen, Netherlands; P. Vecchia, Chairman (until 2012), Italy; B. Veyret, France (until 2012), S. Watanabe; Japan.

The Commission Task Group, which prepared the draft guidelines, was lead by K. Jokela, Finland. ICNIRP also gratefully acknowledges the useful comments received from all the reviewers for their contribution received via the open online consultation.

Finally, the support received by ICNIRP during that period from the International Radiation Protection Association, the European Commission (Health and Safety at Work), and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety is gratefully acknowledged.

All ICNIRP members are requested to fill in and update a declaration of personal interests. Those documents are available online at www.icnirp.org/cv.htm.

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GLOSSARY

Basic restrictions

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

Central nervous system (CNS)

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

Conductivity (σ)

A property of materials that determines the magnitude of the electric current density when an electric field is applied to the material, expressed in units of Siemens per meter (Sm^{-1}); the inverse of resistivity.

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 Volt per meter ($NC^{-1} = Vm^{-1}$).

Electro-stimulation

Stimulation of excitable tissue in the body by an applied electrical stimulus.

Electromotive electric field (E_{vB})

Electric field induced by a movement of a conducting body in a magnetic field.

Frequency

The number of cycles completed by electromagnetic waves in 1 s; usually expressed in Hertz (Hz).

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

The creation of an electric field and current in a conducting or dielectric body caused by an external time-varying magnetic field or by movement of a body in a magnetic field.

Magnetic flux density (B)

A vector quantity that determines the force on a moving charge or charges (electric current) in a magnetic field. Magnetic flux density is expressed in Tesla (T).

Magnetophosphenes

The sensation of flashes of light caused by electric fields and currents that are induced in the retina by a time-varying magnetic field.

Nerve

A bundle of nerve fibers.

Nerve fiber

Long protrusion of a single neuron.

Neuron

A cell in the nervous system usually consisting of a cell body and a number of protrusion: a long one, the axon, and a number of shorter ones, forming the dendritic tree.

Occupational exposure

Exposure to electromagnetic fields experienced by individuals as a result of performing their regular or assigned job activities.

Peripheral nervous system (PNS)

The portion of the vertebrate nervous system consisting of the neuronal tissue found outside the central nervous system.

Permittivity (ε)

A constant defining the influence of an isotropic medium on the forces of attraction or repulsion between charged bodies, and expressed in farad per meter (F m^{-1}).

Reference levels

The Root-Mean-Square and peak electric and magnetic field strengths or flux densities and contact currents to which a person may be exposed without an adverse effect and with acceptable safety factors. Reference levels may be used in practical situations for determining compliance with the basic restrictions.

Vestibular system

An organ consisting of motion receptors sensitive to linear and rotational accelerations of the human body. It is the sensory organ that provides perception of movement and sense of balance. The vestibular system is located in the inner ear.

Static field

An electric or magnetic field that does not vary with time.

Threshold

The minimum level of a stimulus that will produce a response or specified effect.

Time derivative of magnetic flux density (dB/dt)

Change of the magnetic flux density divided by the duration of the change.

Vertigo

A type of dizziness, where there is a false feeling of motion.

Waveform

The variation of an amplitude of field vector with time.

■■

COMMENT ON ICNIRP GUIDELINES FOR LIMITING EXPOSURE TO ELECTRIC FIELDS INDUCED BY MOVEMENT OF THE HUMAN BODY IN A STATIC MAGNETIC FIELD AND BY TIME-VARYING MAGNETIC FIELDS BELOW 1 HZ

Dear Editors:

WE ARE dismayed by the way in which ICNIRP has apparently used our 2007 paper (Glover et al. 2007) to draw up its recent Guidelines on low frequency magnetic field exposure (Ziegelberger 2014). It appears that these Guidelines are going to be incorporated into the EMF Directive and made legally binding within the 28 member countries of the European Union without further scrutiny [Directive 2013/35/EU See Article 11(2) (2013)].

The guidelines' limits aimed at preventing vertigo are based entirely on our paper, which was effectively the first in the field and which has not been replicated by anyone else. Although we stand by our data, it was a very small study, and the lines on Figure 1 of the guidelines have been drawn about single data points from a single subject at two frequencies (Ziegelberger 2014). This seems to be a remarkably flimsy basis on which to make international guidelines.

However, we are keen to point out that there was a more serious problem with using that data in this way. At the time we wrote the paper, we proposed that the dominant mechanism was induced electric currents. However, as ICNIRP noted in the new guidelines, this mechanism has been questioned by Roberts, who proposed a Lorentz force mechanism (Roberts et al. 2011). Crucially, ICNIRP apparently failed to realize that this Lorentz force mechanism depends on the amplitude and direction of the field, whereas the induced current mechanism depends on the absolute rate of change of field. In our experiment, we asked subjects to move their head at high field; this would induce an electric current and would have also produced a Lorentz force, so our previous data was consistent with both mechanisms.

