PHYSIOLOGIC AND DOSIMETRIC CONSIDERATIONS FOR LIMITING ELECTRIC FIELDS INDUCED IN THE BODY BY MOVEMENT IN A STATIC MAGNETIC FIELD

Kari Jokela* and Richard D. Saunders†

Abstract—**Movement in a strong static magnetic field induces electric fields in a human body, which may result in various sensory perceptions such as vertigo, nausea, magnetic phosphenes, and a metallic taste in the mouth. These sensory perceptions have been observed by patients and medical staff in the vicinity of modern diagnostic magnetic resonance (MR) equipment and may be distracting if they were to affect the balance and eye-hand coordination of, for example, a physician carrying out a medical operation during MR scanning. The stimulation of peripheral nerve tissue by a more intense induced electric field is also theoretically possible but has not been reported to result from such movement. The main objective of this study is to consider generic criteria for limiting the slowly varying broadband (<10 Hz) electric fields induced by the motion of the body in the static magnetic field. In order to find a link between the static magnetic flux density and the time-varying induced electric field, the static magnetic field is converted to the homogeneous equivalent transient and sinusoidal magnetic fields exposing a stationary body. Two cases are considered: a human head moving in a non-uniform magnetic field and a head rotating in a homogeneous magnetic field. Then the electric field is derived from the magnetic flux rate (d*B*/d*t*) of the equivalent field by using computational dosimetric data published in the literature for various models of the human body. This conversion allows the plotting of the threshold electric field as a function of frequency for vertigo, phosphenes, and stimulation of peripheral nerves. The main conclusions of the study are: The basic restrictions for limiting exposure to extremely low frequency magnetic fields recommended by the International Commission on Non-Ionizing Radiation Protection ICNIRP in 1998 will prevent most cases of vertigo and other sensory perceptions that result from induced electric fields above 1 Hz, while limiting the static magnetic field below 2 T, as recently recommended by ICNIRP, provides sufficient protection below 1 Hz. People can experience vertigo when moving in static magnetic fields of between 2 and 8 T, but this may be controlled to some extent by slowing down head and/or body movement. In addition, limiting the static magnetic field below 8 T provides good protection against peripheral nerve stimulation.**

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INTRODUCTION

Movement in a static magnetic field induces electric fields and currents in the tissues when the magnetic flux penetrating the body changes. Depending on the magnetic flux density, the spatial gradient and the speed of movement, this may result in physiologically significant sensory perceptions such as vertigo, nausea, magnetic phosphenes (the perception of faint flickering light in the periphery of the visual field), and a metallic taste in the mouth (e.g., ICNIRP 2009; Chakeres and de Vocht 2005; WHO 2007; AGNIR 2008; Schenk 2000). The likelihood of experiencing these sensations increases when human exposure exceeds 2 T (Tesla). Most of the static magnetic field sources exceeding this level are used today for medical magnetic resonance (MR) diagnostic procedures, but exposure problems also arise in specific research facilities where bubble chambers, superconducting spectrometers, particle accelerators, and nuclear magnetic resonance equipment have been installed (WHO 2006). In the case of MR equipment, the exposure of medical and technical staff to high static fields may be even more problematic (Moore and Scurr 2007; Capstick et al. 2008) than that of the patient because the medical worker must move irregularly in the high magnetic field, while the movements of the patient can be efficiently restricted by immobilization and controlling the speed of the patient bed.

In contrast to induction by time varying (AC) magnetic fields, where the variations are rapid and relatively regularly repeated, the electric field induced by a movement varies slowly, displaying various transient waveforms with the spectral energy mainly distributed between 0.1 Hz to 10 Hz (Glover and Bowtell 2008;

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* STUK Radiation and Nuclear Safety Authority, P.O. Box 14, FIN-00881, Finland; † Health Protection Agency, Centre for Radiation, Chemical and Environmental Hazards, Radiation Protection Division, Chilton, Didcot, Oxfordshire, OX11 0RQ, United Kingdom.

For correspondence contact: Kari Jokela, STUK Radiation and Nuclear Safety Authority, P.O. Box 14, FIN-00881, Finland, or email at kari.jokela@stuk.fi.

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Kännälä et al. 2009; Fuentes et al. 2008). This is also close to the frequency range 0.4 Hz to 8 Hz observed for natural movements of the human head (Pozzo et al. 1990; Grossmann et al. 1988; Das et al. 1995; McDougall and Moore 2005). Despite this, there is no fundamental difference between induction due to body movement in a static field and that due to time variation of the magnetic flux.

The present ICNIRP guidelines define the exposure limits for sinusoidal time-varying magnetic fields, including the ELF frequencies down to 1 Hz (ICNIRP 1998), while the frequencies less than 1 Hz are limited by the static magnetic field guidelines (ICNIRP 2009). Therefore, the frequency range of the electric field induced by the movement in the static magnetic field covers those addressed by both the ELF and static magnetic field guidelines. In order to establish a link between the static magnetic field restriction and the basic restriction on induced electric fields, it is necessary to consider the concept of an equivalent magnetic field where the movement in a static field is transformed to an equivalent time-varying transient and sinusoidal magnetic field.

The main objective of this paper is to consider generic criteria for limiting occupational exposure to electric fields induced by movement in a static magnetic field. First, the relation between the static magnetic field, body motion and induced electric field is discussed briefly. The problem is simplified by converting the static magnetic field to the equivalent time-varying magnetic field. Then the induced electric field can be estimated by employing data from computational dosimetric studies using realistic models for the human body (Bencsik et al. 2007; Brand and Heid 2002; So and Stuchly 2004; Ilvonen and Laakso 2009; Dimbylow 2005). The non-sinusoidal field is converted to the equivalent sinusoidal field by applying the equivalent frequency concept developed by Reilly (1998) for non-sinusoidal magnetic fields. Translational and rotational movements of the head will be considered separately.

Secondly, equivalent electric field thresholds for vertigo are derived from the volunteer study by Glover et al. (2007) and derive restrictions on electric fields induced by movement in a static magnetic field based on the recent recommendations by ICNIRP (2009). These guidelines on exposure to static magnetic fields recommend that occupational exposure to a static magnetic field should normally be restricted to a level of 2 T, below which normal movement in and around the magnet does not result in vertigo; however, in controlled environments, where staff are adequately warned and trained to minimize the sensation by, for example, moving more slowly, exposure may be allowed to exceed this value up to 8 T.

CHARACTERIZATION OF EXPOSURE

General considerations

The characterization of the electric fields induced in the tissues of a body moving in a static magnetic field is a complex task where the induced field is determined as much by the velocity of the tissue as by the magnetic flux density and its spatial gradient. All these exposure factors are vector quantities where both the magnitude and the direction of the field must be taken into account. Formidable problems arise from the variation of the dielectric properties of the human tissue as a function of frequency and direction. In this respect, it is particularly worth mentioning that neural tissue is strongly non-isotropic, and the motion-induced electric fields show complex broadband waveforms, which makes the dosimetry very demanding.

