6 DOSIMETRY

To understand the biological effects of electric and magnetic fields, it is important to consider the fields directly influencing cells in different parts of body and tissues. A dose can then be defined as an appropriate function of the electric and magnetic fields at the point of interaction. The establishment of a relationship between the external non-perturbed fields and internal fields is the main objective of dosimetry. Microscopic dosimetry is the quantitative study of the induced electric environment on size scales comparable to, or smaller than, the living cell. Macroscopic dosimetry deals with dosimetric quantities averaged over volumes or areas where the dimensions are greater than the dimensions of most individual cells (ICNIRP, 2003).

6.1 Static electric fields

The distortion of fields due to bodily presence is characteristic of exposure to static electric fields. External perturbed electric field strength near the skin is the most relevant dosimetric quantity when studying skin surface effects, such as hair vibrations and static discharges, caused by extremely intense electric fields.

Relatively few experimental studies of static electric fields effects have been undertaken. A discussion of dosimetric aspects of static fields can be found in ICNIRP (2003) and in section 9.1 of this monograph.

6.2 Static magnetic fields

Chapter 3 discussed the sources of static fields while the focus in this section is mostly on static magnetic fields relevant to the health risk assessment provided in section 9.1. A main concern with respect to exposure of static magnetic fields is the proliferation of magnetic resonance systems, but the following discussion applies equally to any static magnetic source.

In the case of exposure to static magnetic fields, the human body has very little influence on the magnetic field. External magnetic field strength or magnetic flux density can be used for both dosimetry and exposure assessments.

In terms of MRI or NMR systems, the magnetic sources mostly used are superconductor solenoids. Typically, the magnetic field vector inside solenoidal magnets is aligned with the patient's long axis. Many lower field magnets have the static magnetic field vectors aligned with the anterior/posterior patient axis, though some magnets place the field along the left/right axis. In general, magnets (not just MRI magnets) may be actively shielded to limit the spatial extent of the fringe field, but many are not. In MRI applications, magnets up to about 4 T can be actively shielded, but current technology prohibits active shielding above this level. Therefore, significant fields are present around 7 T magnets, for example, but actively shielded magnets may in fact have large gradients near the ends of magnets due to the effect of active shielding. In NMR, which is used for chemical analysis and spectroscopy, small bore magnets are used to house test tube sized samples. These magnets are routinely 12 to 21 T and workers are exposed to stray fields and field gradients when changing samples or the probes within the magnet.

Static magnetic field effects are likely to be caused by the magnetic field vector, B, the gradient of the magnetic field, $\partial B/\partial z$, the 'force product', or by motion or flow induced magnetic fields. The force product, P_F, may be expressed as:

$$P_F = B.\frac{\partial B}{\partial z} \tag{6.1}$$

where z is taken as the direction of B. Note, however, that B is a vector and that all components should be considered. Flow induced electric fields, E_f, depend on the product of flow velocity, v, the magnetic field vector, B, and the angle, θ, between them:

$$E_f = v\,B\,\sin(\theta) \tag{6.2}$$

The motion-induced electric field, E_m, depends on the geometry and on the time rate of change of the magnetic field:

$$\oint \bar{E}_m \bullet d\bar{l} = -\int \frac{d\bar{B}}{dt} \bullet d\bar{s} \tag{6.3}$$

where $d\bar{l}$ is the incremental length vector of the body part enclosing the changing magnetic field and $d\bar{s}$ is the normal vector to the incremental area. It is clear from equation 6.3 that electric fields may be induced when the dot product of B and s changes with time. For static magnetic fields, this happens because the area vector changes with time or because the magnetic field vector changes with location due to motion in a static field gradient or both.

Forces, and even torques, on ferromagnetic, paramagnetic, or diamagnetic objects are proportional to the force product (see section 5.2.2). This effect is a primary concern with static magnetic fields. Affected objects (e.g., tools and implants) may move with sufficient force to be hazardous. Force products depend on the field gradient and the field. Thus, even low field magnets could have high force products.

Flow and motion-induced electric fields may result in vertigo or, potentially, nerve or muscle stimulation. Flow-induced cardiac stimulation has not been reported in the literature. However, it is a potential concern for sufficiently high static magnetic fields. It is not clear whether the orientation of the body with respect to B will affect flow potentials.

