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REVIEW ARTICLE

Occupational exposure in MRI

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ABSTRACT. This article reviews occupational exposure in clinical MRI; it specifically considers units of exposure, basic physical interactions, health effects, guideline limits, dosimetry, results of exposure surveys, calculation of induced fields and the status of the European Physical Agents Directive. Electromagnetic field exposure in MRI from the static field B_0, imaging gradients and radiofrequency transmission fields induces electric fields and currents in tissue, which are responsible for various acute sensory effects. The underlying theory and its application to the formulation of incident and induced field limits are presented. The recent International Commission on Non-Ionizing Radiation Protection (ICNIRP) Bundesministerium für Arbeit und Soziales and Institute of Electrical and Electronics Engineers limits for incident field exposure are interpreted in a manner applicable to MRI. Field measurements show that exposure from movement within the B_0 fringe field can exceed ICNIRP reference levels within 0.5 m of the bore entrance. Rate of change of field dB/dt from the imaging gradients is unlikely to exceed the new limits, although incident field limits can be exceeded for radiofrequency (RF) exposure within 0.2–0.5 m of the bore entrance. Dosimetric surveys of routine clinical practice show that staff are exposed to peak values of $42 \pm 24\%$ of B_0, with time-averaged exposures of 5.2 ± 2.8 mT for magnets in the range 0.6–4 T. Exposure to time-varying fields arising from movement within the B_0 fringe resulted in peak dB/dt of approximately $2\ \mathrm{T\,s^{-1}}$. Modelling of induced electric fields from the imaging gradients shows that ICNIRP-induced field limits are unlikely to be exceeded in most situations; however, movement through the static field may still present a problem. The likely application of the limits is discussed with respect to the reformulation of the European Union (EU) directive and its possible implications for MRI.

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The formulation of EU directive 2004/40/EC on physical agents (electromagnetic fields) [1] has focused attention on the issue of occupational exposure in MRI. Numerous articles and editorials have been published outlining the concerns of the MR and wider radiology community regarding the possible implications of the directive [2–4]. Subsequently commissioned studies [5, 6] have indicated that exposure limits contained in the original directive, which were based on guidelines from the ICNIRP dating back to 1998, would adversely impact several aspects of clinical and research MRI within the EU. As a consequence, implementation of the directive has been delayed until 2012 [7] and will be formulated in the light of new ICNIRP guidance [8] and other international standards.

The situation in Europe has shown that little is known about the actual levels of exposure of MR workers, despite the prior existence of relevant national and international occupational exposure guidance [8–11] and a significant body of literature on MRI safety for the patient [12–14]. This review aims to summarise the relevant information for the radiology community by specifically considering units of exposure, basic physical interactions, health effects and limits, dosimetry, results of exposure surveys and calculation of induced fields. The latter two will be considered with regard to the recently published ICNIRP guidelines, other existing limits and how they might inform the reworked EU directive.

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Overview of MRI technology

MRI has evolved rapidly over the past 30 years to become a major imaging modality. An estimated 60 million MRI scans are performed worldwide each year. There are currently over 500 scanners in the UK [14], the majority of which operate at 1.5 T, but 3 T scanners are proliferating in the clinical setting and a small number of 7 T scanners are emerging within universities.

MRI uses the combination of a strong static magnetic field (B_0) and pulsed gradient (G_x, G_y, G_z) fields in the extremely low frequency (ELF) and voice frequency (VF) regions, and pulsed RF magnetic fields (B_1) in the very high frequency (VHF) region. Ionising radiation, with its associated health risks, is not used. Table 1 shows the typical range of magnetic field exposures in MRI.

The static field B_0 is most commonly produced by a solenoidal superconducting magnet in a closed bore

Table 1. Typical range of magnetic field exposures in MRI

Field	Range	Frequency	Duration
Static field in bore	0.2–7 T	0 Hz	Always present.
Static fringe field gradient	0–25 T m^{-1}	0 Hz	Always present. Movement within it acts like a slowly time-varying field.
Imaging gradients	0–50 mT m^{-1}	0−>10 kHz	Multiple trapezoidal pulses of few milliseconds duration. High duty cycles. Rise time 0.1–1 ms. Slew rates up to 200 Tm^{-1}–s^{-1}.
Radiofrequency	0–50 μT	8–300 MHz	Amplitude modulated pulses of few milliseconds duration. Low duty cycle.

configuration producing a magnetic field horizontally along the bore axis. Various so-called open systems using superconductive, resistive or permanent magnets also exist, usually with a vertical field. These allow better access to the patient to provide essential care or carry out interventional procedures, and offer a less claustrophobic environment for the patient [15]. Higher field strengths offer the advantage of greater signal-to-noise ratio, which benefits most clinical applications, permitting faster scan times or higher spatial resolution, but potentially with greater artefacts [16].

The static field extends beyond the confines of the scanner bore and this fringe field is important with regard to interference with medical devices such as pacemakers. Consequently the area around the scanner is subject to strict control of access [17–18]. The rate at which the static field changes over distance, or the B_0 fringe field spatial gradient, is responsible for the magnetic attraction of ferromagnetic objects. Movement within the fringe field is deemed to be responsible for various mild sensory effects (described later) and becomes more of an issue at high field strengths. Patients and staff are routinely exposed to the fringe field of B_0.

The B_1 field is an amplitude-modulated sinusoid used to effect transitions between magnetic spin states of the nucleus, most commonly of hydrogen (^{1}H), according to the Larmor equation:

$$f = \bar{\gamma} B_0 \quad (1)$$

where $\bar{\gamma}$ is the gyromagnetic ratio of the nucleus (for ^{1}H$\bar{\gamma}$=42.57 MHz T^{-1}). The B_1 field is generated by RF transmit coils operating in the near field, applied orthogonally to B_0. The RF frequency varies between scanners of different static field strengths, and the amplitude and specific waveform of B_1 varies between different pulse sequences. The main body transmit coil is integral to the bore of the magnet. Sometimes smaller transmit coils are used for the head or extremities. B_1 also has a fringe field, which an MR worker may be exposed to when close to the bore during scanning.

To acquire an image, three orthogonal magnetic field gradients provide short-term linear variations of the z component of static magnetic field. The gradients and RF pulses together form a pulse sequence that manipulates the phase and frequency of the MR signals and encode them to enable image reconstruction, usually by two-dimensional (2D) or three-dimensional (3D) Fourier transformation. The particular waveforms, amplitudes and timings of the gradient pulses vary for different sequences, and the gradient amplitudes generally scale with the spatial resolution. There is a trend for more powerful and rapid gradient systems to enable faster scanning. This is particularly important for MRI guidance of interventions [19] and biopsies [20], especially when using open magnet systems [21]. Occupational exposure during interventional MRI has been one of the major areas of concern regarding the EU directive and exposure guidelines [2–4].

The combination of the large current pulses through the gradient coils and the static field produces significant levels of acoustic noise [22]; hence, ear protection is required for anyone in the magnet room during scanning. Staff are only exposed to the fringe fields of the gradients if they remain within the MR room during the scan acquisition. All the fringe fields from B_0, B_1 and $G_{x,y,z}$ decrease rapidly with distance from the bore entrance.

Electromagnetic fields

Units and definitions

Magnetic field intensity (H) is measured in amperes per metre (A m^{-1}). However, in MRI it is more usual to consider magnetic induction or flux density, commonly called magnetic field strength B_0, measured in tesla (T). In a medium, the magnetic flux density, B, is:

$$B = \mu_0 (1 + \chi_m) H \quad (2)$$

where μ_0, the permeability of vacuum, has a value $4\pi \times 10^{-7}$ henry m^{-1} and χ_m is the dimensionless magnetic susceptibility. Schenk [23] has provided a comprehensive overview of magnetic materials in MRI. The fringe field of B_0 varies spatially and has a gradient dB/dr measured in tesla per metre (T m^{-1}).

The imaging gradients are defined as linear spatial variations in B_z:

$$G_x = dB_z/dx; G_y = dB_y/dy; G_z = dB_z/dz \quad (3)$$

and are specified in millitesla per metre (mT m^{-1}). Within the imaging field of view the gradients produce a static magnetic field whose z-axis components are additive to B_0:

$$B_z(x,y,z) = B_0 + xG_x + yG_y + zG_z \quad (4)$$

The gradient slew rate (SR), defined in T m^{-1} s^{-1}, is given by:

$$\text{SR} = \text{maximum amplitude/rise time} \quad (5)$$

The RF field B_1 is measured in microtesla (μT), but is also specified as H_1 (Equation 2) and has an electric field component E_1. Electric fields (E) are measured in volts per metre ($V\,m^{-1}$). For a plane wave in the far field, the ratio of E/H has a constant value of 337 Ω and the power density is:

$$P = EB/\mu_0 = E^2/337 \quad (6)$$

measured in watts per square metre ($W\,m^{-2}$). The specific absorption rate (SAR) is the RF power absorbed per unit body mass ($W\,kg^{-1}$). An SAR value may apply for the whole or partial body (*e.g.* head or extremities).

In general, all the field quantities defined above (B, H, E) are vectors and may have directional components that are not used in image formation. For both patient and occupational exposure, it is important to consider the magnitude of these vector fields, *e.g.* for B:

$$|B| = \sqrt{\left(B_x{}^2 + B_y{}^2 + B_z{}^2\right)} \quad (7)$$

Exposure limits are often expressed as root mean square (RMS) values. The RMS value of a time-varying function (*e.g.* B_1 and the imaging gradients) is derived by squaring the function and then determining the mean value of the squares obtained, and taking the square root of that mean value. For a sinusoidal waveform the peak value is $\sqrt{2}$ times the RMS value.

Basic physical laws

Faraday's law of induction underpins the generation of induced fields in tissue:

$$\oint E_i.dl = -\frac{d}{dt}\int_S B{\cdot}dS \quad (8)$$

where E_i is the induced electric field around a closed path and dS is the differential area vector normal to the applied field. For a circular loop of radius, r, in a uniform medium normal to the applied field this simplifies to [24]:

$$E_i = 0.5r\ dB/dt \quad (9)$$

Thus, the magnitude of induced electric field around a closed loop in tissue is proportional to the loop radius and the rate of change of magnetic field. The induced electric field generates a current density J_i ($A\,m^{-2}$) in tissue:

$$J_i = \sigma E_i \quad (10)$$

where σ is the electrical conductivity of the tissue in siemens per metre ($S\,m^{-1}$). Both induced E_i and J_i vary linearly with the loop radius, and therefore increase with body size.

In a more realistic geometry with an elliptical body cross-section perpendicular to the magnetic field, the maximum current density was calculated by McRobbie and Foster [25] as:

$$J_{max} = \frac{a^2 b}{a^2 + b^2}\sigma\ dB/dt \quad (11)$$

where a is the semi-major axial length and b the semi-minor. The choice of axes will depend upon the orientation of the subject within the field. For a patient lying in a conventional closed bore magnet, a would be in the left–right direction and b in the anteroposterior. Typical values of a and b might be 0.2 m and 0.1 m, respectively, giving a geometric multiplier of 0.08. For a person standing close to the bore, a would be in the head–foot direction and b in the left–right; typical values for a and b are 0.4 m and 0.2 m, respectively, and the geometric multiplier would be 0.16. This latter orientation is generally the more relevant to occupational exposure.