In the case of a general non-uniform magnetic field, the motion-induced electric field can be determined by numerical calculations (Liu et al. 2003; Crozier and Liu 2005; Sanchez et al. 2009). The equivalent magnetic field can be constructed based on the electric field calculated in a critical position in the head, for example in the retina, vestibular organ, or in a position where a peak value occurs in brain tissue. The equivalent time-varying magnetic field can then be defined as a homogeneous magnetic field inducing the same electric field, with the same magnitude and direction, in the critical position. Because the induced electric field is directly proportional to the time derivative of the magnetic field, the magnitude of the electric field E_i can be most conveniently estimated by multiplying the time derivative of the static field dB/dt with a factor expressed in units of [(V m^{-1})/(T s^{-1})] (Glover and Bowtell 2008). It is called a geometric factor (GF) because from Faraday's law (eqn 2), it is evident that the unit is equivalent to the unit of length. Table 1 shows some examples for GF computed by using various models of the human body. Note that the induced electric field is expressed in mV m^{-1}.

For practical safety assessment, numerical calculation is too complicated. It is necessary to find a simpler way based on the direct measurement of a magnetic field along the path of the head during the movement. This can be done by employing the simplest model of the head or brain, the homogeneous sphere consisting of conducting biological material. It will also be assumed that along the path of the movement, the sphere is relatively small in relation to the change of flux density and direction of the magnetic field in the sphere. This allows us the possibility of replacing the local magnetic field with a homogeneous field where the time derivative d$\boldsymbol{B}_0$/dt attains approximately the same value in each position of the sphere.

Table 1. Geometric factors for electric field induced by magnetic field in a stationary biologic body (time varying field) and in a head rotating in a static field.

Biological body model	Geometric factor $[(\mathrm{mVm}^{-1})/(\mathrm{Ts}^{-1})]$	B-field, direction	Reference
Brain, NORMAN	97.4	homog., AP[a]	Dimbylow (2005)
Homog. sphere of 15 cm (diam.)	37.5	—	—
Retina, NORMAN	22.6	homog., AP	Dimbylow (2005)
Homog. ellipsoid $a = 40$ cm, $b = 20$ cm	140	homog., AP (perpendicular to b-axis)	IEC 60601
Heterogeneous body	340	MR-gradient, LR[b]	Brand and Heid (2002)
Heterogeneous body	200–250	MR-gradient, AP	So et al. (2004)
Heterogeneous body	650[c]	MR-gradient, AP	Bencsik et al. (2007)
—	650	homog.	ICNIRP (1998)[d]
Heterogeneous rotating head in a static field	95[e]	homog., LR	Ilvonen and Laakso (2009)

[a] Anterior to posterior (front to back).
[b] Left to right.
[c] 3300 $(\mathrm{mVm}^{-1})/(\mathrm{Ts}^{-1})$ with clasped hands.
[d] From the relation of the basic restriction and reference level.
[e] Inner ear.

Fig. 1 shows a tissue-equivalent sphere moving in a non-uniform static magnetic field. Due to the movement a magnetic (Lorentz) force is exerted on the free charges in the material, and an electric field E_i and current density $\boldsymbol{J}_\mathrm{i} = \sigma \boldsymbol{E}_\mathrm{i}$ (σ is conductivity) is induced. The electric field can be presented as

$$\mathbf{E}_i = \mathbf{E}_C + \mathbf{v} \times \mathbf{B}_0, \tag{1}$$

where $\boldsymbol{v} \times \boldsymbol{B}_0$ is the electric field component associated directly with the static magnetic field $\boldsymbol{B}_0$ and velocity $\boldsymbol{v}$, and $\boldsymbol{E}_C$ is the electric field arising from the scalar potential needed to satisfy Maxwell's equations. Additionally, in certain movements such as rotating spheres there arises a negative or positive volume charge in the conducting body (Lorrain et al. 1998; Redzic 2004; Bringuer 2003). It is important to note that the electromotive force moving charged particles is due primarily to the $\boldsymbol{v} \times \boldsymbol{B}_0$ term, while the $\boldsymbol{E}_\mathrm{C}$ term and corresponding scalar potential are needed to ensure the continuity of the current in the boundaries.

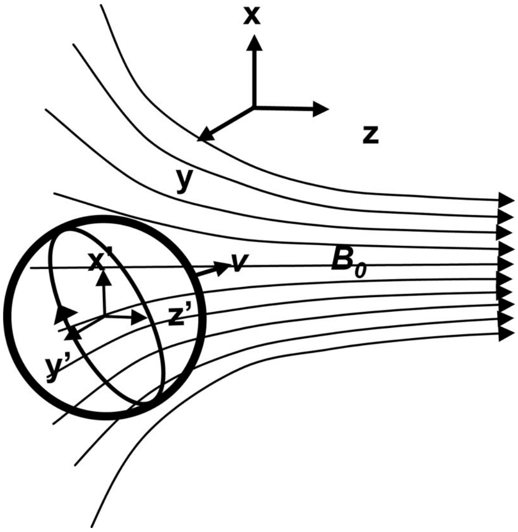

Fig. 1. Spherical model of a human head moving in a non-uniform magnetic field from a low to high field. The circle with arrow depicts the maximum electric field induced by the movement in the sphere.

Maxwell's equation as originally proposed by Faraday is particularly useful. It combines the induced electric field with the magnetic flux penetrating the body (WHO 2006):

$$\boldsymbol{E}_\mathrm{i} \times \mathrm{d}\boldsymbol{l} = -\int \frac{\mathrm{d}(\boldsymbol{B}_0 \times \mathrm{d}\boldsymbol{S})}{\mathrm{d}t}, \tag{2}$$

where $\boldsymbol{E}_i$ is the induced electric field vector, $\mathrm{d}\boldsymbol{l}$ is the differential length vector of the body part penetrated by the magnetic field $\boldsymbol{B}_0$, and $\mathrm{d}\boldsymbol{S}$ is the differential area vector directed normal to the differential area. Eqn (2) indicates that the change in the flux caused by the movement or the time variation of the magnetic field generates circulating electric fields and currents in the moving body. On the basis of the (Galilean) invariance for Faraday's law on motion (Jackson 1999), it is irrelevant whether the change in the magnetic flux density penetrating the body is caused by the change in the source current of the field or the change in the body position. Therefore, it is possible to fix the body in a stationary coordinate and to characterize the magnetic field in terms of equivalent $\mathrm{d}B_0/\mathrm{d}t$ determined by the static magnetic field and velocity (Ilvonen and Laakso 2009).