Past exposure standards and guidelines have included time-weighted magnetic field exposure limits. It is, however, currently unclear which form of dose is the most appropriate to monitor. Dosimetry for future exposure limits must depend on a realistic effects mechanism. Limiting forces and torques requires restricting ferromagnetic objects from the vicinity of magnets and limiting the peak force product that an object may experience. Protection from nerve and muscle stimulation during patient exposure requires limiting peak dB/dt, either by limiting motion or by limiting peak B. Flow potential concerns require limiting peak B or at least peak $v\ B\ \sin(\theta)$ - see equation (6.2). Some mechanism may require limiting the root mean square of the static field vector, though this is not clear.

6.3 Motion induced effects in MRI

The example presented in the following section details theoretical investigations into the spatial distribution of induced currents and electric fields in a tissue equivalent human model when moving at various positions around a magnet. The numerical calculations are based on a quasistatic, finite difference scheme (Liu et al., 2003b; Liu & Crozier, 2004).

Three dimensional field profiles from an actively shielded 4 T magnet system are used as an example and the body model is projected through the field profile with normalised velocity. Most clinical MRI systems are actively shielded in that the stray field emanating from the MRI system is restricted by the use of a counterwound coil exterior to the main or primary magnet windings. The methodology presented herein is not restricted to MRI, but can be used to calculate induced fields due to patient or occupationally exposed worker movement around a magnetic field source.

There has been a concerted effort in the past decade to enable MRI to operate at very high field strengths. The most common system in current clinical use has a 1.5 T central field. However, 3 T systems are now accepted for routine clinical work and more than 100 systems were operational worldwide by 2004. Research systems from 4 - 9.4 T are now being developed for clinical imaging. As the field strength of the MRI system increases, so does the potential for tissue/field interactions of a variety of types. Understanding the interactions between the electromagnetic fields generated by MRI systems and the human body has become more significant with this push to high field strengths (Schmitt et al., 1998; Schenck, 2000; Kangarlu & Robitaille, 2000; Liu et al., 2003b).

The static magnetic fields used in MRI may be associated, in varying degrees, with biological influences such as diamagnetic and paramagnetic effects (Kangarlu & Robitaille, 2000). Another concern in high-field MRI is related not to the strength of the static field, but to electromagnetic induction. The 3D pattern of the static magnetic field can induce current in moving conductive objects, such as the body. Systematic study using volunteers (Schenck et al., 1992) and anecdotal evidence that some patients experience uncomfortable sensations when moved into MRI or when moving their head during entry to the scanner or once in the system, has motivated the study of the induced fields inside a patient model (Liu et al., 2003a). Reported sensations included phosphenes (light flashes), vertigo, and a metallic taste in the mouth. The motion-induced effects in patients, and the eddy currents induced in an occupationally exposed worker (radiographer or MRI technician) moving around the magnet, are discussed below. These calculations provide assistance in the evaluation of the risks involved for health workers and patients when moving through intense, static magnetic fields.

6.3.1 Numerical calculations of the induced fields

The human model used for the calculations represents a large male and was obtained from the United States Air Force Research Laboratory (http://www.brooks.af.mil/AFRL/HED/hedr/). The original spatial resolution of the model was 1 mm, but the model was mapped onto a 4-mm grid with volume-averaged conductive properties.

The simulations presented here are based on the fields generated by a 4 T, actively-shielded MRI magnet (Crozier & Doddrell, 1997). This magnet has a length of 1.5 m with a homogeneous imaging region (or Diameter Spherical Volume [DSV]) of 50 cm. The shielding area (to 0.5 mT) is 4.5 m in the z direction and 4.0 m in the radial direction from the magnet iso-centre. The numerical method for the calculation of the static magnetic field was based on Forbes et al. (1997). The vector magnetic potential components are used to calculate the induced fields inside the body.

The calculation of the E-fields induced by the relative movement of the body inside the static magnetic field is based on a finite difference scheme (Liu et al., 2003b). The time-varying magnetic flux is expressed by the difference of vector potentials of two neighbouring cells divided by the time difference. The formulation supports multi-direction translation using vector analyses of velocity. To simulate a realistic human movement, the velocity of different parts of the body can be set to different values.