Movement through the gradient of the static field (*i.e.* through the fringe field) effectively acts as a time-varying magnetic field. In the simplest case of a uniform body moving with a constant velocity, v, ($m\,s^{-1}$):

$$E_i = 0.5rv|dB/dr| \quad (12)$$

and therefore moving more slowly will result in lower induced fields in tissues. The elliptical geometric term (Equation 11) may also be used in place of r, with appropriate values of a and b.

Concerning the RF field B_1, for a spatially uniform rectangular RF pulse with duty cycle, D, and a uniform spherical medium of density ρ ($kg\,m^{-3}$) [26]:

$$\mathrm{SAR} = 0.5\sigma\pi^2 r^2 f^2 B_1{}^2 D/\rho \quad (13)$$

thus, SAR has a square dependence upon Larmor frequency or B_0, B_1 and patient ''radius'' and a linear dependence upon duty cycle or sequence repetition time (TR). SAR can be reduced by reducing the number of RF pulses (smaller echo-train length, fewer slices), reducing the flip angle (and hence B_1) and increasing TR.

Equations 9–13 represent an ideal geometry because the electrical properties and morphology of the human body are highly inhomogeneous and anisotropic, but they serve to illustrate general principles and are used within the established guidance [8–11] to derive some of the occupational limits for incident fields.

Health effects and occupational exposure limits

There have been a number of recent reviews of the biological effects of magnetic fields [23, 27–30] and this review will only highlight key effects relevant to MRI and occupational exposure limits. Exposure guidelines for electromagnetic fields cover the frequency range 0–300 GHz for all aspects of work-related exposure, not just MRI. The European directive formalised the 1998 ICNIRP guideline limits into a regulatory framework. The reformulated directive, postponed to April 2012, is now unlikely to become effective within UK law until 2014 [31]. MR manufacturers are already subject to self-regulation through compliance with the International Electrotechnical Commission (IEC) standard 60601-2-33 [32]. Patient exposure limits have been considered elsewhere [14, 32–35].

In most guidance, basic restrictions are set to avoid short-term acute adverse effects and are defined in terms of RMS induced electric field E_i in tissue. The United States-based Institute of Electrical and Electronics

Engineers (IEEE) has separate induced field limits for three tissue types: brain, heart and other [9,11]. New German Federal Ministry of Work and Social Affairs [Bundesministerium für Arbeit und Soziales (BMAS)] limits [36] specify exposure limit value (ELV) for whole-body induced E_i with a higher trunk-only limit for controlled situations. In the UK the National Radiological Protection Board (NRPB) basic restrictions [10], which are identical to the 1998 ICNIRP limits, are specified as RMS induced current densities J_i. The induced field limits for 0–100 kHz have complex frequency dependences, as shown in Figure 1a.

As the induced fields are not directly measurable, compliance can be demonstrated using derived reference levels (RL) (ICNIRP, NRPB), maximum permissible exposures (MPE, IEEE) or upper and lower action levels (AL, BMAS) specified in terms of the incident fields. These are commonly derived using the simple models in the Electromagnetic Fields section, particularly Equations 9–11, using a worst-case scenario or some other estimate of uncertainty. Compliance with the incident field limits is sufficient to ensure that the basic restrictions will not be exceeded. In cases where an incident field limit is exceeded, further calculation of the induced fields is necessary to demonstrate compliance with the basic restrictions. The various incident field limits for 0–100 kHz are shown in Figure 1b as RMS values. A comparison review of these and other national standards is given by Roy and Martin [37].

Static fields

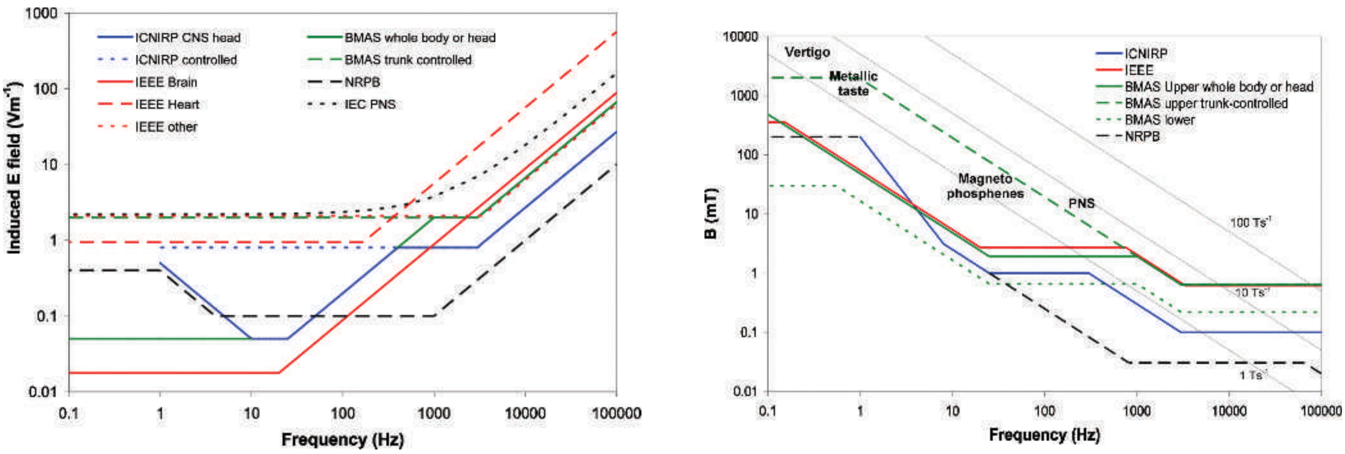
Biological effects

The principal established biological effects of static fields in and around MR scanners are dizziness, nausea, headaches, a metallic taste and visual disturbances [38–42]. Cognitive effects are extremely mild [43] or absent [39, 44]. Sensory effects are thought to arise as a consequence of head motion in the static field and have thresholds in the region of $2\,T\,s^{-1}$. Visual electrophosphenes (induced from currents passed through tissue via external electrodes) have been used by ICNIRP to provide the lowest limit value of $50\,mV\,m^{-1}$ for 10–25 Hz. Magnetophosphenes (induced by time-varying magnetic fields without direct electrical connection) have a peak sensitivity for a *dB/dt* of approximately $1.5\,T\,s^{-1}$ occurring within the frequency range 10–20 Hz [45]. The approximate loci of these and other sensory effects with regard to stimulus amplitude, frequency and rate of change (*dB/dt*) are shown in relation to the incident field limits in Figure 1b.

Occupational limits

Occupational limits for static fields are shown in Table 2. ICNIRP has a 2 T ceiling, but allows for peak exposures of up to 8 T in controlled situations [46]. Notably the EU directive did not have an ELV for static fields—only an action value of 200 mT, which was applied as a ceiling rather than a time-weighted average (TWA), as in the NRPB guidelines [10]. With a time-averaged limit of 200 mT applied to an 8 h day, a worker, for example, could be exposed to 1.5 T for up to 64 min, but 3 T for only 32 min. The IEEE limit [9] applies for a slowly varying sinusoidal field of <0.153 Hz and is given as an RMS value, but in Table 2 it is converted to a peak value for comparison. IEC 60601-2-33 [32] operates a three-tier system of limits, with the limit shown being the first (intermediate) level controlled operating mode.

Movement of persons within the static fringe field gradient ($|dB/dr|$) will induce fields within tissues, and these may exceed some low-frequency exposure limits. For example, a movement that takes 1 s could be related to a frequency of 1 Hz, whereas more rapid movements relate to higher frequencies. Table 3a shows the induced and incident field limits that are most relevant to movement within the static field gradient. These limits are presented here as peak rather than RMS values as these are more relevant to MRI, and the basic restrictions



(a) (b)

Figure 1. Induced and incident field limits up to 100 kHz. All values are RMS except BMAS (peak). (a) Basic restrictions and exposure limit values. NRPB values have been recalculated as induced electric field for a CNS tissue conductivity σ=0.1 S m^{-1} [10]. (b) Reference levels, action levels and maximum permissible exposures. Lines of constant *dB/dt* (oblique dashed lines) and approximate regions for sensory effects are shown after Glover et al [38]. BMAS, Bundesministerium für Arbeit und Soziales; CNS, central nervous system; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEC, International Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; NRPB, National Radiological Protection Board; PNS, peripheral nerve stimulation; RMS, root mean square.

Table 2. Static field limits for occupational exposure. All values peak

Institution	Whole body—time-weighted average (T)	Trunk and head—instantaneous ceiling (T)	Limbs (T)
IEEE [9][a]		0.5	0.5
NRPB [10]	0.2	2	5
ICNIRP [44]		2[b]	8
BMAS [36]		2[b]	8
IEC (first level) [32]		4	4

BMAS, Bundesministerium für Arbeit und Soziales; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEC, International Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; NRPB, National Radiological Protection Board.
[a]For $f<0.153$ Hz the limit is 353 mT root mean square.
[b]For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.

for NRPB are shown in terms of induced electric field rather than current density as published [assuming a central nervous system (CNS) tissue conductivity of $0.1\,\mathrm{S\,m^{-1}}$ [10]]. Both ICNIRP and BMAS have a general basic restriction based on the avoidance of all acute sensory effects, and a less stringent one applicable to a controlled situation, where the worker is conversant with the possible effects and may control his or her movement. Equivalent values of *dB/dt* are shown in the final column of Table 3a. In frequency ranges where the incident field limit has a $1/f$ dependence, the equivalent maximum *dB/dt* is constant [47, 48].

To illustrate the extent of variations between the guidelines, we can compare incident field limits for a movement, *e.g.* head nodding with a notional frequency of 1 Hz (0.5 s upward motion, followed by 0.5 s down, repeatedly); this gives limit values of 48 mT (BMAS), 76.8 mT (IEEE) and 280 mT (NRPB, ICNIRP), which gives an overall a range of nearly 6 times. For the induced field limits we have the extremes of $0.025\,\mathrm{V\,m^{-1}}$ (IEEE) to $0.7\,\mathrm{V\,m^{-1}}$ (ICNIRP), which gives a range of 28 times.

Time-varying fields up to 100 kHz

Biological effects

Time-varying field exposure from the imaging gradients is one of the best studied aspects of biomagnetism. Glover [30] has provided a recent MR-related review. The basic effects are stimulation of the CNS or peripheral nervous system and other electrically excitable tissues. ELF time-varying magnetic fields are used in clinical practice to purposely induce peripheral (motor nerves and skeletal muscle) and central (cerebral cortex) nerve stimulation in humans [49]. Much greater exposures are achievable than in MR scanners. Disruption of respiration [50] in humans and cardiac stimulation [51, 52] in dogs has been demonstrated, but, notably, ventricular fibrillation has not.