Strictly speaking, eqn (2) can be applied only for movements which are slow enough, as the human motions are, to ensure that the induced electric field and current inside the body are produced only by the change of the magnetic flux (Liu et al. 2003). For constant velocity, the electric field arising from the movement-induced charges is static and cancels the $\boldsymbol{v} \times \boldsymbol{B}_0$ component; but for accelerating, decelerating and rotational movements there remains a small net electric field due to the change of the "static" charges. In most practical exposure cases, this electric field can be expected to be small compared to the electric field induced by the change of the magnetic flux because the charges follow quickly the changes of $\boldsymbol{v} \times \boldsymbol{B}_0$. In an abrupt change, the charges find a new equilibrium within the time of the dielectric relaxation ε/σ, where ε is the dielectric constant and σ is the conductivity (Redzic 2004). In biological materials the conductivity varies from 0.01 to 1 S (siemens) m^{-1} below 10 Hz, but the relative dielectric constant varies as much as from 100 to 4×10^6 (Gabriel et al. 1996). This frequency dependency complicates the evaluation of the equilibrium time constant. However simple calculations using 10 Hz values for the dielectric parameters indicate that for muscle, the most abundant tissue in the human body, the time constant is 1.1 ms, while for some tissue such as the grey matter of the brain it may be as high as 13 ms, which is not vanishingly small compared to most rapid movements.

Translational movement

Consider a human head-equivalent homogeneous sphere moving with a constant velocity v in a static non-uniform magnetic field $\boldsymbol{B}_0$ (Fig. 1). Due to the change of the magnetic flux density $\boldsymbol{B}_0$, a circulating electric field is induced in the sphere. The circle with an arrow shows the maximum electric field, which is approximately induced around the cross-section through which the average d$\boldsymbol{B}_0$/dt is in maximum. Let the variation of d$\boldsymbol{B}_0$/dt be small over all cross-sections of the sphere. In order to find an equivalent time-varying magnetic field inducing the same electric field in a stationary body, the average time derivative is presented by

$$\frac{d\mathbf{B}_0}{dt} = \mathbf{v} \cdot \nabla \mathbf{B}_0, \tag{3}$$

where v is the velocity, ∇ is the differential del (nabla) operator, and $v \cdot \nabla$ is called the convective derivative operator (Jackson 1999). The vector components of the time derivative vector at position x,y,z are given by

$$\frac{dB_{eq,x}}{dt} = v_x \frac{\partial B_{0x}}{\partial x} + v_y \frac{\partial B_{0x}}{\partial y} + v_z \frac{B_{0x}}{\partial z} \tag{4}$$

$$\frac{dB_{eq,y}}{dt} = v_x \frac{\partial B_{0y}}{\partial x} + v_y \frac{\partial B_{0y}}{\partial y} + v_z \frac{B_{0y}}{\partial z} \tag{5}$$

$$\frac{dB_{eq,z}}{dt} = v_x \frac{\partial B_{0z}}{\partial x} + v_y \frac{\partial B_{0z}}{\partial y} + v_z \frac{B_{0z}}{\partial z}, \tag{6}$$

where v_x, v_y, and v_z are the vector components of velocity, and $\partial B_0/\partial x$, $\partial B_{0y}/\partial y$, and $\partial B_{0z}/\partial z$ are the spatial derivatives of the magnetic field averaged over the cross-sections normal to the x, y and z coordinates. The magnitude of the d$\boldsymbol{B}_{eq}$/dt vector is given by

$$\frac{dB_{eq}}{dt} = \sqrt{\frac{\partial B_{0x}^2}{\partial t} + \frac{\partial B_{0y}^2}{\partial t} + \frac{\partial B_{0z}^2}{\partial t}}, \tag{7}$$

which is directly proportional to the maximum electric field induced in the sphere. These equations define uniquely the time derivative of the equivalent time-varying magnetic field.

The change of the magnetic flux during the movement is given by the time integral

$$\Delta\mathbf{B}(t) = \int_{t1}^{t2} \frac{d\mathbf{B}_{eq}(t)}{dt} dt, \tag{8}$$

where the movement starts at time t_1 and ends at t_2, and $\boldsymbol{\Delta B}$ is the magnetic field change experienced by the head during the movement in the spatial gradient zone. It is the average magnetic field over the cross-section of the sphere perpendicular to the velocity vector. Fig. 2 shows the change of the

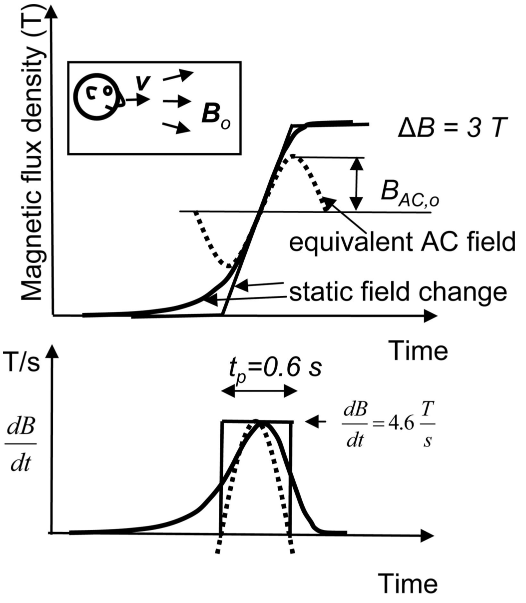

Fig. 2. Equivalent transient (solid lines) and sinusoidal (dot lines) magnetic flux density (B) and dB/dt for a biological body moving linearly through a spatial gradient of a static field. The smoothly varying solid lines have been computed for a body moving with a speed of 1 ms^{-1} through the gradient zone of a true 3 T MR scanner (Kännälä et al. 2009). Time scale for both graphs is indicated by the 0.6-s length of the pulse. The length scale (m) is equal to time scale (s).

magnetic flux during the movement and the corresponding dB/dt. Assuming a linearly-rising trapezoidal gradient (straight line in Fig. 2), the equivalent transient dB_{eq}/dt becomes

$$\frac{dB_{eq}}{dt} = \frac{\Delta B}{t_p}, \tag{9}$$

where ΔB is now the change of the magnetic flux density, and t_p is the duration of the movement in the gradient zone ($t_p = t_2 - t_1$).

