MAGNETIC RESONANCE SAFETY
BIOEFFECTS OF GRADIENT MAGNETIC FIELDS

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ABSTRACT

From the safety point of view, there are areas to consider in operating a Magnetic Resonance (MR) facility. Time-varying magnetic fields, caused by the switched gradient on imaging systems, will induce currents in conductive pathways in the body. There are different thresholds for eliciting excitation for different tissues. Information was obtained from a MR research facility which could be bear in mind when a small sample is investigated although there are limitations upon the use of this information for biological tissues. Because a number of effects in man occur, there are recommendations made by the National Radiological Protection Board (NRPB) in the UK and the US Food and Drug Administration (FDA) has issued safety guidelines as well, which are considered in this work.

INTRODUCTION

MR involve exposure to three types of magnetic and electromagnetic fields. These are, the main magnetic field B_0 , the alternating magnetic field produced by the gradients and the radiofrequency field.

The aim of this work is to point out the effects in the body that may result from the alternating magnetic fields produced by gradients and the important factors which are responsible for inducing a physiologic response to an induced voltage.

During Magnetic Resonance (MR) imaging numerous gradient magnetic fields are turned on and off at rapid rates, for varying amount of times, and to varied peak gradient amplitudes. Placing the body within the MR system and rapidly switching the current on and off within the gradient magnetic field coils, two effects are produced, a) the creation of a gradient magnetic field b) the potential for induced voltages within the patient (and / or other electrical conductors) in the bore of the MR system.

There are potential bioeffects related to gradient magnetic fields from induced currents or voltages in the human body.

CAUSES AND EFFECTS OF TIME-VARYING MAGNETIC FIELDS

The production of eddy currents is a well known physical mechanism whereby time-varying fields can induce changes in biological systems. Biological tissues, containing ions in water, are conductive and it may be assumed that at certain rates and magnitudes of field changes, sufficient density of eddy current could be produced to affect the more sensitive biological tissue.

There are potential bioeffects related to gradient magnetic fields from induced currents or voltages in the human body. It is necessary to determine the amplitude of the induced voltages to know whether or not tissues will be affected by such induced voltages and currents. To calculate induced current densities, it is important to know the electrical resistivity of the induced current loop. This is determined by the tissue through which the induced voltage will attempt to produce a current flow (1).

Several factors are responsible for physiologic responses to induced voltages, including the strength of the static magnetic field, the orientation of the gradient magnetic fields being switched relative to the patient's tissue, the size of the greatest diameter of the patient's body, the frequency of the stimulus, the duration of the induced voltage, the shape of the waveform, the width of the pulse and the sensitivity of tissues. The magnitude of the voltages and /or currents induced within the patient will be determined by several factors as well, these include the electrical resistance in the circuit produced in the tissue, the cross-sectional area of the induced current flow, and the rate of change (versus time) of the gradient magnetic field itself. All induced voltages or currents will occur during the times that the gradient magnetic field strengths are changing - the rise and fall times of the gradients-. The greater the magnitude of the rise and fall times, the greater the induced voltage and current. There is a greater changing magnetic field over time (or dB/dt) as one proceeds further away from the centre and toward the ends of the gradient coils, where the time rate of change of the gradient magnetic fields is the greatest.

In MR, the health consequences due to time-varying magnetic fields in the extremely low frequency range are concerned with nervès, blood vessels and muscles that act as conductors in the body. Rapidly changing magnetic fields induce electric currents in tissue that could be sufficiently large to interfere with the normal function of neurones and muscle. The threshold current density above which the effects may occur varies according to the tissue involved, the pulse width and the pulse repetition frequency of the induced current (2).

Ventricular fibrillation is the most serious adverse response that may be anticipated during exposure to rapidly changing magnetic fields. The heart is most sensitive to stimulation at frequencies between 10 Hz and 100 Hz. 3 A m^{-2} rms is considered therefore to represent a conservative value for fibrillation threshold at frequencies outside this range. Significant disturbance of the heart beat (pump failure) may begin to occur above about 3 A m^{-2} rms.