The basic law of magnetic stimulation is largely analogous to electrical stimulation resulting in the magnetic strength duration (SD) curve first demonstrated by McRobbie and Foster [53]:

$$(dB/dt)_{\mathrm{thresh}}(\tau)=(dB/dt)_{\mathrm{rheo}}/(1-e^{-\tau}/t_c) \quad (14)$$

where $(dB/dt)_{\mathrm{rheo}}$ is the rheobase or the minimum stimulation threshold for long stimuli, τ is the stimulus duration and t_c is the cell membrane time constant. Time constants vary according to tissue type; peripheral motor nerves have time constants of the order of 0.1 ms, while cardiac muscle has t_c in the region 2–3 ms and synapses up to 25 ms [54]. The alternative Weiss–Lapicque [55] hyperbolic form for the SD curve is sometimes used. Expressed below in terms of induced E_i this is:

$$E_{\mathrm{thresh}}(\tau)=E_{\mathrm{rheo}}(1+c/\tau) \quad (15)$$

where c is the chronaxie or the stimulus duration for a threshold double the rheobase. The forms for Equations

Table 3a. Low frequency occupational exposure limits relevant to movement within the static field. All values are peak. Italics denote derived values. For simplicity *H* field limits are omitted. They can be calculated from Equation 2

	Induced fields: basic restriction			Incident fields: reference level/AL/MPE			
Institution	Tissue/region	Frequency (Hz)	Induced E_i ($\mathrm{Vm^{-1}}$)	Tissue/region	Frequency (Hz)	*B* (mT)	Equivalent dB/dt ($\mathrm{T\,s^{-1}}$)
IEEE[a] [9]	Brain	<0.153	0.025	Head and torso	<0.153	500	*3.1 f*
	Brain	0.153–20	0.025	Head and torso	0.153–20	76.8/f	*0.48*
NRPB [10]	Head and trunk[b]	<1	*0.56*	Body[c]	0–1	280	*1.8 f*
ICNIRP[d] [8]	Head CNS	1–10	0.7/f	Body[d]	1–8	280/f[b]	*1.8/f*
	All head and body[e]	1–3000	1.1				
BMAS[e] [36]	Whole body or head	0–25	0.05	Whole body or head	0.024–25	48/f	*0.3*
	Trunk/controlled[f]	0–25	2.0	Trunk/controlled[f]	0.96–25	1920/f	12

AL, action level; BMAS, Bundesministerium für Arbeit und Soziales; CNS, central nervous system; f, frequency; h ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEEE, Institute of Electrical and Electronics Engineers; MPE, maximum permissible esposure; NRPB, National Radiological Protection Board.
[a]E_i arithmetic average determined over a straight line segment of 0.5 cm length orientated in any direction within the tissue.
[b]Based upon $J=40\,\mathrm{m\,Am^{-2}}$ for CNS conductivity of $0.1\,\mathrm{S\,m^{-1}}$ [10].
[c]Spatial average over body. Reference level may be exceeded locally, but BR must not.
[d]E_i spatially averaged over $2\times2\times2\,\mathrm{mm^3}$.
[e]BMAS action values shown are upper action value.
[f]Trunk only in controlled situation.
Italics indicate derived rather than primary measured values.

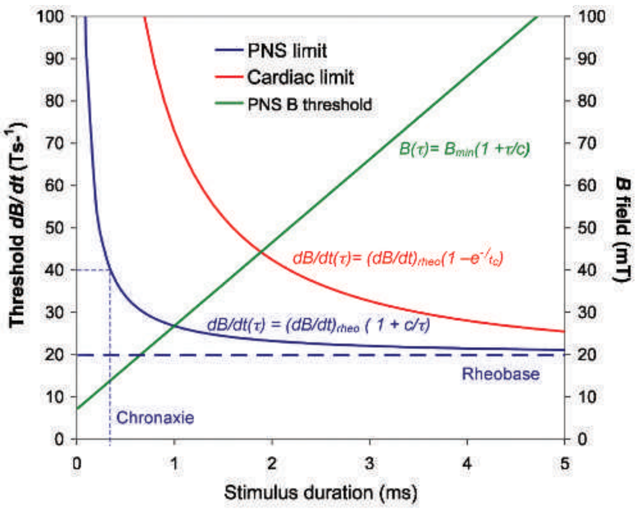


Figure 2. Strength-duration curves for *dB/dt* and *B*. Peripheral nerve stimulation (PNS) curve is the 100% median threshold following the hyperbolic form (Equation 15) with rheobase and chronaxie indicated. The cardiac curve includes a factor of three safety margin, following the exponential form (Equation 14). Both curves are from the International Electrotechnical Commission [32]. The second axis shows the *B* field stimulus for PNS (Equation 16).

14 and 15 are shown in Figure 2. In both versions the minimum stimulation threshold in either *dB/dt* or induced E_i (or current density J_i) occurs for long stimulus durations or for low frequencies. For longer stimuli (lower frequencies) a larger amplitude of *B* field (in comparison to its rate of change) is required to achieve stimulation.

An alternative approach is to consider the *B* field as the stimulus, in which case [56]:

$$B(\tau) = B_{\min}(1 + \tau/c) \qquad (16)$$

where $B_{\min}$ is the minimum changing field to cause stimulation in the limit of a very short or high-frequency stimulus, as shown in Figure 2, for the IEC peripheral nerve stimulation curve.

Many authors have investigated peripheral nerve stimulation perception thresholds for various combinations of axes on whole-body MR gradient systems [57–62]. By taking an average of all these results, we can deduce a peripheral nerve stimuation rheobase for *dB/dt* of $19.9 \pm 3.9\,\mathrm{T\,s^{-1}}$ and a chronaxie of 0.5 ± 0.14 ms. For a circular body cross-section with r=0.2 m perpendicular to the *dB/dt* field and an average tissue conductivity, σ, of $0.2\,\mathrm{S\,m^{-1}}$ [32], we can calculate (from Equations 9 and 10) the rheobase for E_{i} and J_{i} to be in the region of $2\,\mathrm{V\,m^{-1}}$ and $0.4\,\mathrm{A\,m^{-2}}$, respectively. Applying Equation 16 indicates a B_{min} of 10 mT for very short stimuli. This means that, in terms of the change in *B* field, peripheral nerve stimulation, and not magnetophosphenes, has the lowest threshold as is indicated in Figure 1b.

The threshold for discomfort or pain from peripheral nerve stimuation is approximately 50–100% higher than the perception threshold [63]. The longer time constant for heart tissue and the smaller conduction loops make direct cardiac stimulation extremely unlikely with an estimated *dB/dt* rheobase for the most sensitive percentile of the population of $62\,\mathrm{T\,s^{-1}}$ [32]. It is estimated that at least 50 times the electrical stimulus for cardiac stimulation is required to cause ventricular fibrillation [54].

Occupational limits

Table 3b shows the occupational exposure limits most relevant to the imaging gradients. The values are all expressed as peak values, with equivalent *dB/dt* shown in the final column. The IEEE basic restrictions are specific to body part—brain, heart and other—while ICNIRP's are for CNS tissues in the head or for any tissue in a controlled situation. BMAS also have a general and a controlled exposure limit value. The NRPB basic restrictions are here reinterpreted as induced electric fields (using $\sigma=0.1\,\mathrm{S\,m^{-1}}$). The various incident field limits generally apply to the whole body. BMAS has a lower and upper action level.

The final column shows the equivalent peak *dB/dt* limits. For ICNIRP this is constant ($2.6\,\mathrm{T\,s^{-1}}$) over the frequency range 300–3000 Hz, most relevant to certain fast MRI sequences. IEC 60601-2-33 stipulates that the MR worker should not experience peripheral nerve stimulation and, in the absence of experimental data from a specific MR system, proposes a rheobase of $2.2\,\mathrm{V\,m^{-1}}$ or $20\,\mathrm{T\,s^{-1}}$ and chronaxie of 0.36 ms, as shown in Figures 1a and 2.

Comparing the incident field limits at a notional frequency of 1 kHz, appropriate to an echo-planar imaging (EPI) acquisition, we have 0.043 mT (NRPB), 0.42 mT (ICNIRP), 1.92 mT, (BMAS) and 2.91 mT (IEEE), which is a range of 68 times. For the induced field limits we have $0.56\,\mathrm{V\,m^{-1}}$, (NRPB), $1.1\,\mathrm{V\,m^{-1}}$ (ICNIRP), $2\,\mathrm{V\,m^{-1}}$ (BMAS), $2.97\,\mathrm{V\,m^{-1}}$ (IEEE, other) and $3.78\,\mathrm{V\,m^{-1}}$ (IEC), which is a range of seven times. In terms of *dB/dt* the IEC limit would be $23.6\,\mathrm{T\,s^{-1}}$ (using a geometric factor of 0.16 from Equation 11) compared with $12\,\mathrm{T\,s^{-1}}$ for BMAS, but only $2.6\,\mathrm{T\,s^{-1}}$ for ICNIRP, which is a discrepancy of 13 times.

Radiofrequency exposures

Biological effects

RF effects in MRI have been reviewed previously [26, 64]. The main effect of acute EMF exposures in the RF region is tissue heating. ICNIRP has recently stated that "the plausibility of the various non-thermal mechanisms that have been proposed is very low" and reconfirms its exposure limits for frequencies over 100 kHz [65].

Occupational limits

Both ICNIRP and IEEE define their basic restrictions in terms of whole-body SAR as $0.4\,\mathrm{W\,kg^{-1}}$ time-averaged over 6 min. This is one-tenth of the upper limit suggested for patients, deemed to restrict core body temperature rise to $\leq 1^{\circ}$C. Also specified are localised (over 10 g of tissue) SAR limits of $10\,\mathrm{W\,kg^{-1}}$ for the head and trunk and $20\,\mathrm{W\,kg^{-1}}$ for the limbs. The IEEE incident field limits have a frequency, and therefore scanner $B_{0,}$ dependence. The IEC standard allows the MR worker to receive the same RF exposure as the patient, *i.e.* a whole body SAR of up to $4\,\mathrm{W\,kg^{-1}}$ [32]. The limits relevant to various scanner field strengths are given in Table 4.

Table 3b. Occupational exposure limits relevant to the imaging gradients. All values are peak. Italics denote derived values. For simplicity *H* field limits are omitted. They can be calculated from Equation 2

	Induced fields: basic restriction			Incident fields: reference level/AL/MPE			
Institution	Tissue/ region	Frequency (Hz)	Induced E_i ($V m^{-1}$)	Tissue/ region	Frequency (Hz)	*B* (mT)	Equiv *dB/dt* ($T s^{-1}$)
IEEE[a] [9]	Brain	0–20	0.025	Head and torso	20–759	3.83	*0.024 f*
		20–3350	0.00125 f				
	Heart	0–167	1.33	Head and torso	759–3350	2913/f	*18.3*
		167–3350	0.008 f				
	Other	0–3350	2.97	Head and torso	$3350–5\times10^6$	0.870	*5.5×10^{-3} f*
		3350 –	0.886×10^{-3} f				
NRPB[b] [10]	Head and	4–1000	*0.28*	Body[c]	25–820	35/f	*0.22*
	trunk	1000–100000	*$f/14\times10^3$*		820–65000	0.043	*0.27×10^{-3} f*
ICNIRP[d] [8]	CNS head	25–400	2.8×10^{-3} f	Body[d]	25–300	1.4	*8.8×10^{-3} f*
		400–3000	1.1		300–3000	420/f	*2.6*
	All[e]	1–3000	1.1				
BMAS [36]	Whole body	25–1000	2×10^{-3} f	Whole body or head	25–1000	1.92	*0.012 f*
		1000–3000	2		1000–3000	1920/f	*12*
	Trunk[f]	25–3000	2	Trunk[f]	0.96–3000	1920/f	*12*

AL, action level; BMAS, Bundesministerium für Arbeit und Soziales; CNS, central nervous system; f, frequency; h ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEEE, Institute of Electrical and Electronics Engineers; MPE, maximum permissible exposure; NRPB, National Radiological Protection Board.
[a]E_i arithmetic average determined over a straight line segment of 0.5 cm length orientated in any direction within the tissue.
[b]Based upon $J=40\ m A m^{-2}$ for a tissue conductivity of $0.1\ S m^{-1}$ [10].
[c]Spatial average over body. Reference level may be exceeded locally, but basic restriction must not.
[d]Vector average E_i over contiguous tissue volume of $2\times2\times2\ mm^3$.
[e]Controlled environment.
[f]Controlled environment, upper action level.
Italics indicate derived rather than primary measured values.