We have now carried out further studies that support Roberts' Lorentz force mechanism (Antunes et al. 2012; Glover et al. 2014; Mian et al. 2013). Furthermore, the new mechanism explains the previously anomalous observation of apparent vertigo-type effects in small rodents, which are physically too small to be able to develop sufficient current densities in their heads to cause nerve excitation (Houpt and Houpt 2010).

It now seems likely that the perceptual effects of the changing Lorentz force are the primary reason why movement causes vertigo. Unfortunately, this does not lead to neat, frequency-dependent limits that can be dovetailed with other limits. We propose that at the current stage of knowledge, a practical way to limit the experience of vertigo would be to accept some disconnect in the limits and simply apply the previous static field limit; i.e., 2 T for uncontrolled exposures and 8 T for controlled exposures.

The authors declare no conflicts of interest.

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ISSN: 0017-9078

DOI: 10.1097/HP.0000000000000142

RESPONSE BY ICNIRP TO THE COMMENTS OF GOWLAND AND GLOVER

Dear Editors:

GOWLAND AND Glover expressed dismay that their 2007 paper (Glover et al. 2007) had been used by ICNIRP in setting limits on exposure to electric fields induced by movement of the human body in a static magnetic field and by time-varying magnetic fields below 1 Hz (ICNIRP 2014). As Gowland and Glover correctly state, their study was the first in the field, and there is a clear need for more data. At the time of writing the guidelines, their study was the only research providing useful information for setting guidelines. Important new findings from two studies were recently published (Mian et al. 2013; Glover et al. 2014), but they do not provide sufficient reason for fundamental changes in the exposure guidelines.

The main target of the criticism is the protection against vertigo by limiting the change of the magnetic flux density in order to limit slowly varying induced electric fields. This was indeed an important aspect, but it was not the only one taken into account. The guidelines explicitly state that "…. *given the possibility of direct magnetic fields on the body, it is important to restrict both the static magnetic flux density (B) and the maximum change of the magnetic flux density (Δ B) experienced by the body during movement*" (ICNIRP 2014). Given the present state of knowledge, to which Gowland and Glover have contributed much, it is best to assume that both the direct Lorentz force and electric field effects contribute to motion-induced vertigo. The new findings have increased the likelihood that the Lorentz force on ionic currents in the vestibular organ explains the vertigo effect, but other mechanisms and particularly those due to the induced electric field still cannot be neglected. It has been well known for 150 years that the electric field induced by the galvanic current in the vestibular system causes vertigo.

The new research findings indicate that the balance system in humans seems to react more to the change of the magnetic flux density than to the magnetic field itself. It should be noted that the new ICNIRP guidelines should be applied together with the guidelines for static magnetic fields (ICNIRP 2009). Therefore, ICNIRP recommends restricting both the static magnetic flux density and its change during movement. This does not contradict the Lorentz model. A relevant issue is the relatively short integration time of 3 s, during which the change of the magnetic flux density should not exceed 2 T. In a 7 T field, it would be possible to move into the field in 10 s in order to comply with the guidelines, while the study of Glover et al. (2014) indicates that the adaptation time constant would be approximately 40 s or even longer. However, it is important to remember that the 2014 guidelines provide for controlled exposures where there is need to minimize sensations of vertigo without a strict requirement to avoid them.

More studies are needed to clarify this important safety issue concerning movement in strong magnetic fields. ICNIRP awaits with interest results of new studies. ICNIRP will regularly revise its Guidelines and Statements. If there is an obvious need for adjustments and clarifications of the existing guidelines, they will be provided.

The author declares no conflicts of interest.

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ATOMIC BOMB SURVIVOR CATARACT SURGERY PREVALENCE DATA ARE CONSISTENT WITH NON-ZERO THRESHOLD DOSE—COMMENT ON ARTICLE BY NAKASHIMA ET AL. 2013.

Dear Editors:

THIS COMMENT is with reference to the recent article titled "Radiation Dose Responses, Thresholds, and False Negative Rates in a Series of Cataract Surgery Prevalence Studies among Atomic Bomb Survivors" by Nakashima et al. (2013). In this study estimating the dose threshold for cataract surgery in atomic bomb survivors, the authors concluded that the data for each 2-y period is compatible with zero dose threshold. This conclusion is surprising since it contradicts the recognition of a threshold dose of 0.5 Gy for cataracts in a recent statement by ICRP (Stewart et al. 2012). Another reason why the possibility of zero threshold is not credible is that the eye lens has a high concentration of reduced glutathione (Ganea and Harding 2006), which would protect the lens from the oxidative damage that may be caused by a small increase in radiation exposure. Since the authors' conclusion on the