SMRT-ISMRF FORUM: SAFE EXPOSURE LIMITS FOR STAFF & PATIENTS

STAFF EXPOSURE DATA

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INTRODUCTION
The formulation of EU Directive 2004/40/EC \(^1\) has focussed attention on the issue of occupational exposure in MRI. Whilst the EU’s attempts to regulate occupational exposure to electro-magnetic (EM) fields is recent, the underlying exposure guidance from ICNIRP has been in existence for some time\(^2\). Other occupational exposure guidance is also available\(^3\,4\) but has been ignored by regulators.

BIOLOGICAL EFFECTS
An estimated 60 million MRI scans are performed worldwide each year. There are no recorded instances of deleterious biological effects. Studies of the biological effects of static and time-varying magnetic fields have yielded inconclusive and sometimes contradictory results \(^5\,6\,7\). These have tended to focus on long term exposures to low frequency fields or mobile telephone exposures although some consider MR specific bio-effects\(^8\,9\). Magnetic nerve stimulation is a well documented acute effect \(^10\,11\) used clinically in transcranial magnetic stimulation (TMS) and also may occur as an unwanted side-effect in MRI\(^12\). For reviews of RF heating in MRI and static magnetic field effects see references \(^13\,14\).

STAFF EM FIELD EXPOSURES
MRI staff will typically be exposed to the B\(_0\) fringe field and its spatial gradient dB/dr during the common activities of patient positioning and coil selection. Staff who remain close to the scanner during an acquisition, for example with a child or unconscious patient, will also be exposed to time-varying magnetic fields dB/dt from the imaging gradients and RF B\(_1\) fringe field. Both movement through the fringe field gradient and exposure to the imaging gradient fields will induce electric fields in the body which will give rise to induced current densities, J (Am\(^{-2}\)), in electrically conductive tissues. In a simplistic model the magnitude of current induced in a circular path of radius r is:

\[
J = 0.5 \sigma r \frac{dB}{dt}
\]

\[
= 0.5 \sigma r v \frac{dB}{dr} \quad \text{(for movement, where v is the subject’s velocity)}
\]

Occupational exposure limits or ‘Basic Restrictions’ are expressed in terms of the induced current density in central nervous system tissues or SAR (Wkg\(^{-1}\))\(^1\,2\). As these cannot be easily measured in-vivo, ‘Reference Values’ are also defined in terms of physical EM fields: electric field E (Vm\(^{-1}\)), magnetic field H (Am\(^{-2}\)) or magnetic flux density B (μT). Compliance with a Reference Value is deemed sufficient evidence that the corresponding Basic Restriction is not exceeded. Where a Reference Value is exceeded, a demonstration that a Basic Restriction is not exceeded is required. This generally entails modelling of the induced currents or SAR.

EM FIELD MEASUREMENT
Static fringe field and fringe field gradient plots are provided as part of the IEC606-2-33 standard by MRI manufacturers\(^15\). The presence of ferromagnetic building structures or magnetic shielding can result in distortions in the fringe field. The fringe field contours, particularly the 0.5 mT (pacemaker exclusion zone) and 200 mT contours can be verified or plotted using a Hall-effect magnetometer. Commercial models are capable of measuring up to

2T. This is sufficient to plot the fringe field of a clinical 3T MR system. It is convenient to use a three-axis probe to avoid directional uncertainties in the magnitude of the static fringe field. In addition, the IEC standard 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. The attractive force on a ferromagnetic object of volume \( V \) and magnetic susceptibility \( \chi \) is proportional to this product:

\[
F \propto \chi \cdot V \cdot B \cdot \frac{dB}{dr}
\]  

(2)

The imaging gradient fringe fields inside and outside the magnet bore can be measured using instruments based upon a search coil. The IEC standard defines appropriate measurement methods. In the simplest case a search coil connected to an oscilloscope may suffice. This will enable the calculation of \( \frac{dB}{dt} \) from

\[
\frac{dB}{dt} = \frac{V}{nA}
\]  

(3)

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 in terms of magnetic flux density which can be directly related to ICNIRP reference values in tesla. It is however simpler to measure \( \frac{dB}{dt} \) (which is more directly related to the induced currents in tissues). The ICNIRP reference value most relevant to the imaging gradients can be reformulated as a \( \frac{dB}{dt} \) of 0.22 T s\(^{-1}\), assuming a tissue conductivity of 0.2 S m\(^{-1}\) and a worst-case body radius of 0.64 m\(^{16}\).