Interpreting the limits for MRI

All the limit values for incident and induced time-varying EMF exposures apply to single-frequency sinusoidal fields, and in the case of RF limits, plane waves. None of these conditions are valid for MRI. For non-sinusoidal pulses, in the region 1–100 kHz, one approach advocated by ICNIRP [47] is to apply the limits to each frequency component present in the waveform:

$$\sum_{f_{\min}}^{f_{\max}} \frac{B_i}{L_i} \leq 1 \tag{17}$$

where B_i are the individual frequency components of the field, L_i the appropriate limit values and f_{min} and f_{max} define the frequency range. This can lead to overly conservative limits, as it assumes a coherent phase between the spectral components [48].

An alternative approach is the weighted *dB/dt* method [47, 48], which uses the property that the maximum value of the time derivative of a sinusoid $B\sin(2\pi ft)$ is $|2\pi f B|$ to deduce the peak *dB/dt* limit relating to limit B_L as:

$$(dB/dt)_{pk} = \sqrt{2}2\pi f B_L \tag{18}$$

For the frequency range where the incident field limit has an inverse relationship to frequency, its time derivative *dB/dt* will be constant and the peak *dB/dt* may be used to test compliance even for complex waveforms. The other frequency ranges of the limits can be investigated by using a measurement instrument with a high- or low-pass

Table 4. Radiofrequency limits for occupational exposure as applicable to MRI. All time-averaged over 6 min

			Basic restriction	Reference level, limit or maximum permissible exposure			
Institution	Scanner B_0	Frequency (MHz)	SAR ($W kg^{-1}$)	*E* ($V m^{-1}$)	*H* ($A m^{-1}$)	*B* (µT)	Power density ($W m^{-2}$)
ICNIRP [8] NRPB [10]	Any	10–400	0.4	61	0.16	0.2	10
IEEE[a,b] [11]	1T	42.57	0.4	61.4	0.163		55.2
	1.5T	63.9		61.4	0.163		25.5
	3T	127.7		61.4	0.128		10
	7T	298.0		61.4	0.0547		10
IEC[c] [32]	Any	All f_0	4				

f, frequency; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEC, International Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; NRPB, National Radiological Protection Board; SAR, specific absorption rate.
[a] IEEE power density limit 10–100 MHz is $10^5/f^2\ W m^{-2}$.
[b] IEEE *H* field limit 100–300 MHz is 16.3/f A/m.
[c] The maximum allowed specific absorbed energy is $14.4\ kJ\ kg^{-1}$.

filter that matches the frequency weighting of the reference level. Applying this approach, the ICNIRP reference level becomes 2.6 T s^{-1} from 300 to 3000 Hz. Similarly, the IEEE head and trunk MPEs below 20 Hz become 0.48 T s^{-1} and for the heart below 3.325 kHz become 18.4 T s^{-1}. Equivalent *dB/dt* limits are shown in the final column of Table 3a,b. This methodology is particularly useful for MRI where gradient waveforms are usually of trapezoidal form with multiple harmonics but a single peak *dB/dt*.

Measurement of electromagnetic fields

Static field

The static magnetic field can be measured using a hall-effect gaussmeter. It is important to recognise that although MRI is only sensitive to the *z*-component, B_z, other components, B_x and B_y, may also be present, particularly in the fringe field, and therefore three-axis probes are required. Commercial gaussmeters are capable of measuring up to 2 T with a resolution of 0.01 mT, which is sufficient to plot the fringe field outside the bore for a clinical 3 T MR system. Careful zeroing of the probe is required prior to its use near an MR facility. The earth's field is approximately 0.05 mT. Fringe field measurements are often carried out on new systems to verify the position of the 0.5 mT (pacemaker) limit. All equipment should be calibrated to traceable standards.

Static fringe field and fringe field gradient plots are provided in manufacturers' compatibility statements. In addition, IEC60601-2-33 requires MR manufacturers to indicate the locations of the highest spatial gradient of the static field and the largest value of the product of static field and its spatial gradient where projectile effects are at their greatest.

Time-varying gradient fields

The imaging gradient fringe fields inside and outside the magnet bore can be measured using instruments based upon a search coil [32] giving direct measurement of *dB/dt* from:

$$dB/dt = V/(nA) \qquad (19)$$

where V is the induced voltage, n the number of turns and A the coil area. More sophisticated commercial instruments allow three-axis vector measurement and use an integrator to provide readings of magnetic flux density, B. Some instruments also use the weighted *dB/dt* method of checking compliance with the older ICNIRP limits [47]. These instruments will require recalibration to apply to the current RLs. Nominal sensitivities of 1 nT, with a range up to tens of millitesla, are achievable to frequencies well over 100 kHz. The Institute of Physics and Engineering in Medicine (IPEM) has recently published a review of measurement techniques and technology for EMF exposure [66].

Radiofrequency fields

A search coil will enable the measurement of B_1 outside the bore of the magnet and may be used to demonstrate compliance with the B_1 RL and MPEs of Table 4. As the RF exposure occurs in the near field, independent measurement of E_1 and H_1 is required. Commercial systems have three-axis dipoles (for *E*) and loops (for *H*) with sensitivities up to approximately 0.01 V m^{-1} and 0.01 mA m^{-1}. Measurement of SAR requires a phantom containing tissue-equivalent material. IEC 60601-2-33 also defines methodologies for assessing temperature rise (in a phantom) and SAR or RF pulse energy calculation from forward and reflected power measurements from the RF transmission system [32]. A device for monitoring SAR, which does not involve a phantom, has recently been proposed [67], although it may not be sensitive enough to monitor occupational exposure outside the magnet bore. IPEM reports 98 reviews of RF measurement equipment [66].

Staff dosemeters

Monitoring of staff directly requires the ability to measure static and time-varying magnetic fields. Several commercial and bespoke devices have used a combination of Hall effect sensors, induction coils and integrators [68–72] to measure *B* and *dB/dt* or, uniquely, to measure the induced E_i field directly [73]. Any monitoring device must be lightweight, unobtrusive, non-ferromagnetic and have sufficient battery life for at least one work shift. An isotropic spatial response and an appropriate frequency response and sampling rate are required, particularly if *dB/dt* from the imaging gradients is to be monitored. Possible dose metrics are peak static field, TWA static field, field-time product and instantaneous and peak *dB/dt*, along with its spectral components. RF personal dosemeters also exist [66], but there has been no report of their use in MRI.

Field survey results

Static field

Static field surveys [6, 74] show that 200 mT (the action value for 0 Hz in the original EU directive and the current ICNIRP RMS reference level below 1 Hz) is exceeded at approximately 0.5 m from the bore opening for most 1.5 T and 3 T systems (Table 5). Of particular interest are open MR systems where, although the 200 mT field contour is very close to the edge of the scanner, an MR worker may be wholly or partially within the bore [6, 75]. The 500 mT contour (IEEE MPE for $<$0.153 Hz) lies in the region 0.2−0.3 m from the bore entrance. Capstick et al [6] measured the field throughout a 3D gridded volume within the MR examination room, and from these measurements calculated the fringe field gradient. Examples are shown in Figures 3a,b.

Time-varying gradient fields

The fringe field of the gradients was the original point of contention with both the 1998 ICNIRP guidance and the European directive. Early measurements involving a single search coil established that significant gradient fringe fields exist beyond the bore of the scanner [76]. These results have been extended using three-axis calibrated meters [6, 70, 74,

Table 5. B_0 fringe field measurements (from bore entrance)

B_0 (T)	System	B_0 at bore entrance (T)	Distance on *z*-axis to 200 mT (m)	Distance on *z*-axis to 500 mT (m)	Reference
1.0	Philips Panorama[a] (Philips Healthcare, Best, Netherlands)	0.2	1.35[a]	0.90[a]	Capstick et al [6]
1.5	Philips Intera (Philips Healthcare)	0.9	0.42	0.19	Riches et al [74]
1.5	Siemens Avanto (Siemens Healthcare)	0.9	0.45	0.21	Capstick et al [6]
3.0	Philips Achieva (Philips Healthcare)	1.2	0.55	0.27	Capstick et al [6]
7.0	Philips Intera (unshielded) (Philips Healthcare)	1.9	1.50	0.68	Capstick et al [6]

[a]Distance measured from isocentre.

77–80]. Table 6 summarises all the known results for exposure measurements at the entrance of the bore in terms of peak *B*, *dB/dt* or percentage of the ICNIRP and NRPB (old ICNIRP) RLs. While the old (NRPB) RLs were readily exceeded for many pulse sequences, the new ICNIRP RL is rarely exceeded outside the bore.

In general, fast sequences [*e.g.* EPI, balanced turbo field echo (b-TFE), balance fast field echo (b-FFE), true fast imaging with steady state precession (TrueFISP)] had higher peak *dB/dt*. However, it should be noted that some systems are programmed to use the highest possible SR, making the peak *dB/dt* more independent of the sequence type. For the open systems [Fonar Upright Multi-Position MRI (Fonar, Melville, NY) and Philips Panorama (Philips Healthcare, Best, Netherlands)], where it is possible for MR staff to have a significant part of their head or trunk within the bore, much greater exposures may occur [6, 78, 79]. For the other scanners, bore length is important, with the very long bore of the 7 T scanner ensuring that the fringe field of the gradients is negligible outside the bore [6]. In general, all these studies used parameters from typical clinical scan protocols. The exposure values scale with various factors including pixel size, field-of-view [74], slice thickness and orientation, bandwidth, echo time and acoustic noise reduction [80]. Figure 4 shows the instantaneous |*dB/dt*| (vector sum for all gradients) for various sequences from one system measured at the bore entrance [6]. In addition to *z*-axis measurements, Capstick et al [6, 78] also measured the gradient fringe fields from a test sequence throughout a 3D volume.

The fundamental frequency of the sequences ranged from as low as 80 Hz (turbo spin-echo) to 1 kHz (EPI). Most of the fast sequences relevant to interventional MRI (*b*-TFE, *b*-FFE, TrueFISP) had fundamental frequencies in the range 300–500 Hz, appropriate to the application of the ICNIRP *dB/dt* limit of 2.6 $\mathrm{T\,s^{-1}}$. Figure 5 shows the frequency components of two different MR sequences on different scanners. In both cases, there are significant harmonic components. For establishing compliance with the RLs, the weighted *dB/dt* or the summation of Fourier components can be used [46, 47]. The summation method (Equation 17) results in significantly greater estimations of exposure than either the weighted *dB/dt* or RMS value of the fundamental frequency [74].