The visual sensations are referred to as magnetophosphenes (3). Retinal stimulation is considered to be the most sensitive index of induced currents and it occurs when the peak rate of change of magnetic flux density is about 2 T s^{-1}.

EVALUATIONS IN A MR RESEARCH FACILITY

In a volume distribution of electrical current the parameter of importance is the current density (J). The biological system may be regarded as a loop and the important factors to consider is the current density induced in this loop, which can be calculated as:

$$J = 0.5\, r\, \sigma\, (dB/dt) \qquad [1]$$

where, r: the loop radius, σ: conductivity of the sample and (dB/dt:): the rate of change of magnetic field.
There are limitations upon the use of this equation for biological samples since biological tissues are not homogeneous. For example, the skeletal muscle, which acts as the main eddy currents conductor, is anisotropic. The presence of boundaries between different types of tissue will cause distortions to the idealised circular current path and alter the magnitude of currents. Bearing in mind these limitations, it is possible to obtain an estimated current density in the air inside the small gap of an MR research facility and from this, it could be possible to do an approximation of the threshold value in a small sample inside the magnet.

In the experimental work, X and Y flat rectangular gradient coils made by etching technique were used with a permanent magnet (B_0 = 0.59 T, gap: 18 mm). Trapezoidal waveforms were generated with 5V amplitude, rise time 480 μs, pulse width 20 ms, period 26 ms, (dB/dt)air = 4 T/s. Gap for sample: 15 mm (r = 0.0075 m) (4).
From equation [1], the current density in air , Ja, inside the gap of the magnet was calculated as: Ja = 0.037 x 10^{-14} A/m^2 with $\sigma a = 2.5 \times 10^{-14}$ S/m and (dB/dt)a = 4 T/s. The current density in any sample is : Js = 0.5 r σs (dB/dt)s
The threshold value (dB/dt)s can be calculated as:

$$(dB/dt)s = (Js/Ja)\,(\sigma a/\sigma s)\,(dB/dt)a \qquad [2]$$

If σs = 0.3 S/m (2) and Js = 2.5 A/m^2 , the threshold value in a small sample will be: (dB/dt)s = 2222 T/s. This value can be compared with other estimations made for different authors. Thresholds values for different tissues and different density currents can be evaluated in this way bearing in mind the limitations of these approximations.

CONCLUSIONS

These last years there has been increased public concern about the bioeffects of gradient magnetic fields. The health consequences are not related to the strength of the gradient field, but rather to changes in the magnetic field that cause induced currents. Because of this, it is important to obtain information concerning the pulse generation, to examine the conditions for the production of a detectable response and to obtain better understanding of biological effects involved.

This issue must be reconsidered as the maximum strengths and the rise time capabilities (dB/dt) of the newer and faster MR systems continue to improve.

Thresholds values for different tissues and different density currents can be evaluated for a small sample. The previous calculations can be carried out bearing in mind the limitations of these approximations, as was mentioned before. The threshold value obtained in this evaluation was, $(dB/dt)s = 2222$ T/s.

In view of the rapid progress in clinical imaging as a diagnostic aid, The National Radiological Protection Board recommends continue modifications to the original advise given in 1981. Some of these new recommendations are, (NRPB 1981,1983) (5), a) the root mean square value of rate of change of dB/dt should not exceed 20 Ts^{-1} for pulse widths above 10 ms, b) for periods of magnetic field change shorter than 10 ms: $(dB/dt)^2_{rms}\, t < 4$ where t is the duration of the change of the magnetic field in seconds.
For sinusoidally or other continuously varying periodic magnetic fields, the duration of the change can be considered to be the half period of the magnetic flux waveform.

The US Food and Drug Administration (FDA) has issued safety guidelines as well and suggested operating limitations for MR imaging devices regarding the gradient magnetic fields associated with MR imaging procedures Concerned with the rate of change of magnetic field, the limit patient exposure to time-varying magnetic fields with strengths less than those required to produce peripheral nerve stimulation, was suggested. An alternative is to demonstrate that the maximum dB/dt of the system is 6 T/s or less. There are other alternatives related to axial and transverse gradients (6).

Working with alternating magnetic fields the NRPB or/and the FDA recommendations must be considered.

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