Next, an equivalent sinusoidal (AC) field is defined where the amplitude is equal to the peak value of the transient field, and the frequency is determined by the pulse duration (Reilly 1998). The frequency is given by

$$f_{eq} = \frac{1}{2t_p}, \tag{10}$$

and the amplitude by

$$B_{AC} = B_{AC,o} \cos(2\pi f_{eq} t). \tag{11}$$

The time derivative of the equivalent AC field is

$$\frac{dB_{AC}}{dt} = -2\pi f_{eq} B_{AC,o} \sin(2\pi f_{eq} t), \tag{12}$$

where the maximum value is

$$\frac{dB_{AC,o}}{dt} = 2\pi f_{eq} B_{AC,o}. \tag{13}$$

By equating this with the maximum value of the time derivative of the equivalent transient magnetic field eqn (9) and replacing f_{eq} by eqn (10), the amplitude of the equivalent AC field is obtained.

$$B_{AC,o} = \frac{\Delta B}{\pi}. \tag{14}$$

The equation implies that the static magnetic field change can be divided by a factor that is called here a static magnetic field reduction factor MF, which has a value of π in this particular case. For a non-linearly rising gradient, the pulse duration can be defined by the intersection of the slope with the time axis (0 T) and 3 T lines as depicted in Fig. 2. This definition ensures that the product dB/dt(peak) × ΔB is equal to the change of the magnetic flux density during the movement, which is the exposure quantity best associated with vertigo. Indeed, the study of Glover et al. (2007) indicates that vertigo perception depends more on ΔB than on dB/dt.

The simple spheroidal model presented above for the motion-induced electric field has an interesting connection with the meters used for the measurement of exposure to movement-induced electric fields. The measurements are presently carried out by using three small orthogonal induction coils calibrated to measure dB_0/dt exactly as eqns (4)–(7) indicate. (Kännälä et al. 2009; Glover and Bowtell 2008; Fuentes et al. 2008). Typically, the diameter of each coil is approximately 3 cm, which can be compared to 15 cm representing a spheroidal model of the brain. The signal combined from the three channels according to eqn (7) is directly proportional to the maximum electric field depicted in Fig. 1 unless the magnetic field is not too uniform in the space occupied by the sphere and measurement loops. If the probe is accompanied by an inertial velocity meter measuring the three vector components of the velocity vector $\boldsymbol{v}$, the gradient vector d$\boldsymbol{B}_0$/ds can be solved from eqns (4)–(6).

It must be stressed that the presented definition of the equivalent field for a translational motion is a linear approximation that is exact only for an infinitesimally small sphere where the magnetic flux lines become parallel and d$\boldsymbol{B}_0$/dt uniform. It cannot be taken for granted that for many practical magnetic field distributions, the spheres equivalent to the human brain (diameter approximately 15 cm) are small enough to be used for an accurate estimation of the exposure. The validity of the linear approximation depends on the relation of the curvature of the magnetic field lines to the size of the sphere. The curvature is always related to the gradient of the local field by the requirement of zero divergence. For increasing size of the sphere and non-uniformity of the magnetic field, the deviation from the true induced electric field increases. The maximum value is still found in most practical exposure cases on the surface, but the electric field/current current loops are placed on curved surfaces and the field strength is not necessarily uniform along the loop. However, it is of interest to note that in many non-uniform exposure situations, the average dB_0/dt in the brain is a relatively good indicator of the exposure (Stuchly and Dawson 2002).

Rotational movement

In the second case, the head makes an angular rotation, such as shaking and nodding, in a static homogeneous magnetic field directed perpendicular to the axis of the rotation (Fig. 3). By changing the fixed coordinate frame x,y,z to the rotating frame x',y',z', the head becomes stationary and the circularly polarized magnetic field $\boldsymbol{B}_0$ rotates in the x'--z' plane as depicted in Fig. 4 (Ilvonen and Laakso 2009). In the case of the homogeneous sphere model, a circumferential electric field and current are induced by the movement. The field decreases linearly from the maximum in the surface to the zero in the center of the sphere. Maximum induction occurs in the plane of the magnetic field where the magnetic flux change is a maximum but the magnetic flux itself is a minimum. The plane of the maximum induced electric field E_i rotates in the coordinate frame of the sphere by the angular velocity of the sphere. If the

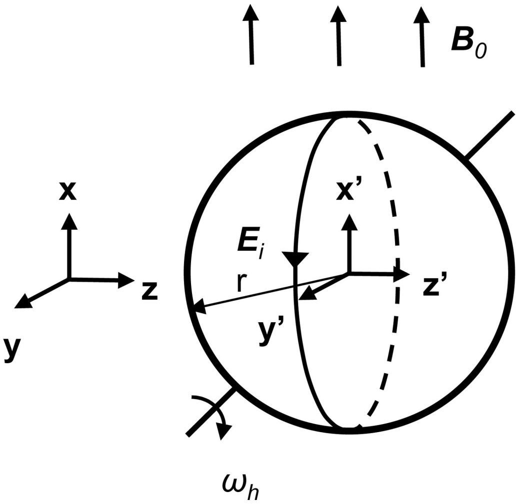

Fig. 3. Spherical model of a human head rotating by angular velocity ω_h around the *y*-axis in a homogeneous static magnetic field directed along the x-axis. E_i depicts the maximum electric field induced in the x-y plane in the surface of the sphere.

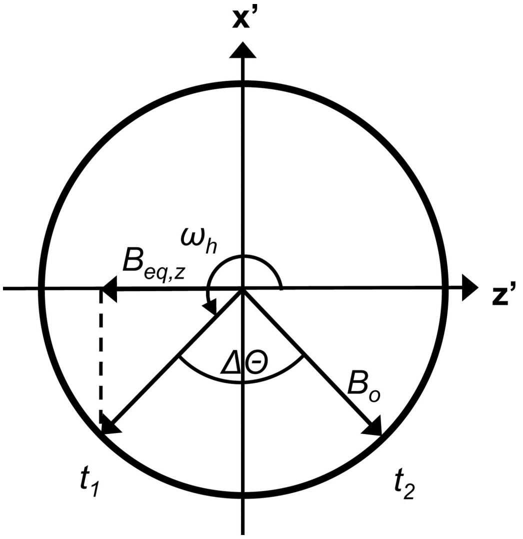

Fig. 4. Circularly-polarized equivalent transient magnetic field in the rotating coordinate frame ($\boldsymbol{B}_{\mathrm{eq}} = \boldsymbol{B}_0$ for $t_1 < t < t_2$).

rotation axis were parallel to the magnetic field, there would be no significant induction of the current, but only a build-up of a static volume and surface charge of opposite sign (Lorrain et al. 1998; Redzic 2004).