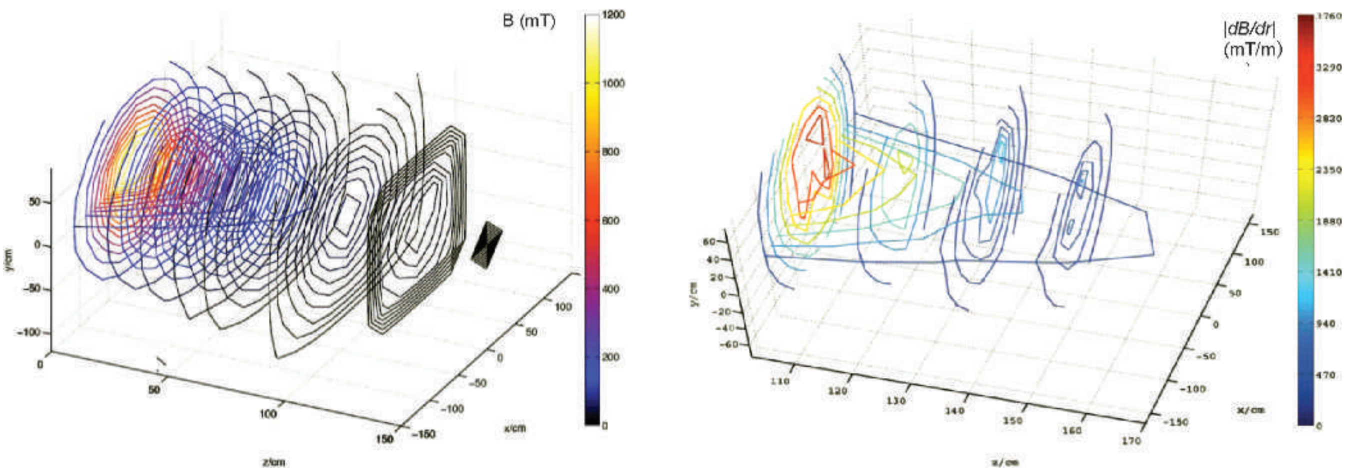
Radiofrequency field

The RF fringe field has received much less attention, but has been assessed for an RF-dense TSE sequence used for MRCP examinations [77] and a bespoke test sequence on a range of scanners [6, 78]. Table 7 shows that RLs can be exceeded close to the bore, within 0.45 m for an open scanner and 0.2 m for a short closed bore system.

Staff survey results

Time-motion studies

Capstick et al [6] observed staff during real clinical procedures using an MR-compatible two-camera video system and, combined with their 3D volumetric field measurements, characterised staff exposure during actual clinical activities in a 1 T open and 1.5, 3 and



(a) (b)

Figure 3. (a) Static field contours and (b) static field gradient contours from a 3 T MRI system. Centre of bore entrance is at position (0,0,0). With permission from Capstick et al [6].

Table 6. *B* and *dB/dt* fringe field values and percentage limit exposures from the imaging gradients. Negative distance indicates distance into the bore

B_0 (T)	System	|B|RMS (μT)	Peak *dB/dt* ($T s^{-1}$)	% ICNIRP reference levels	% NRPB reference levels	Distance from bore entrance (m)	Sequence	Fundamental frequency	Reference
0.6	Fonar Upright Multi-Position (Fonar, Melville, NY)		0.22	8.5	100	0.06	Angio	Unknown, used 25–820 Hz *dB/dt* NRPB limit	Bradley et al [70]
			0.22	8.5	100	0.18	Intertrak		
			0.22	8.5	100	0.30	FSE		
1.0	Philips Panorama (Philips Healthcare, Best, Netherlands)		0.31	12	141	0.0	DW–EPI	450 Hz	Capstick et al [6,78]
			0.32	12	145	0.0	b-TFE	260 Hz	
			0.28	11	127	0.0	TSE	80 Hz	
			12.0	(462)	(5450)	−0.93[a]	DW–EPI	450 Hz	
1.0	Philips Panorama		0.1	3.8	45	0.0	EPI	Unknown, used 25–820 Hz *dB/dt* NRPB limit	Kännälä [79]
			2.0	77	909	−0.75[b]	EPI		
1.5	Siemens Vision (Siemens Healthcare, Erlangen, Germany)		3.6	138	1636	0.0	Custom	390 Hz sine wave $20 T m^{-1} s^{-1}$	McRobbie [76]
1.5	GE Signa Twin (GE Healthcare, Little Chalfont, UK)		1.14	44	518	0.0	EPI	Unknown, used 25–820 Hz *dB/dt* NRPB limit	Bradley [70]
			0.44	17	200	0.0	SE		
1.5	Unspecified A	1500		141	1280	0.0	b-FFE	300 Hz	Riches [74]
1.5	Unspecified B	700		85	720	0.0	b-FFE	360 Hz	Riches [74]
1.5	Philips Intera (Philips Healthcare)	650		110	930	0.0	FFE	500 Hz	Riches [77]
1.5	Siemens Avanto[c] (Siemens Healthcare)		1.98	76	900	0.15[d]	DW–EPI, TrueFISP	670 Hz	Capstick [6]
			1.99	77	905	0.15		400 Hz	
1.5	Siemens Espree (Siemens Healthcare)	39	*0.55*	20	250	+0.3	TSE	Unknown, used 25–820 Hz *dB/dt* NRPB limit	Wilen [80]
		100	*0.77*	29	350	+0.3	TrueFiSP		
		71	*0.44*	16	200	+0.3	EPI		
		33	*0.38*	14	173	+0.3	TSE		
		94	*0.52*	19	236	+0.3	TrueFiSP whisper		
3.0	Philips Achieva[c] (Philips Healthcare)		0.31	12	141	0.11	TSE	100 Hz	Capstick [6]
			0.81	31	368	0.11	b-FFE	240 Hz	
			1.1	42	500	0.11	DTI	710 Hz	
			1.69	65	768	0.11	EPI	1 kHz	
3.0	Philips Achieva		1.6	62	727	0.0	EPI	Unknown, used 25–820 Hz *dB/dt* NRPB limit	Kännälä [79]
7.0	Philips Intera[a]	662	1.68	<<RL	<<RL	−0.85	EPI	500 Hz	Capstick [6]
		350,	1.47	<<RL	<<RL	−0.85	TSE	96 Hz	
		510	1.78	<<RL	<<RL	−0.85	perfusion	770 Hz	

b-FFE, balanced fast field echo; b-TFE, balanced turbo field-echo; DTI, diffusion tensor imaging; DW–EPI, diffusion weighted echo-planar imaging; FSE, fast spin echo; NRPB, National Radiologiacal Protection Board; SE, spin echo; TrueFISP, True fast imaging with steady state precession; TSE, turbo spin echo.

[a] 0.3 m from isocentre.
[b] 0.5 m from isocentre.
[c] 0.95 m from isocentre.
[d] 0.95 m from isocentre.
[e] 0.85 m from isocentre, 0.85 m into bore.

Italics indicate derived rather than primary measured values.

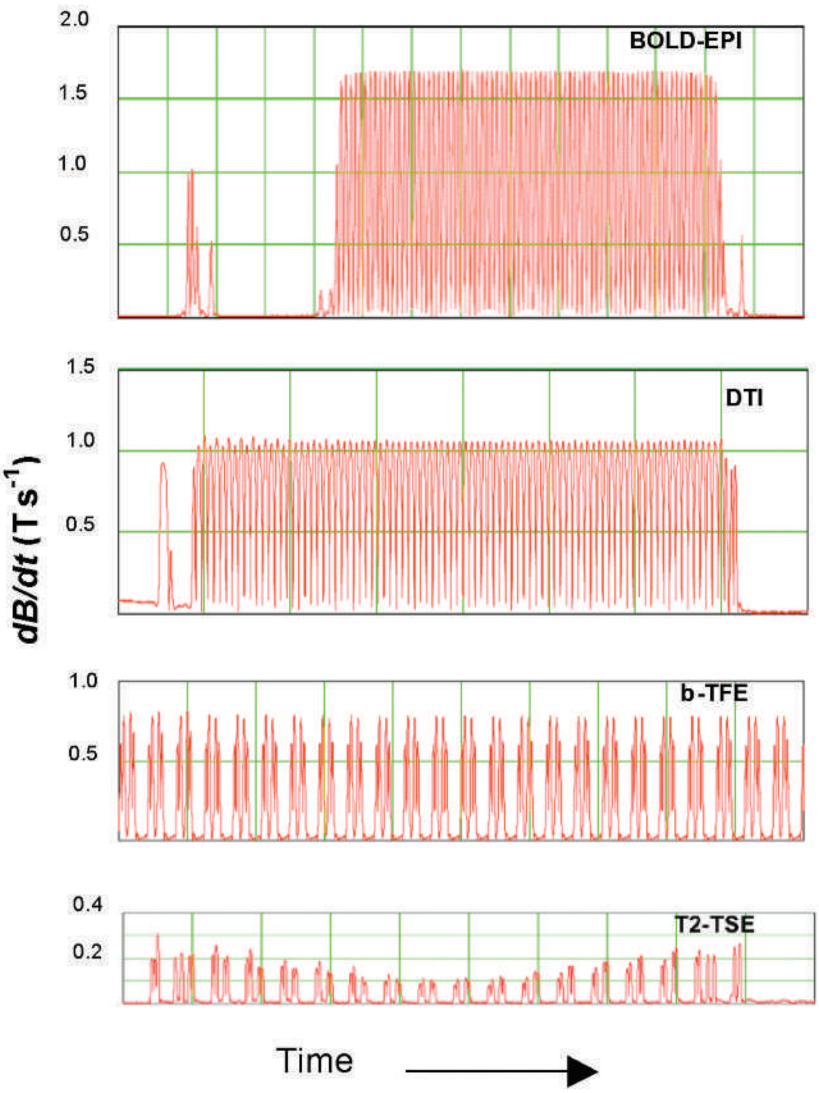


Figure 4. Instantaneous *dB/dt* from the imaging gradients (vector sum of all gradients) measured outside the bore 95 cm from the isocentre: BOLD-EPI, BOLD-echo planar imaging; DTI, diffusion tensor imaging; b-TFE, balanced turbo-field echo; TSE, turbo spin-echo. With permission from Capstick et al [6].

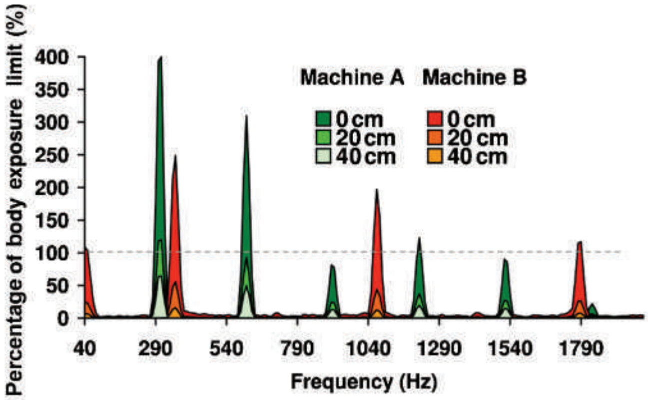
7 T closed-bore scanners. They measured the position, velocity and exposure times for the key staff member (*e.g.* radiographer, anaesthetist, interventionalist or cleaner) and determined the maximum and mean static field, maximum static field gradient ($|dB/dr|$), maximum B, dB/dt and fundamental frequency from the imaging gradients, B_1, H_1 and E_1 (time-averaged over 6 min). From these they were able to calculate induced currents in tissue from movement and imaging gradients, and the SAR from simple models (Equations 9–13) or by complex numerical modelling (Modelling of induced fields in tissue section).