During the period when the body is moving around the magnet, the transient induced fields at each position in the body relative to the magnet centre are registered. The peak values and their positions in the human body are obtained for further evaluation. A variety of movement directions and velocities were modelled.

Figure 6.1 provides curves describing the peak E-fields and current densities induced in the human model for all the positions near the magnet. In Fig. 6.1(a,c), the E-field and current density curves are both shown. These curves depict the obviously stronger electromagnetic induction when the body moves near a magnet end, where the magnetic field gradient is large. Fig. 6.1(b,d) shows the amplitudes of the E-fields for maximum induction at various layers within the body.

An example of histogram distributions for the front-back movement along the end of the magnet is shown in Fig 6.2(a,b). For the skin/subcutaneous fat regions of the body (*i.e.* those parts expected to be most sensitive to peripheral nerve stimulation (Dawson & Stuchly, 1998; Stuchly & Dawson, 2000)) the largest induced E-field (1% threshold) was 2.0 V m^{-1}. For deeper structures in the chest, however, the value was 3.1 V m^{-1}.

Detailed calculations have been made of induced field during patient movement and head-shake while in the magnet. Fig 6.3a shows typical induced field results for movement at 0.5 m s^{-1} in the 4 T magnet, which indicates E-fields around the 2.0 V m^{-1} range at maximum, and Fig 6.3b shows extrapolated results to higher fields and velocities. Note that at higher fields, magnets are unshielded and significantly longer, and that the curves in Fig 6.3b do not account for that because they only provide indicative values. Importantly, the threshold induced current density for peripheral nerve stimulation is estimated to be about 0.48 A m^{-2}, (Kangarlu & Robitaille, 2000) but this is frequency dependent, and so Fig 6.3b gives a rough indication of the field strengths and patient velocities capable of such induction. At 7 T, for example, it is estimated that a body velocity of about 0.8 m s^{-1} would result in induced current density at the peripheral nerve stimulation level. No reports of peripheral nerve stimulation due to table motion have appeared in the literature. Note, however, that recommended restrictions on occupational exposure to low frequency EMFs where weak electric fields and currents are also induced in the body are based on effects on neural tissue in the central nervous system where thresholds are considerably lower than those for peripheral nerve stimulation (e.g. (ICNIRP, 1998); see (ICNIRP, 2003) for a full discussion).