The equivalent circularly polarized transient magnetic flux density B_{eq} is given by

$$B_{eq,z} = B_o \cos(\omega_h t) \quad t_1 \le t \le t_2 \tag{15}$$

$$B_{eq,x} = B_o \sin(\omega_h t) \quad t_1 \le t \le t_2 \tag{16}$$

$$B_{eq,z} = B_{eq,x} = 0 \quad t_1 \ge t \text{ or } t \ge t_2, \tag{17}$$

where $B_{eq,z}$ is the *z*-component and B_{eqx} the *x*-component of the field where the $\boldsymbol{B}_0$ vector rotates counter-clockwise in the x'–z' plane by rotation angle $\Delta\Theta$ around the *y*-axis (Fig. 4). The rotation angle is given by

$$\Delta\Theta = \omega_h t_p, \tag{18}$$

where $t_p = t_2 - t_1$ is the duration of the movement beginning at time t_1 and ending at t_2, and ω_h is the angular velocity of the head during the movement. The time derivatives of $\boldsymbol{B}_{eq}$ are given by

$$\frac{dB_{eq,z}}{dt} = -\omega_h B_o \sin(\omega_h t) \quad t_1 \le t \le t_2 \tag{19}$$

$$\frac{dB_{eq,x}}{dt} = \omega_h B_o \cos(\omega_h t) \quad t_1 \le t \le t_2 \tag{20}$$

$$\frac{dB_{eq,z}}{dt} = \frac{dB_{eq,x}}{dt} = 0 \quad t_1 \ge t \text{ or } t \ge t_2, \tag{21}$$

where the d$\boldsymbol{B}_{eq}$/d*t* vector is perpendicular to $\boldsymbol{B}_{eq}$ in the x'–z' plane. Both vectors rotate around the head and show 90 degrees phase difference. The induced circumferential $\boldsymbol{E}_i$ field rotates in the plane perpendicular to d$\boldsymbol{B}_{eq}$/d*t*. The $\boldsymbol{E}_i$ vector is generally elliptically polarized, varying in the sphere from linear polarization at the equator to circular polarization at the poles.

A linearly-polarized transient magnetic field may be defined as the vector component of the circularly-polarized field B_{eq} along any direction in the *x'*-*z'* plane. In Fig. 4 the *z'*- axis has been chosen for that direction, in which case the linearly polarized equivalent transient field is given by $B_{eq,z}$ in eqn (15). Additionally, it has been assumed that the rotation angle $\Delta\Theta$ is centered symmetrically along the x-axis (direction of the static field), which ensures that the change of the magnetic flux $\Delta B = 2B_o \sin(\omega_h t_p/2)$ and peak d*B*/d*t* are maximized. Fig. 5 shows the (linearly-polarized) equivalent transient magnetic field and corresponding d*B*/d*t* (thick solid lines). For a full 360 degrees rotation, the equivalent magnetic field would follow the dashed line. It is most interesting to observe the sudden change in d*B*/d*t* when the rotation begins and ends. These changes are associated with short acceleration and deceleration periods when the induced electric field changes abruptly, and consequently the spectral energy is shifted toward higher frequencies. For smooth and slow movements the electric field is low, and the spectrum is shifted towards lower frequencies.

Having now defined the linearly-polarized equivalent transient magnetic field, the equivalent linearly-polarized sinusoidal AC field (dotted thick d*B*/d*t* line in Fig. 5) is defined by

$$B_{AC} = B_{AC,0} \cos(\omega_{AC} t), \tag{22}$$

where the angular frequency of the equivalent sinusoidal AC field is

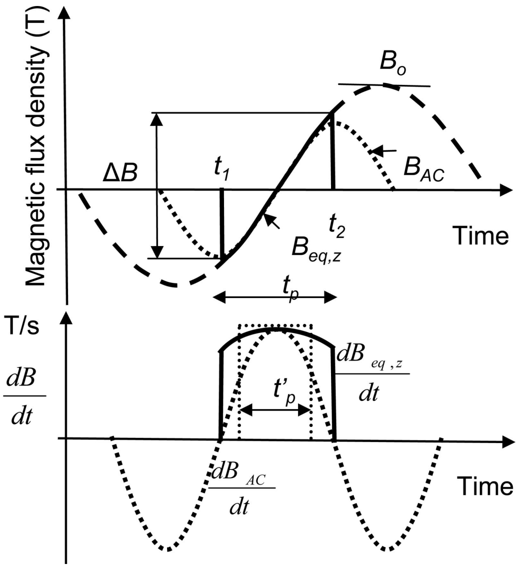

Fig. 5. Equivalent transient (dashed line) and sinusoidal (thick dot lines) magnetic flux density and dB/dt for a human head which rotates in an homogeneous static magnetic field B_0 with a constant angular velocity ω_h.

$$\omega_{AC} = 2\pi f_p = \frac{\pi}{t_p} = \frac{\pi}{\Delta\Theta}\omega_h, \tag{23}$$

where $t_p = \Delta\Theta/\omega_h$ is the duration of the movement within the static field [see eqn (18)]. The amplitude of the equivalent AC field is obtained by fitting the maximum (amplitude) time derivative ($\omega_{\mathrm{AC}}B_{\mathrm{AC,o}}$) with the peak time derivative of the equivalent transient magnetic field $\omega_h B_0$ from eqn (19) and substituting eqn (23) for ω_{AC}, which results in

$$B_{AC,o} = \frac{B_o}{MF}. \tag{24}$$

$$MF = \frac{\pi}{\Delta\Theta} \qquad \Delta\Theta \leq \pi. \tag{25}$$

These equations show that for a decreasing movement angle, the amplitude decreases linearly toward zero and the equivalent frequency f_p increases in inverse proportion to the angle. The maximum angle for the head rotation without turning the body is approximately 90 degrees ($\Delta\Theta = \pi 2^{-1}$), in which case MF = 2. In an extreme case, the turning of the upper part of the body increases the angular rotation of the head to 180 degrees and even more, in which case MF = 1. In the previous discussion, it was assumed that the rotation axis is perpendicular to the direction of the static magnetic field. This is not a necessary condition because, on the basis of the superposition principle, the magnetic field can always be decomposed into two components, the one parallel to the rotation axis and the one perpendicular to the axis. In this case only B_0 is replaced with the perpendicular component $\sin(\psi)B_0$, where ψ is the angle between the rotation axis and direction of the static magnetic field. The perpendicular component produces the rotating electric field inside the sphere whereas the parallel component only produces static surface and volume charges, as stated previously. If the angle of the rotation axis to the magnetic field ψ rotates randomly, the average perpendicular magnetic field component becomes $2\ \pi^{-1}\ B_0$. In this case the average motion reduction factor for 90 degrees ($\Delta\Theta = \pi 2^{-1}$) rotation of the head becomes MF = π, which is equal to the value derived for the translation motion from the zero field to B_0.