The largest velocities occurred for emergency evacuation of the patient (range, 0.8–2.3 m s^{-1}). Other velocities recorded for both head and body lay in the range 0.2–2.0 m s^{-1}. Figure 6a [81] summarises the results for B, both from the static field and the gradients shown, with respect to the various incident field limits. All the static field limits were exceeded for all the activities at 7 T and a majority of the others. ICNIRP RLs for exposure from the imaging gradients were exceeded for clip insertion (by 7% with a sequence fundamental frequency of 260 Hz) and monitoring patients under general anaesthesia (by 16% for a fundamental frequency of 670 Hz). None of the exposures exceeded the relevant IEEE or BMAS incident field limits.

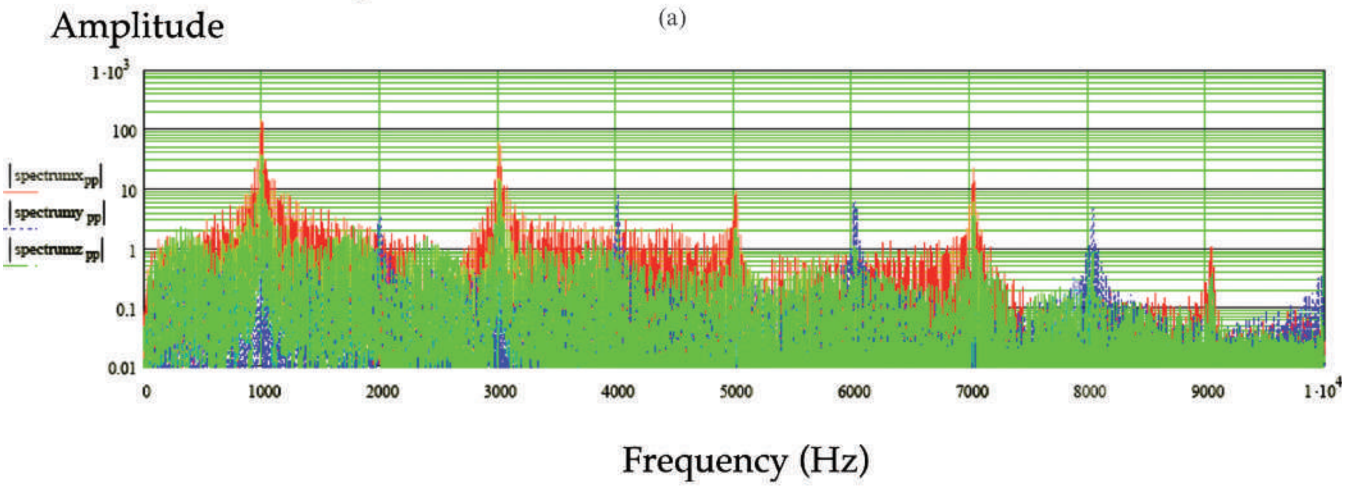
For non-sinusoidal waveforms, it is better to consider *dB/dt* as shown in Figure 6b for movement and imaging gradient exposures. Most movement-related exposures exceeded the various low frequency limits. Imaging gradient *dB/dt* exceeded the ICNIRP RL (300–3000 Hz) for the clip insertion by 1.9 times. This is in marked contrast to the NRPB limits, which were exceeded in several of the out-of-bore procedures.

In no instance was a RF reference level exceeded, although for the breast intervention this was largely due to time averaging (the procedure only lasted 42 s).

A similar study was carried out for MRI engineers [40] where the speed of movement for particular actions correlated with the occurrence of sensory effects. Riches et al [74] also examined movement in the static field and concluded that, for the 1.5 T systems, examined staff should restrict their velocity to $<$0.26 m s^{-1} to comply with the NRPB (ICNIRP 1998) basic restrictions. Assuming a movement equivalent to a 1 Hz changing B field, this translates to 0.32 m s^{-1} in order to comply with the new ICNIRP limits, with a velocity of up to 0.5 m s^{-1} permitted in a controlled situation. It has been shown that staff do exceed this velocity and consequently will have exposures exceeding the reference level [6].



(a)



(b)

Figure 5. Examples of spectral content of pulse sequences. (a) Balanced SSFP from Riches et al [74]; (b) echo planar imaging from Capstick et al [6], with permission.

Dosimetry studies

There are two substantive studies where EMF dosemeters were worn by MRI radiographers and technologists while they undertook routine duties. In an Oxford-based study [70] static fields were measured in four closed bore systems of 1.5 T, one closed bore system of 3 T and one open 0.6 T magnet. Staff carried the dosemeter in the pocket closest to the magnet. Peak and 24 h time-averaged *B* fields were reported. The Queensland study [5, 71] involved thee clinical 1.5 T scanners and research systems at 2 T and 4 T. Peak *B*, peak *dB/dt* and average *B* over the shift were reported. The results are summarised in Table 8 where the time-weighting from the Oxford study has been recalculated over 8 h for consistency.

The average maximum instantaneous exposure from both studies combined was 42 ± 24% of B_0. There is a remarkable consistency regarding the TWA fields, with a weighted mean of 5.2 ± 2.8 mT over all 165 shifts. This is significantly less than the UK general public time-weighted limit of 40 mT [10]. The IEEE limit (500 mT) is exceeded in a majority of cases irrespective of field

Table 7. Radiofrequency fringe field measurements, root-mean square values. Italics indicate calculated values

B_0 (T)	System	E_1 (V m^{-1})	H_1 (A m^{-})	B_1 (μT)	Power density (W m^{-2})	Distance on axis to exceed ICNIRP reference level (m)	Sequence	Reference
	ICNIRP reference level	61	0.16	0.2	10			
1.0	Philips Panorama (Philips Healthcare, Best, Netherlands)	84	0.27	0.34	22.7	0.45	Custom[a]	Capstick et al [6,78]
1.5	Philips Intera (Philips Healthcare)				0.3	<RL	MRCP–TSE	Riches et al [77]
1.5	Siemens Avanto (Siemens Healthcare, Erlangen, Germany)	33	0.36	0.45	*11.9*	0.20	Custom[a]	Capstick et al [6]
3.0	Philips Achieva (Philips Healthcare)	48	0.06	0.08	*2.9*	<RL	Custom[a]	Capstick et al [6]
7.0	Philips Intera (Philips Healthcare)	<RL	<RL	<RL	<RL	<RL	Custom[a]	Capstick et al [6]

[a] ICNIRP, International Commission on Non-Ionizing Radiation Protection; MRCP–TSE, MR cholangiopancreatography–turbo spin-echo; RMS, root mean square. 1 ms pulse, 5 μT peak B_1, 33% duty cycle, 2.88 μT RMS.
Italics indicate derived rather than primary measured values.

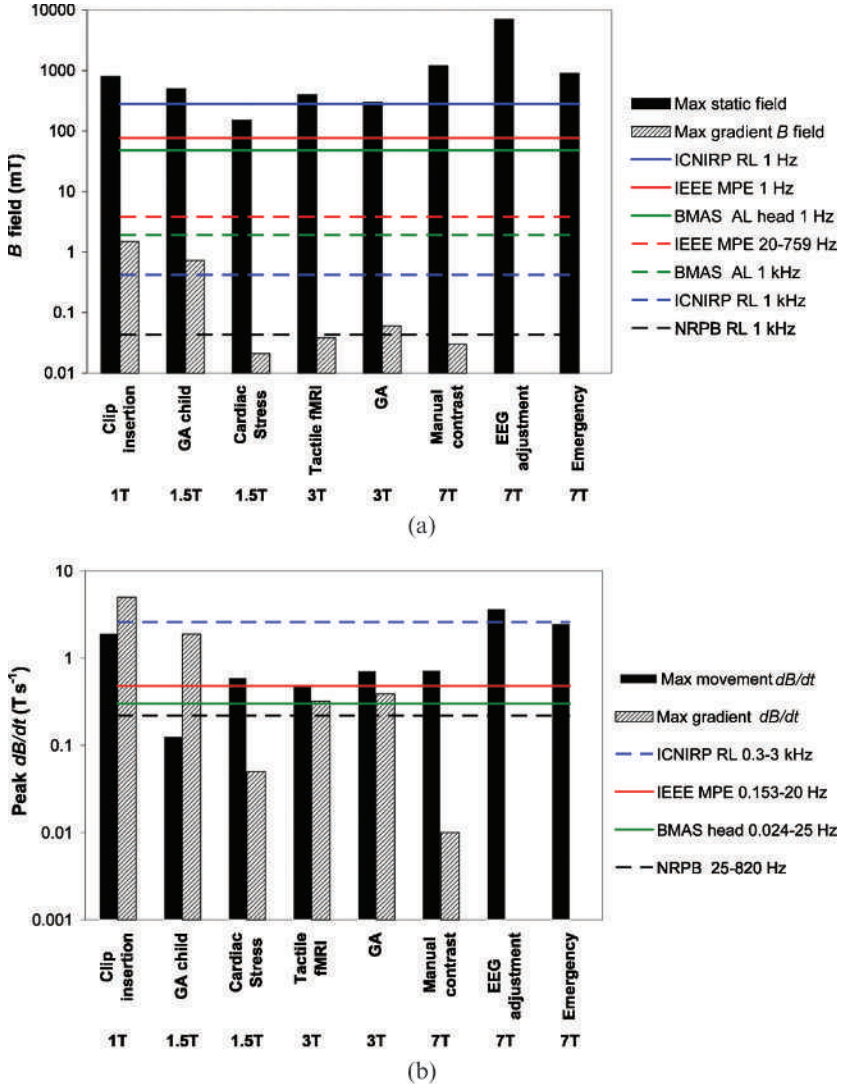


Figure 6. (a) Peak *B* and (b) *dB/dt* exposures from a survey of working practices from 1 T–7 T. With permission from McRobbie et al [81]. The solid lines and black bars relate to static field exposures. The dashed lines and hatched bars relate to the imaging gradient exposures AL, action level; BMAS, Bundesministerium für Arbeit und Soziales; EEG, electroencephalogram; GA, general anaesthesia; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEEE, Institute of Electrical and Electronics Engineers; NRPB, National Radiological Protection Board; MPE, maximum permissible exposure; RL, reference level.

strength and the ICNIRP 1 Hz reference level (280 mT) is universally exceeded. Interpretation of the results with respect to field strength is complicated by the different configurations and bore lengths of the systems. In particular the 2 T and 4 T systems had longer bore lengths, hence their lower-than-expected peak *B* values.

For the Queensland survey, the study mean of peak *dB/dt* exposures was $2.1 \pm 1.3\,\mathrm{T\,s^{-1}}$. These are harder to interpret as the precise frequency component or duration of the event is unknown. However, from time-motion studies, it is reasonable to assume a maximum frequency of 1 Hz for voluntary body motion and if this is the case, then all the applicable limits (last column Table 3a) are routinely exceeded except for the BMAS controlled situation limit.

Other studies [73, 79] have investigated exposures and induced fields from specific movements by volunteers chosen to mimic actual movements performed by staff carrying out their duties close to the magnet. *dB/dt* values in the range $1–3\,\mathrm{T\,s^{-1}}$ are in good agreement with the dosimetric studies. The directly measured induced electric field E_i was in the range $0.042–0.17\,\mathrm{V\,m^{-1}}$ for movements, compared with $2.4–3.8\,\mathrm{m\,V m^{-1}}$ from the gradients for a person standing next to the bore opening and a gradient slew rate of $10\,\mathrm{T\,m^{-1}s^{-1}}$ [73].