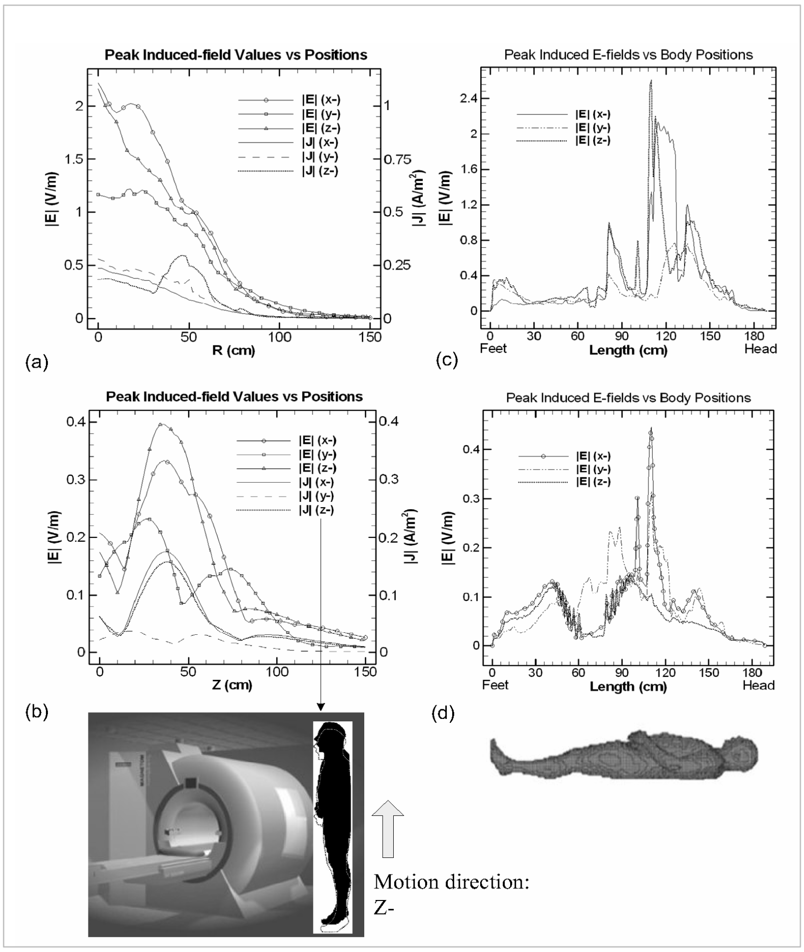

Figure 6.1. Curves of the induced fields for the body moving around the magnet. (a,b): peak E-fields and current densities in the human model for all the positions (0 ~ 1.5 m) when the body is moving around the 4 T magnet (a: near the magnet end; b: along the cylinder); (c,d): the amplitudes of the E-fields for various layers of the human body model. These induced values are calculated when peak E-fields occur in (a,b). In all the figures, ‘x-, y-, z-’ denotes the body motion direction: ‘x-’: left-right direction, ‘y-’: front-back direction and ‘z-’: up-down direction. (Crozier & Liu, 2005)

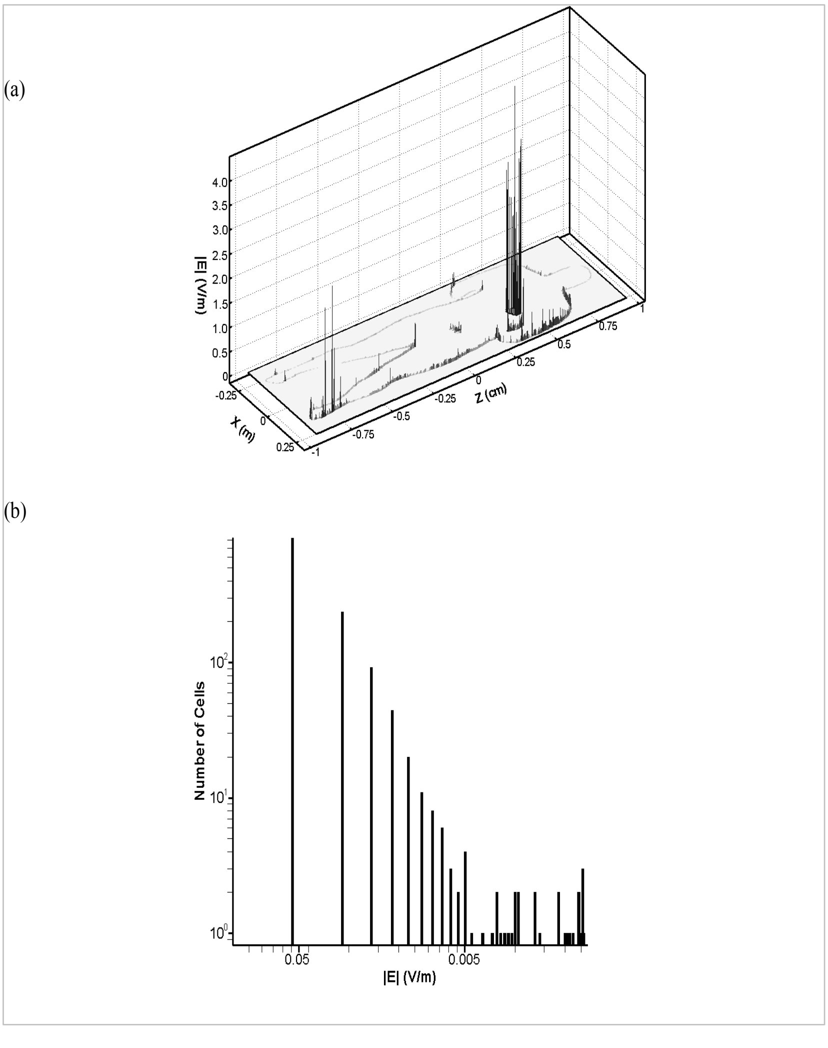

Figure 6.2. Histogram distribution of induced electric field in different voxels (cells) of the phantom for front-back movement at 1.0 m s^{-1} along the end of the 4 T magnet. For the skin/subcutaneous fat regions of the body, the largest induced E-field was 2.0 V m^{-1}. For deeper structures in the chest, however, the value was 3.1 V m^{-1}.