Instead of using the physical rotation time of the head (t_p) for the defining of the equivalent sinusoidal field, it is possible to define the effective duration of the rotation by letting $t'_p \times \mathrm{d}B_{peak}/\mathrm{d}t = \Delta B$, where d$B_{peak}$/d$t$ is the peak value of equivalent dB/dt and ΔB is the change of the magnetic flux through the head during the movement (Fig. 5). In this case, the critical exposure parameter ΔB has been defined in the same way as the translational motion. When t_p is changed to t'_p, MF decreases significantly at large rotation angles. For a 180 degree rotation, MF decreases from 1 to $\pi 2^{-1}$, while below 40 degrees the difference is small. Overall, the practical range of the amplitude of the equivalent AC field for a rotating head varies from 0 to B_0/π, even though some higher values up to $B_0/(\pi 2^{-1})$ are possible in some rare exposure situations.

A static magnetic field limit can be converted easily to the equivalent AC electric field (amplitude) by combining

$$E_i = GF\frac{dB}{dt}, \tag{26}$$

with dB/dt = $2\pi f_{AC}\ B_{AC,0}$ from eqn (22), which results in

$$E_i = \frac{GF}{MF}2\pi f_{AC}B_o, \tag{27}$$

where $B_{AC,0}$ was substituted by eqn (24). The AC electric field equivalent to 2 T and 8 T static field limits have been presented in Fig. 6.

Concluding remarks for exposure assessment

In summary, when a human head moves into a static magnetic field B_0 through a steep spatial gradient, the amplitude of the equivalent sinusoidal field is B_0/π and the frequency is determined by $(2\ t_p)^{-1}$. In the case of the head rotating in a homogeneous static field, the maximal amplitude may theoretically be equal to $B_0/(\pi 2^{-1})$, but in the majority of real exposure situations the amplitude can easily be kept within the range from 0 to $B_0\ \pi^{-1}$. The

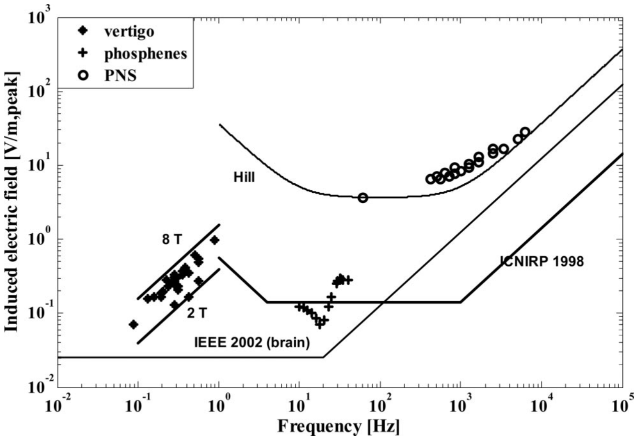

Fig. 6. Critical biological threshold values, basic restrictions for ELF magnetic fields and basic restrictions for static magnetic field equivalent AC fields. These basic restrictions are applied to the central nervous system tissue. The ICNIRP (1998) basic restrictions for the ELF magnetic fields are presented as induced electric fields converted from the basic restrictions for the current density by assuming 0.1 S m^{-1} conductivity. Equivalent ICNIRP (2009) static magnetic field basic restrictions for the general (2 T) and specific controlled work environment (8 T) were computed by using eqn (27) with the static field reduction factor MF $= \pi$ and geometric factor GF $= 97$ $(Vm^{-1})/(Ts^{-1})$. The IEEE (2002) basic restrictions are applied to any controlled environment.

amplitude decreases linearly as a function of the duration of the movement. For rapid and sudden movements, the induced electric field is high and the spectrum shifts to higher frequencies.

In a practical exposure assessment, it may be most convenient to convert the reference level for the sinusoidal magnetic flux density to the peak d*B*/d*t* and compare this value to the measured peak d*B*/d*t* weighted with a function derived from the reference level (ICNIRP 2003b; Kännälä et al. 2009; Jokela 2000). The use of the spectral decomposition and multiple frequency rule (ICNIRP 1998) may not be the best choice, because the motion-induced field is a transient field where the peak value is heavily influenced by the phases of the spectral components. The multiple frequency rule is based on amplitudes alone.

VOLUNTEER STUDIES OF MOVEMENT-INDUCED EFFECTS

There are a number of experimental studies and numerous reports by patients and workers moving in or around MR systems >2–3 T of magnetic phosphenes, vertigo and nausea, and sometimes of a metallic taste in the mouth (e.g., Schenck et al. 1992; Chakeres and de Vocht 2005; de Vocht et al. 2003, 2006a, 2006b; Glover et al. 2007; Cavin et al. 2007). Calculation and measurement (Crozier and Liu 2005; Glover and Bowtell 2008) suggests that the induced electric fields resulting from movement around and within 3–4 T magnets may range between 10's of mV m^{-1} and several V m^{-1}, which may be sufficient to account for these effects, since they can also be induced by weak electric currents applied directly to the head or tongue.

Adrian (1977), for example, demonstrated that passing 5–80 Hz electric currents of up to 0.8 mA between electrodes attached to the head could induce phosphenes similar to those induced by exposure to ELF magnetic fields (Lövsund et al. 1980a and b), showing a minimum threshold of 0.01 mA at 20 Hz. Both result from the interaction of the induced electric field with neural tissue in the retina, which is an outgrowth of the forebrain and therefore part of the CNS. Indeed, Attwell (2003) notes that the retina is a good but conservative model of the neurophysiological processes that occur in CNS tissue in general. Threshold-induced electric field strengths in the retina have been estimated to lie between about 50 and 100 mV m^{-1} at 20 Hz (Saunders and Jefferys 2007), although there is considerable uncertainty attached to these values.

The most severe effect is that of vertigo, which has been examined in some detail in a recent study by Glover et al. (2007) described below, and is used as the basis for restrictions on exposure to static fields (ICNIRP 2009). Vertigo or motion sickness occurs in those people who are unable to unconsciously resolve the conflict that happens when there are discordant inputs from various senses about the apparent position and movement of the head and body (Probst and Schmidt 1998; Brandt 2003). These sensory inputs include those principally from the vestibular (balance) organ of the inner ear and from the eye relating to the position and movement of the head and also those from other somatosensory receptors within the body. Potentially the electrical fields induced in the head by movement in a static magnetic field are a possible source of the movement-induced vertigo experienced by some patients and workers moving in and around certain MR systems. It has been well established for some time that a "galvanic" (DC) stimulus current of ~1 mA applied directly to the head can upset a person's balance and equilibrium [see Fitzpatrick and Day (2004) for a review]. The responses described most frequently are nystagmus (a compensatory eye movement), body sway, and the sensations of movement, dizziness, and nausea (Balter et al. 2004). The DC current affects the firing rate of the afferent vestibular nerves onto which the movement-sensitive hair cells synapse and so alters the vestibular sensory output, which is interpreted as a head movement leading to the compensatory eye and body movements (Wardman and Fitzpatrick 2002). For

AC currents, the sensation of head movement is maximum around 1–2 Hz (Stephan et al. 2005), which corresponds to the dominant head frequency experienced during walking (McDougall and Moore 2005).