De Vocht et al [72] monitored occupational exposure for MR engineering staff who performed various tasks,

Table 8. Occupational exposure measurements from radiographers/technologists

B_0 (T)	Number of scanners	Number of shifts	Average peak *B* (mT)	Time-weighted average *B* (mT)	Maximum *B* (mT)	Mean peak *dB/dt* ($\mathrm{T\,s^{-1}}$)	Maximum *dB/dt* ($\mathrm{T\,s^{-1}}$)	Reference
0.6	1	19	380	5.7 ± 3.0	380			Bradley et al [70]
1.5	4	103	467 ± 103	5.1 ± 2.8	518			Bradley et al [70]
1.5	3	23	601 ± 240	5.1 ± 3.1	1281	2.2 ± 1.5	5.98	Fuentes et al [71]
2.0	1	2	561 ± 33	6.9 ± 1.2	584	1.5 ± 0.4	1.75	Fuentes et al [71]
3.0	1	12	822	4.8 ± 2.4	822			Bradley et al [70]
4.0	1	5	513 ± 67	6.4 ± 2.9	616	1.7 ± 0.4	2.04	Fuentes et al [71]

including shimming, body coil adjustment, magnet ramping and system tests. Of these, shimming generally produced the worst exposures with TWA B values of 17, 25 and 86 mT for 1.0, 1.5 and 3.0 T scanners, respectively. Peak exposures lay in the range 54–1094 mT with a mean of 549 $\pm$ 303 mT. Values for dB/dt of up to 3.97 T s^{-1} were recorded, but did not correlate with B_0.

Modelling of induced fields in tissue

As the basic restrictions are given in terms of induced fields or SAR, numerical simulations [82] of the field interactions using anatomically realistic models may be required to demonstrate compliance. Both quasistatic finite difference [83, 84] and finite integration numerical [85] techniques have been applied. These techniques provide highly detailed anatomical distributions of induced fields and currents, but inherently involve several uncertainties. The first is that detailed knowledge of the coil windings and MR system construction is required to calculate the incident fields. This information is generally proprietary, thus generic coil geometries have to be assumed. The second approximation is that gradient and RF waveforms are usually simplified, possibly to a single frequency and normalised to a standard amplitude, *e.g.* 1 m Tm^{-1}. Approximations in the computational methodology may arise owing to computational time-saving techniques such as frequency scaling. The basic restrictions require spatial averaging over a specified extent, which may introduce partial volume errors where multiple tissue types exist within a voxel. For estimation of SAR most models do not account for the body's thermoregulation and blood flow. Finally, virtual human models are generally immobile having limited flexibility and therefore may not adequately simulate real human motion or posture.

Motion in the static field

Studies of linear motion of workers around MR magnets (1.5–7 T) have confirmed that induced field limits may be exceeded for motion at 1 m s^{-1} within 0.5–1 m of the magnet [86]. Induced electric field and current density scaled with B_0. Figure 7a summarises the worst case situations, irrespective of sex. Generally these occurred for motion parallel to the z-axis towards the magnet (motion I in Figure 7b). The ICNIRP 1 Hz basic restriction is exceeded in the spine and brain for 4 T and 7 T. The IEEE basic restriction for brain of 0.025 V m^{-1} is exceeded in every case. Figure 7b shows the E_i field distributions in the body, the greatest towards the body's periphery as expected from Equation 12. A further study of bending towards high field scanners [87] revealed similar E_i in CSF with 0.16 to 0.56 V m^{-1} in the brain but much less in the spine.

Capstick et al [6] calculated induced current densities from observed motion of clinical staff in the fringe field. Emergency evacuation which had the greatest velocities (mean, 1.5 $\pm$ 0.5 m s^{-1}) gave a maximum J_{RMS} in the range 9.1 for 1 T to 24.6 mA m^{-2} for 7 T with the maximum induced current in neural tissue approximately 60% less. RMS current densities from movement during other activities [tactile fMRI, general anaesthesia (GA) monitoring, cardiac stress test, manual contrast injection] were in the range 5.7–32.9 mA m^{-2}. Cleaning the bore of the magnet gave up to 16.7 mA m^{-2}. All of these are lower than the NRPB basic restrictions. It is hard to estimate the maximum E_i in neural tissue from movement in these instances, but using a maximum conductivity of neural tissue of 0.10 S m^{-1} (brain grey matter [88]) most of these activities exceed the IEEE basic restriction of 0.0177 V m^{-1} RMS. The only activity investigated that may exceed the ICNIRP basic restriction of 0.5 V m^{-1} RMS (0.8 V m^{-1} controlled situation) was the interventional breast clip insertion in the open 1 T system, which gave maximum J_{RMS} of 84 mA m^{-2} (estimated 0.85 V m^{-1}) averaged over 1 cm^2 in neural tissue.

Induced fields from the imaging gradients

Crozier [89] considered a 1 kHz trapezoidal gradient similar to that used in an EPI sequence normalised to 1 mT m^{-1} with a 0.1 ms rise time. Care is required when scaling up because the full gradient strength assumed in this study (40 mT m^{-1}) is not typical for most clinical scans and would result in an unrealistically high SR. However, assuming this is the worst case, peak E_i >2.2 V m^{-1} (J_{max}=815 mA m^{-2}) in the spinal cord was calculated on axis close to the end of the coil for combined G_x, G_y and G_z. For a more realistic gradient amplitude of 20 mT m^{-1} the ICNIRP head CNS basic restriction was only exceeded within 0.01 m of the end of the coil. However, other tissues also exceeded tissue limits: skin, up to 0.4 m; fat, 0.3 m; muscle, 0.25 m; and heart, 0.1 m.

Li et al [85], in a more occupationally feasible position (0.35 m off-axis laterally, 0.19 m from the end of the coil) with a G_z of 10 mT m^{-1} at 1 kHz, obtained a more conservative E_i of 32 m Vm^{-1} RMS in CNS tissue (J_i=20.6 m Am^{-2}, 1 cm^2 average), a maximum J_i of 59 m Am^{-2} in muscle tissue and maximum E_i of 4.1 V m^{-1} in skin.

A European study [6, 90] calculated induced current densities from the imaging gradients in situations where NRPB and previous ICNIRP RLs (EU action values) were exceeded for real clinical tasks: performing tactile fMRI and GA monitoring near closed-bore 1.5 T and 3 T scanners; and the exposure to the interventionalist within the bore of a 1 T open scanner. These produced up to 60 mA m^{-2} and 220 mA m^{-2} RMS averaged over 1 cm^2 in any tissue, respectively, with values of 10 m A m^{-2} and 140 m A m^{-2} RMS in neural tissue. For the first two scenarios, the maximum E_i of 1.05 V m^{-1} RMS from the x-gradient occurred in the skin of the head (Figure 8a). For the interventionalist in the bore of the 1 T system the peak E_i was 0.74 V m^{-1} RMS in the skin of the head (Figure 8b). As tissue conductivities vary considerably, the maximum J_i does not necessarily coincide with the maximum E_i; nevertheless, these simulations suggest compliance with both the IEEE and ICNIRP basic restrictions.

Radiofrequency exposure and specific absorption rate

A European study [6, 90] investigated two instances when a member of staff may exceed an RF reference level. From their numerical simulations a bystander close to the bore entrance would receive 0.9 mW kg^{-1}

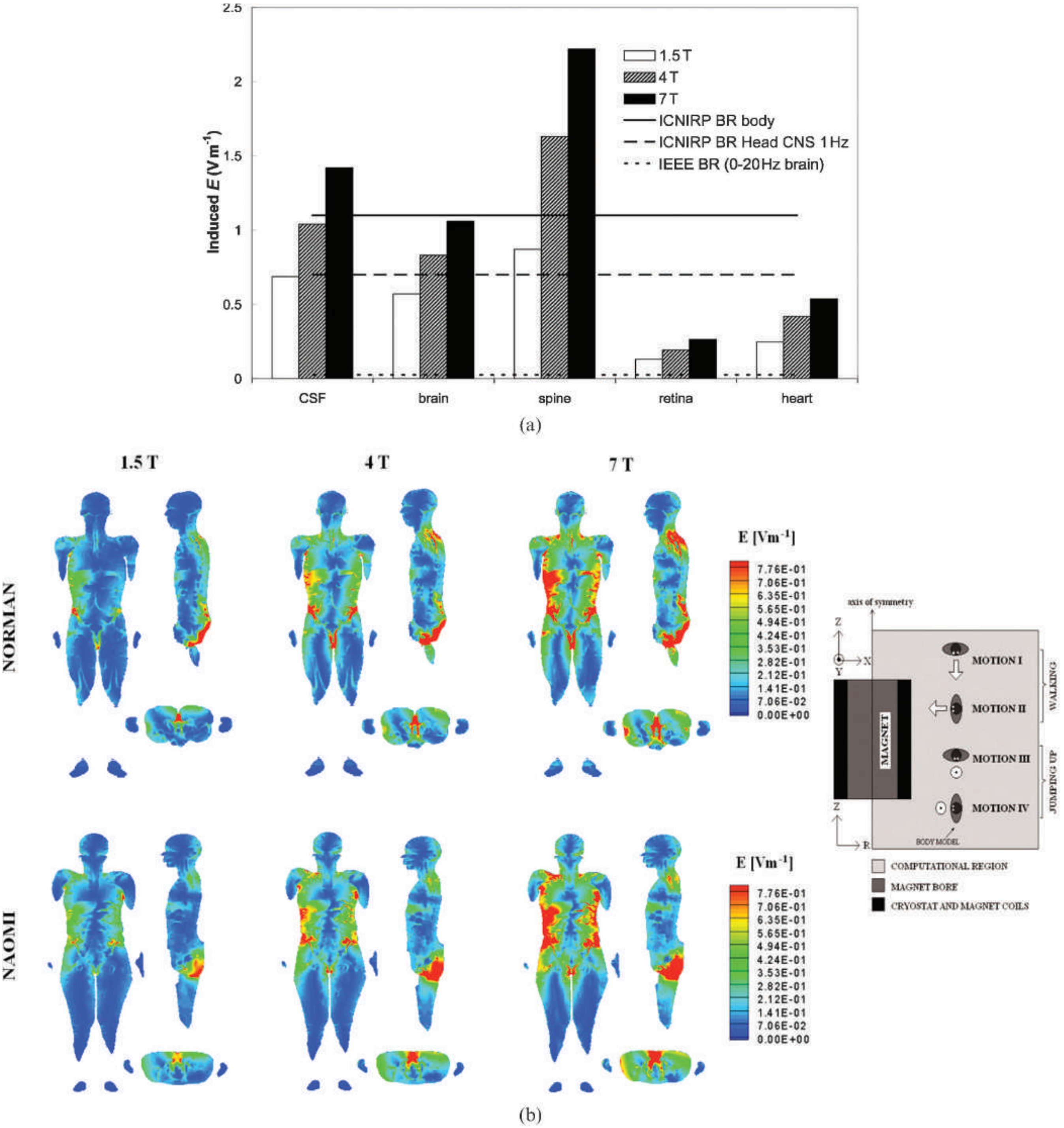


Figure 7. Induced E_i fields from movement around 1.5, 4 and 7 T magnets at 1 m s^{-1}. (a) Maximum values for different tissues. (b) Distribution of *Ei* field in the body and movement types examined. With permission from Crozier et al [89]. BR, basic restriction; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEEE, Institue of Electrical and Electronics Engineers.

whole-body and 14 mW kg^{-1} peak in 10 g SAR. The second situation was an interventionalist within the bore of an open system, who received 0.053 W kg^{-1} whole-body and 0.44 W kg^{-1} in 10 g of tissue. These are well below any SAR limit.