For the consideration of RF exposures, 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 Reference Value of 0.2 \( \mu \)T (averaged over 6 minutes). Details of the pulse sequence and RF pulse waveforms have to be known in order to demonstrate compliance. The IEC standard also defines methodologies for assessing temperature rise (in a phantom) and SAR or RF pulse energy from forward and reflected power measurements from the RF transmission system\(^{15}\).

RESULTS OF EM FIELD SURVEYS
The intended implementation of Directive 2004/40/EC has stimulated a number of studies of the exposure to EM fields of MR workers who may be required to remain close to the scanner during scanning. In particular it has been shown both by measurement\(^{17,18,19}\) and calculation\(^{20}\) that the ICNIRP reference values applicable to the imaging gradients will be exceeded for a person standing within approximately 0.5m of the bore opening during scanning. Additionally RF reference levels may be exceeded for a person standing within 0.2-0.45m of the bore opening\(^{19}\).

MODELLING OF INDUCED CURRENTS
As the basic restrictions are given in terms of induced current densities or SAR, numerical simulations of the field interactions using anatomically realistic models may be required to demonstrate compliance. Both quasi-static finite difference\(^{21,22}\) or finite integration numerical\(^{23}\) techniques have been applied. Studies aimed at assessing occupational exposures have shown that the basic restrictions can be substantially exceeded for induced currents arising from movement through the static field and \( \frac{dB}{dt} \) gradient exposure\(^{19,20,24}\).

WORKING PRACTICE SURVEYS
Actual measurements of personnel exposure to \( \frac{dB}{dt} \) from movement in the static field and gradient activity has been carried out using personal dosimetry instrumentation\(^{25,26}\). Peak \( \frac{dB}{dt} \) exposures from staff movement in the static field lie in the range 1 – 6 T s\(^{-1}\), broadly independent of \( B_0 \), with gradient \( \frac{dB}{dt} \) exposures of a similar magnitude. In an alternative approach\(^{19,27}\), the analysis of video recordings of the movements of MRI workers about the magnet in conjunction with measured field maps\(^{28}\) gave similar results: typical peak
from movement of up to 2 T s\(^{-1}\) for routine clinical activities (for 1T-3T MR systems) with a maximum of 3.7 T s\(^{-1}\) for movement around a 7T research system. Corresponding staff dB/dt exposures from the gradients were in the range 0.5-5 T s\(^{-1}\). All these results are consistent with predictions from modelling \(^{19,20,23,24,25}\). Monitoring of the peak and time-averaged static field exposure of workers has also been carried out \(^{19,25,27}\) giving peak exposures of up to 1 T for routine activities (on 1-7T magnets) but up to the value of B0 when cleaning the bore of the magnet. Time-averaged static field exposures in the range 1.5-12.5 mT have been recorded \(^{25}\).

CONCLUSIONS

There are a number of practical implications from the statutory enforcement of guideline limits for occupational exposure as in the Directive \(^{29,30}\). These include limitations on interventional MR procedures, support for vulnerable patients or children, monitoring of during sedation and general anaesthesia, and the use of manual contrast injections (which may be required for sick or very young patients). A survey of MR clinical practice in the UK \(^{31}\) concluded that just under 3\% of examinations have a member of staff present in the room during scanning, carrying out clinical duties that may entail being close to the bore. This would affect just under 40,000 patients per year in the UK alone. The excess ionising radiation burden from using computed tomography as an alternative to MRI is estimated as 224 man-sievert per year. Extrapolated to the entire European Union an estimated 325 additional fatal cancers per year would be induced in patients from avoidable x-ray exposures.

REFERENCES

3 IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz, C95.6-2002, IEEE Inc. New York 2002