The sensations and postural responses of volunteers moving in magnetic fields produced by a 7 T whole body magnet have been investigated by Glover et al. (2007). Seven out of 10 subjects felt sensations of movement (rotation) when they were pushed into the bore of the magnet on a patient bed moving at 0.1 m s^{-1}, giving peak dB/dt values of about 1 T s^{-1}. Two of these subjects indicated that the sensations were severe, and the direction of apparent motion was reversed when they were pushed into the other end of the magnet or when they turned over from a supine to a prone position. This reversal when the direction of movement in relation to the field orientation changes suggests an effect of an induced electric field (Glover et al. 2007; AGNIR 2008). When the subjects moved their heads in the center of the magnet, nine reported mild or severe vertigo-like effects, and two experienced severe nausea. Further, eight subjects reported feelings of dizziness immediately after the end of the test that persisted for up to 10–30 min.

It was also found that postural sway was significantly increased for three out of 10 subjects standing stationary close to the magnet in a field of ~0.8 T and a field-gradient cross product of 1.0 T^2 m^{-1}. In addition, two subjects reported a feeling of "falling" when standing stationary near the magnet. This effect on postural sway suggests a direct interaction of the magnetic field with a component of the "movement sensor" and was ascribed to a difference in the diamagnetic susceptibility between the surrounding endolymph fluid and the calcium carbonate "otoconia" of the maculae, which are the linear movement sensors of the vestibular organ (Glover et al. 2007). Presumably, this effect, which does not result from time-dependent changes, may contribute to movement-induced vertigo by exerting a changing force on the otoconia as the subject moves in the bore of the magnet, which is interpreted as body movement (AGNIR 2008).

With regard to taste sensations induced by movement in a static field, Cavin et al. (2007) reported that 12 out of 20 (60%) volunteers experienced a metallic taste sensation if they rotated their heads horizontally in the stray field of a 7 T MR system. The threshold d*B*/dt varied between 1.2 and 4 T s^{-1}; the sensation did not persist for more than a few minutes. This taste, experienced by many people when they move their heads in a magnetic field, also seems to be attributable to induced electric fields in the mouth. Electrogustometry, where a DC voltage of up to ~1.6 V is applied directly to the tongue via a pair of electrodes, is a well-established tool for assessing taste detection thresholds (Stillman et al. 2003; McClure and Lawless 2007; Stevens et al. 2008). Threshold DC electric currents as low as 20 μA have been reported, due no doubt to the conductive nature of the medium and the proximity of the taste receptors. There are no quantitative data for taste thresholds as a function of frequency.

BASIS FOR LIMITING MOTION INDUCED ELECTRIC FIELDS

As described above, both phosphenes and vertigo have been reported during movement in static magnetic fields greater than 2 T, which is characterized by a spectral energy mainly distributed between 0.1 and 10 Hz. Phosphenes and myelinated nerve stimulation of both the peripheral and central nervous systems have been induced by exposure to time-varying magnetic fields (ICNIRP 2003a; WHO 2007). Generally, however, because they include larger diameter fibers, peripheral myelinated nerves are probably slightly more sensitive to electrical stimulation than similar nerves in the central nervous system (CNS). Quantitative neural threshold data for peripheral nerve stimulation, phosphenes, and vertigo are presented in Fig. 6 as a function of induced electric field and frequency, along with the basic restrictions for occupational exposure recommended by ICNIRP (1998) and IEEE (2002). Because the biological ELF effects are determined by the temporary peak value of the field and not by the root-mean-square (rms) values, the biological threshold levels values and limit values are expressed as peak (p) values, which are obtained by multiplying the rms value by $\sqrt{2}$.

Quantitative threshold data

The peripheral nerve stimulation thresholds given in Fig. 6 were obtained from studies where the whole body of volunteers was exposed to linear trapezoidal pulses simulating a gradient magnetic field during an MR scan (Nyenhuis et al. 2001). The geometric factor 0.25 $(\mathrm{Vm}^{-1})/(\mathrm{Ts}^{-1})$ (So et al. 2004) used here is assumed to be representative for estimating the induced electric field in the periphery of the body. The data point 3.7 V_p/m for median stimulation threshold at 60 Hz is extrapolated from these data (Bailey and Nyenhuis 2005; Nyenhuis et al. 2001). The minimum and maximum thresholds were 2 V_p m^{-1} and 6.4 V_p m^{-1}, respectively, which reflects the threshold variation of volunteers. The average stimulation threshold can be presented as a function of frequency by the function (Hill 1937; Reilly 1998)

$$E_t = E_{rh}\sqrt{\left(1+\frac{f_o^2}{f^2}\right)\left(1+\frac{f^2}{f_e^2}\right)}, \qquad (28)$$

where f_o is the frequency below which the threshold electric field E_t increases due to the accommodation of the nerve to a slowly depolarizing stimulus[‡], and f_e is the frequency above which the threshold increases due to the charging of the membrane. E_{rh} is the minimum threshold (rheobase) field. The "Hill" curve in Fig. 6 was obtained by computing the relative threshold using eqn (28) fitted to the 3.7 $\mathrm{V_p\ m^{-1}}$ average threshold at 60 Hz and by choosing 10 Hz for f_o and 1 kHz for f_e.

The magnetic phosphene curve was constructed by estimating the available dosimetric data for the minimum threshold electric field at around 20 Hz and then scaling this threshold to other frequencies by using the classical Lövsund et al. (1980b) data expressed as d*B*/d*t* threshold from 10 to 100 Hz. Variation of minimum threshold electric field is large. The electric field threshold for magnetophosphenes has been estimated to lie about 50–100 $\mathrm{mV\ m^{-1}}$ as rms values that correspond to 70–140 $\mathrm{mV_p/m}$ peak values. In Fig. 6 the phosphene threshold has been plotted by using 70 $\mathrm{mV_p\ m^{-1}}$ for a minimum value at 20 Hz.

The vertigo data plotted in Fig. 6 are based on the head movement experiment of Glover et al. (2007) at the iso-center of a 7 T MR scanner. The experiment was carried out by recording the d*B*/d*t* with a small 3-D magnetic field sensor attached to the head. The results were reported in terms of a magnetic field change ΔB integrated from d*B*/d*t* over the duration of the angular rotation (integration) time (t_p). The average d*B/d*t was computed back during the movement, and this equivalent transient d*B*/d*t* was converted to the equivalent sinusoidal AC field, first to d*B*/d*t* and then to the induced electric field. In these conversions, MF = π was used for the motion factor and GF = 97.4 $(\mathrm{mVm^{-1}})/(\mathrm{Ts^{-1}})$ for the geometry factor (Dimbylow 2005; Ilvonen and Laakso 2009).