(Crozier & Liu, 2005)

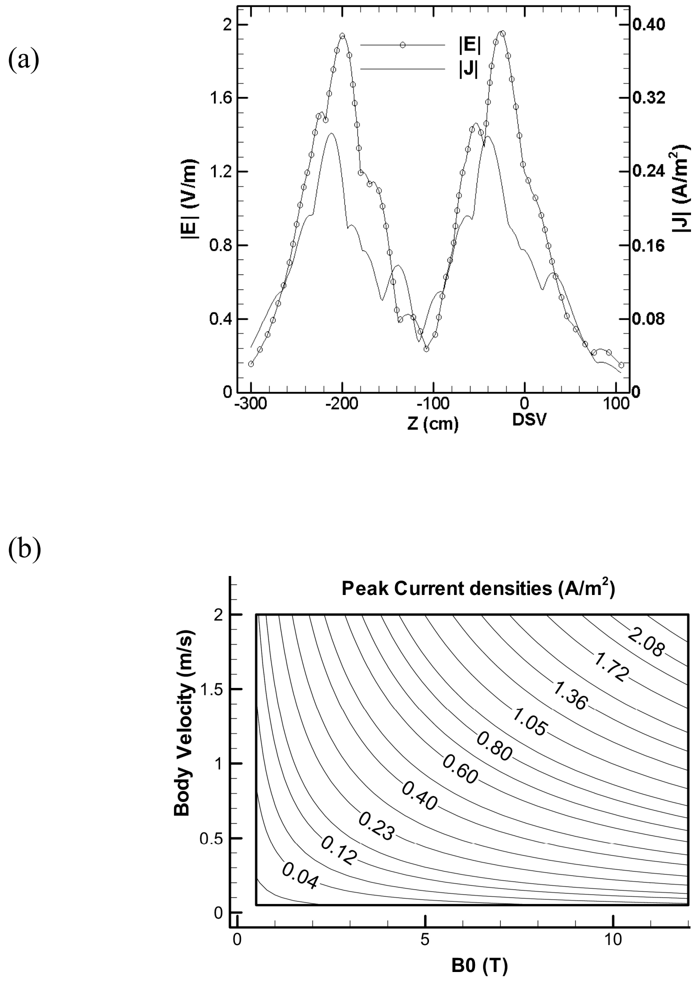

Figure 6.3. Curves of the induced fields for the body moving inside the magnet. (a) shows typical induced field results for movement at 0.5 m s-1 in the 4 T magnet, which indicates E-fields around the 2.0 V m-1 range at maximum, and (b) gives peak induced current densities in the skin as a function of body velocity and field strength. (Crozier & Liu, 2005)

6.4 Personal dosimetry

To assess health risks in relation to static fields, measurements of exposure are useful. Occupationally exposed workers and patients alike may be monitored for exposure using personal dosimeters (Fujita & Tenforde, 1982) or estimates from field plots. In the case of occupationally exposed workers, exposure to either instantaneous or cumulative fields may be monitored, as appropriate. Although the quantities to be measured are not exactly clear, at least the instantaneous B field vector and the B field time derivative should be considered in the static magnetic field case. While a number of commercial products exist for personal dosimetry in ELF electromagnetic regime, this is not the case for personal static magnetic field dosimetry, where there is currently only one instrument available (Wave Instruments, see http://www.waveinstruments.com.au/). It is also noted that the measurement devices themselves must be able to withstand strong magnetic fields and must not alter the local field in any significant manner.

6.5 Conclusions

Appropriate dosimetric parameters depend on the physical mechanism for the safety concern. Clearly, ferromagnetic objects must be restricted from the vicinity of the magnet. Screening is imperative for such objects and for implants that may move either due to forces or torques. Measures of peak magnetic induction vector, *B*, and peak magnetic force product are appropriate. Field maps may be used to estimate these at various locations near the magnets where workers may be exposed, but personal dosimetry may be useful.

Movement of the whole or part of the body, e.g. eyes and head, in a static magnetic field gradient will also induce an electric field and current during the period of movement. Dosimetric calculation suggests that such induced electric fields will be substantial during normal movement around or within fields > 2 - 3 T, and may account for the numerous anecdotal reports of vertigo and occasionally magnetic phosphenes experienced by patients, volunteers and workers during movement in the field.