Discussion

The large discrepancies in both magnitude and frequency bands of the various limits arise from the diverse methodologies applied. The IEEE basic restrictions are based upon rheobases and chronaxies derived from the spatially extended non-linear node model of electrical stimulation applied to the brain, heart and other tissues [54]. The limits are based upon the 50% median threshold E_i rheobase multiplied by factors to account for pain, the probability of inducing the effect in the first percentile and a safety factor (set to 1.0 in a controlled environment). The frequency dependence of the IEEE basic restrictions follow the equation:

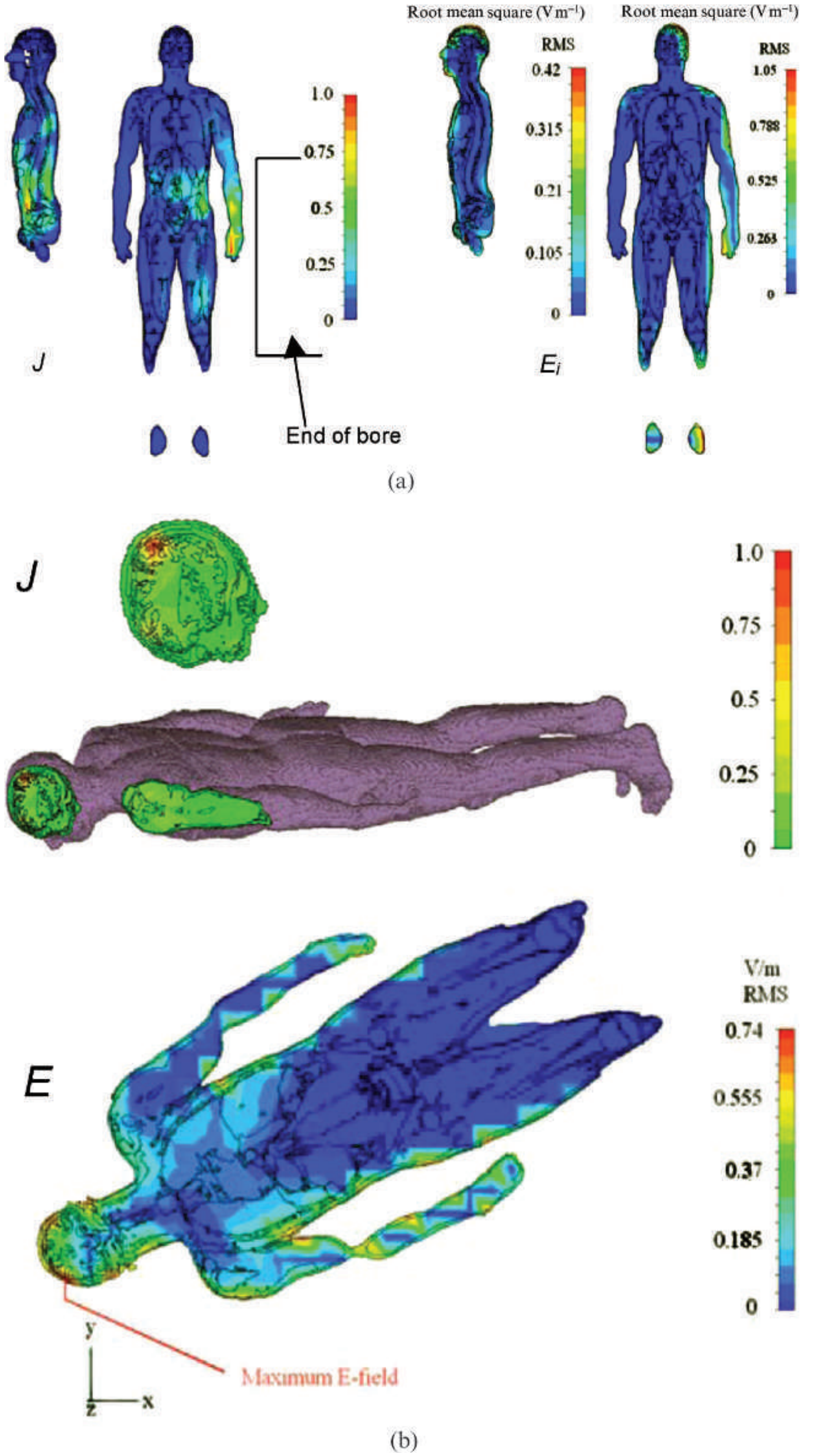


Figure 8. Induced current densities and electric fields from the gradients in staff. E_i field colour bars are shown in volts per meter, J_i colour bars are normalised to the maximum value. (a) Standing adjacent to bore opening closed bore scanner from 40 mT m^{-1} *x*-gradient at 1 kHz. The maximum single voxel J_i is 69 mA m^{-2} (41 mA m^{-2} averaged over 1 cm^2). (b) Induced fields in an interventionalist within the bore of a 1 T open scanner, *z*-gradient, 26 mT m^{-1}. The maximum single voxel J_i is 1.2 A m^{-2} (510 mA m^{-2} averaged over 1 cm^2) and occurs in the central nervous system. With permission from Capstick et al [6].

$$E_i = E_{\text{rheo}} f / f_e \qquad (20)$$

for E_i at frequency f and where f_e is the breakpoint defined in the limits. This results in more conservative limits above f_e. A further level of conservatism is arguably introduced by the use of electrical rather than magnetic stimulation data, owing to reported discrepancies between the chronaxies for each modality [91], and there are issues about waveform dependence differences between the stimulation modes [53, 92, 93]. The IEEE basic restriction for brain remains overly conservative for normal movement around MRI scanners.

The ICNIRP's rationale for frequencies 0–100 kHz is based upon analysis of experimental data from two key areas: visual phosphenes and peripheral nerve stimulation, the latter derived from MR-related peripheral nerve stimulation studies [57–62]. The new basic restrictions are raised with respect to their 1998 values over the whole range to 100 kHz, excluding the phosphene-sensitive band from 10–25 Hz (Figure 1a). The basic restriction for controlled situations is based upon a stimulation threshold of $4\,\mathrm{V\,m^{-1}}$ with a five-fold safety margin. The ICNIRP have also used more sophisticated numerical modelling rather than applying the simple geometries of Equations 9–11 to calculate the geometric coefficient between incident and induced fields. Also, by defining the limit in terms of the induced electric field, uncertainties regarding the conductivity of tissues are removed. The new basic restrictions and RLs are helpful for MRI because, as we have seen for some of the worst-case clinical and research scenarios [6], the RLs are only just exceeded while the basic restrictions are not.

The BMAS exposure limit values and action levels are also based upon phosphenes and peripheral nerve simulation data, but include low-frequency sensory effects (vertigo, taste and nausea) and a thorough review of electrophysiological mechanisms, particularly for short stimuli where the threshold is given by the integral of E_i over the stimulus duration. This is analogous to the B_{min} approach of Equation 16. They are more conservative than ICNIRP for frequencies below 10 Hz. They also incorporate a $\sqrt{10}$ safety margin. The use of the controlled situation limits should, however, enable MRI practice to comply, particularly for the gradient frequency range for which a $12\,\mathrm{T\,s^{-1}}$ *dB/dt* limit applies.

The IEC standard proposes that the worker avoids peripheral nerve stimulation. For patient exposures the standard uses the hyperbolic SD equation (Equation 15) with a simple elliptical body geometry (Equation 12). In terms of the induced field, this means that the occupational limit is the same as patient exposures. The chronaxie value used (0.36 ms) is derived from models, but is slightly less than the available published experimental data (0.5 ms). This results in a slightly more conservative limit, but the limit in terms of *dB/dt*, using the vertical bystander configuration from Equation 11, is still approximately double the BMAS *dB/dt* limit. The IEC limit for cardiac stimulation uses the same theoretical model, but applies the exponential SD curve (Equation 14).

There is more of a consensus between standards regarding the RF exposure. While incident field limits may be exceeded close to the magnet, it has been shown that, even for an interventional procedure involving a radiologist within the bore of an open system, the $0.4\,\mathrm{W\,kg^{-1}}$ whole-body SAR limit is not exceeded. The IEC's standard is the only one that is markedly different; its occupational limit is set equal to the patient limit ($4\,\mathrm{W\,kg^{-1}}$).

It has been shown that time-averaged static field exposures to clinical staff are low, in the region of 5 mT, with peak static field exposures of about 40% of B_0. These are probably higher for engineering staff and researchers. Further study of the occupational RF exposure of MR engineering staff would be welcome. Present RLs for imaging gradients are unlikely to be exceeded in most circumstances. The increase in limits below 100 kHz means that, in contradiction to earlier studies [6, 77, 78, 90], RF exposure is now more likely to become an issue than ELF exposure from imaging gradients for staff who remain close to the bore during scanning. However, this may only affect certain short bore or open scanners, but it is uncertain what the effect would be for the new generations of wide bore systems. It has been estimated that a worker remains in the MR examination room during scanning for 3% of clinical scans in the UK, or 40 000 examinations a year [94], but this proportion is much higher for research scans [95]. Further analysis or measurement of the RF exposure in these cases may be required.

For higher field strengths, induced fields due to movement become comparable with those generated by the gradients and, because of the lower limits in the low-frequency range, routine activity around scanners will frequently result in the exceeding one or more limits. For high field systems the occurrence of sensory effects (nausea, vertigo and metallic taste) is evidence that limits are being exceeded. These induced field exposures can be minimised through staff training and appropriate control measures. Dosimetric surveys of *dB/dt* for clinical and research staff indicate they receive peak *dB/dt* of approximately $2\,\mathrm{T\,s^{-1}}$.

This review has not included a discussion of occupational exposure during pregnancy. Current UK advice for pregnant staff is to avoid being in the MR examination room during scan acquisition, principally on account of the risk to foetal hearing from acoustic noise [14].

Much of the present review has been concerned with the complexities of the various limits in existence. It is our view that there is merit in the short stimulus approach followed by BMAS. This shows that the lowest B field threshold occurs for peripheral nerve stimulation and provides a scientifically sound basis for incident field limits. Furthermore, it can be argued that the restriction of peripheral nerve stimulation is more worthy of regulation because the effect is involuntary, whereas the other sensory effects are related to motion and are generally under the worker's own control.

Previous literature on occupational exposure in MRI has specifically focused on problems arising from the implementation of the original European directive. The replacement directive is currently being drafted. It is likely to define limits based on a combination of international standards, be divided into zones and only specify limits in terms of the measurable incident fields [31]. This will make the demonstration of compliance much simpler. In the current proposals Zone 0 is equivalent to public exposure, Zone 1 corresponds to a level where no adverse health effect should occur, the upper boundary of Zone 2 corresponds to the maximum directly measurable value that guarantees automatic compliance with the exposure limit and Zone 3 is for exposures greater than Zone 2. The intention is to use a combination of various guidelines to define the zones up to 100 kHz, but to use ICNIRP limits from 100 to 300 GHz. The directive may also include details of control measures appropriate to activities in Zones 1 and 2. Although the directive will apply to MRI, there may be scope, provided effective control measures are in place, for MRI activities to not strictly adhere to the limits. It is unlikely that the directive will be incorporated into UK law before 2014; nevertheless, the consideration of occupational exposure in MRI needs to remain on the radiology community's agenda.

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