There is a clear linear decrease in the vertigo threshold of the induced electric field and d*B*/d*t* for decreasing (equivalent) frequency. This is equivalent to the decrease of the d*B/d*t threshold for increasing duration of movement. Consequently the magnetic flux density threshold seems to be relatively independent of frequency and duration. The decrease of the d*B*/d*t* or electric field threshold as a function of frequency is in contradiction to the galvanic current stimulation data where the responses of vestibular nerve afferents to the current are relatively constant in the frequency range from 0.01 to 10 Hz (Goldberg et al. 1984), even though the sensation of the head movement is at maximum around 1–2 Hz (Stephan et al. 2005), as mentionedpreviously. The reason for the difference of frequency responses is not clear. If the vertigo effect were due solely to the induced electric field, then the frequency response of the d*B*/d*t* related vertigo should not deviate from the galvanic current related vertigo, since the induced field in the vestibular organ should be linearly proportional both to the current and d*B*/d*t*. Possibly for slow movements, the vertigo response is mainly due to magnetic force effects, which have time to accumulate over the sensation threshold during movement, while for rapid movements with high d*B*/d*t* the response is predominantly due to the high-induced electric field. Additionally, the assumption on the equivalency of the transient and equivalent magnetic fields may need more verification. In general, there does not seem to be a major difference between the activation of vertigo-involved brain areas due to stimulation of the vestibular organ by AC currents and monopolar DC current pulses (Stephan et al. 2005). Both stimuli modulate the firing of afferent nerves by the same means (Fitzpatrick and Day 2004). Therefore the vertigo threshold of the equivalent AC magnetic field might not deviate radically from the threshold of a transient magnetic flux change either, which provides biological support for using equivalent fields and frequencies. Further studies are clearly needed to resolve these questions.

In summary, in terms of induced electric field sensitivity, it can be seen from Fig. 6 that the transient sensory responses of the retina and vestibular organ, namely phosphenes and vertigo, have much lower thresholds (by up to two orders of magnitude) than the myelinated nerves of the peripheral nervous system and that vertigo appears at lower frequencies than phosphenes, which show a peak sensitivity at 20 Hz. Peripheral nerve stimulation can occur in response to a wide range of frequencies, but sensitivity is limited below 10 Hz by accommodation to a slowly depolarizing stimulus and above a few kHz by the membrane time-constant.

DISCUSSION AND CONCLUSIONS

It can be seen from Fig. 6 that both sets of current ELF guidelines (ICNIRP 1998; IEEE 2002) do not properly address the issues raised by movement in and around MR systems with static magnetic field strengths in excess of 2 T. Much of the data regarding the induction of electric fields and physiological effects of movement have only been published recently (e.g., Crozier and Liu 2005; Chakeres and de Vocht 2005; Glover et al. 2007; Cavin et al. 2007). At present, however, the ICNIRP 1998 ELF guidelines do not address vertigo, while application of the IEEE 2002 guidelines would severely restrict work in static magnetic fields exceeding 1 T. In a controlled environment, for example, the basic restriction applied below 20 Hz for

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[‡] Accommodation does not occur in response to the low frequency component of a complex waveform such as trapezoid or rectangular pulses with quick rise-times but low repetition frequencies found in the switched gradient fields of MRI systems.

the brain is only 25 mV$_p$ m^{-1} (peak value) in the IEEE standard, while common rotational movements of the head in a homogeneous magnetic field inside an MR scanner induce significantly higher electric fields. For example, nodding the head in the equivalent transient dB/dt field of 1 T s^{-1} (peak) results in 95 mV$_p$ m^{-1} in the inner ear (Table 1) as computed by Ilvonen and Laakso (2009). In a 3 T magnetic field, this dB/dt value is achieved when the head rotates approximately 60 degrees within 3 s, which is quite a slow movement. It is clear that for rapid movements, the induced electric field may reach 500 mV$_p$ m^{-1}. For non-CNS tissue, the induced electric field increases further, since the cross-section of the body is larger than that of the head. Crozier and Liu (2005) have computed induced electric fields up to 2–3 V$_p$ m^{-1} in translational movements in the very non-uniform stray magnetic field of a 4 T scanner. Presumably the peripheral nerve stimulation threshold is not exceeded because the spectral energy is distributed below 10 Hz where the accommodation increases the threshold, but the safety margin may be less than 10 (Fig. 6).

ICNIRP (2009) recommends that occupational exposure to a static magnetic field should normally be restricted to a level of 2 T, below which normal movement in and around the magnet does not result in vertigo that may interfere with employees' ability to work; however, in controlled working environments, where staff are adequately warned and trained to minimize the sensation (by moving more slowly, for example), exposure may be allowed to exceed this value up to 8 T (ICNIRP 2009). Implicit in this argument is the notion that, during movement in controlled environments, levels of induced electric field may be allowed that exceed the vertigo threshold. The authors argue here that occupational exposure should normally be limited to avoid vertigo and other transient effects like phosphenes but that in controlled environments such exposures can be exceeded. In addition, peripheral nerve stimulation, which has been associated with perception, discomfort, and pain in volunteer studies, should also be avoided. A two-tier limit on occupational exposure to static magnetic fields such that exposure under controlled conditions can exceed thresholds for vertigo and carries the implication that limits on ELF exposure will be similarly two-tiered, since the effects of electric fields induced by movement in and around these static field sources are indistinguishable from exposure to time-varying fields. The authors propose that occupational exposure during movement in a static magnetic field be restricted to avoid vertigo and effects like phosphenes, which may be distracting and uncomfortable. However, under controlled conditions such as in an MR suite, exposure that exceeds these thresholds is allowed but must be limited to avoid peripheral nerve stimulation. Equivalent basic restrictions on ELF electric fields induced by movement in a static magnetic field for general (2 T) and controlled (8 T) working environment (ICNIRP 2009) are given in Fig. 6.

It is of interest to note that the static field limit 2 T is a factor of 10 higher than the ICNIRP (1998) reference level of 200 mT (rms) at 1 Hz. Most of the difference is explained by the magnetic field reduction factor (eqn 14) and the difference in the GF factor. The ICNIRP reference levels were based on a conservative whole-body exposure model, while the static field limit is applied for the head where the induced electric field and consequently the GF factor are smaller. Additionally, the use of peak value instead of rms value for the ELF magnetic field reduces the difference at 1 Hz.

The 2 T static magnetic field limit provides sufficient protection for limiting vertigo during normal head and/or body movement, but for higher fields it may be prudent to ensure that induced electric fields of frequencies >1 Hz do not exceed basic restrictions by avoiding rapid movement. Vertigo may occur during movement in static fields between 2 T and 8 T or if the basic restrictions on induced electric fields above 1 Hz are exceeded. However, sufficient protection is provided against peripheral nerve stimulation.

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