Assessment of Occupational Exposure of MRI Workers Resulting from a Time-varying Magnetic Field Associated with a Cylindrical Z-gradient Coil

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Introduction

All member states of the European Union are obliged to incorporate Directive 2004/40/EC into national law by April ‘08.

Directive 2004/40/EC prescribes limits on occupational exposure to E-M fields covering the frequency range 0 – 300 GHz.

Concern has been raised regarding the likely impact that these exposure limits will have on MRI practice.

There is currently little information in the literature regarding induced electric fields and current densities within the bodies of workers positioned close to MRI scanners.
We have investigated E-fields and current density $J$ within an anatomically realistic voxel model of an adult male placed at a range of distances from a model of a cylindrical z-gradient coil.

The time-domain solver in CST Microwave Studio together with a frequency scaling method was used to determine spatial distributions of $E$ and $J$ at 1 kHz.
Adult Male Voxel Model

Based on male Caucasian subject height 1.78 m and weight 78 kg.

\( \sim 13.8 \times 10^6 \) voxels, each 1.66 mm \( \times \) 1.66 mm \( \times \) 2 mm, segmented to 33 tissue types.

Tissue Dielectric properties were based on the 4-Cole-Cole analysis reported by Gabriel and Gabriel\(^1\) and calculated online (http://niremf.ifac.cnr.it/tissprop/htmlclie/htmlclie.htm and http://www.fcc.gov/fcc-bin/dielec.sh)


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The cylindrical coil consisted of 24 rings, 0.35 m radius, 0.02 m wide, 1.055 m overall length\(^2\)

<table>
<thead>
<tr>
<th>Coil #</th>
<th>Location on z-axis (m)</th>
<th>Current (A)</th>
<th>Coil #</th>
<th>Location on z-axis (m)</th>
<th>Current (A)</th>
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<tr>
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<td>-180.52</td>
</tr>
<tr>
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<td>-180.52</td>
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<td>-180.52</td>
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<td>0.1672</td>
<td>180.52</td>
</tr>
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<td>-180.52</td>
<td>16</td>
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</tr>
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<td>18</td>
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<td>180.52</td>
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<tr>
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<td>180.52</td>
</tr>
<tr>
<td>8</td>
<td>-0.2251</td>
<td>-180.52</td>
<td>20</td>
<td>0.2990</td>
<td>180.52</td>
</tr>
<tr>
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<td>-180.52</td>
<td>21</td>
<td>0.3286</td>
<td>180.52</td>
</tr>
<tr>
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<td>-0.1672</td>
<td>-180.52</td>
<td>22</td>
<td>0.3653</td>
<td>180.52</td>
</tr>
<tr>
<td>11</td>
<td>-0.0838</td>
<td>180.52</td>
<td>23</td>
<td>0.4167</td>
<td>180.52</td>
</tr>
<tr>
<td>12</td>
<td>-0.0406</td>
<td>180.52</td>
<td>24</td>
<td>0.5177</td>
<td>180.52</td>
</tr>
</tbody>
</table>

Frequency Scaling for Quasi-static Problems

There is a major problem with using any time-domain solver at low kHz frequencies – run times are impractically long.

Quasi-static approximation is valid when:

- dimensions of the problem are small compared to the wavelengths involved
- \( \sigma + j 2 \pi f \varepsilon \gg 2 \pi f \varepsilon_0 \)
  
  \( (\sigma \text{ and } \varepsilon \text{ are the conductivity and permittivity of tissue and } \varepsilon_0 \text{ is the permittivity of free space}). \)
The simulation is performed at a frequency sufficiently low so that a quasi-static solution is still valid and sufficiently high so that the simulation run time is practicable.

Usually a frequency $f'$ in the range 1-5 MHz can be considered.

The simulation is performed using $\sigma$ values at the (low kHz) frequency of interest $f$ and results $E'$ and $J'$ at $f'$ are scaled to $f$:  

$$E = \frac{f}{f'} E'$$

$$J = \frac{f}{f'} J'$$
Position 1: Centre of voxel model is (0.35, 0, 0.9) m. The minimum distance between the body and the coil ~ 0.19 m.

Position 2: Centre of voxel model is (0.35, 0, 1.15) m.

Position 3: Centre of voxel model is (0.35, -0.56, 0.9) m.
Magnitude of $B \sim 0.1 – 0.52$ mT when the $B_z$ gradient was 10 mT/m.

IEEE C95.6-2002 MPE value at 1 kHz for exposure of the head and torso to sinusoidal fields is $B_{(RMS)} = 2.06$ mT

Directive 2004/40/EC Action Value for $0.82 \leq f \leq 65$ kHz is $B_{(RMS)} = 30.7$ $\mu$T
Predicted E-field (Averaged over 5 mm)

Position 1: plane \(x = 0.369\) m \(\quad\) plane \(z = 0.903\) m

\(|E| \sim 2.7\) V/m in the skin of the tip of the nose.

\(|E| \sim 4.1\) V/m and occurred in the skin of inner right leg

\(|E| \) in CNS \sim 32 \) mV/m in spinal cord in the thoracic vertebrae.
# Predicted E-field (Averaged over 5 mm)

Max RMS E-field values averaged over 5 mm (gradient = 10mT/m)

<table>
<thead>
<tr>
<th>Position</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>4.1 V/m located in the skin of inner right leg close to groin. 2.7 V/m in the skin of the tip of the nose. 32.0 mV m(^{-1}) in the spinal cord</td>
<td></td>
</tr>
<tr>
<td>Position 2</td>
<td>1.6 V/m, located in the skin of inner right leg close to groin. 1.1 V/m in the skin at the tip of the nose 18.9 mV/m in the spinal cord</td>
<td></td>
</tr>
<tr>
<td>Position 3</td>
<td>954 mV/m in the head</td>
<td></td>
</tr>
</tbody>
</table>

Basic restrictions (IEEE C95.6 2002) at 1 kHz are:

<table>
<thead>
<tr>
<th>Exposed tissue</th>
<th>(E_0) (RMS) (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>brain</td>
<td>0.885</td>
</tr>
<tr>
<td>heart</td>
<td>5.65</td>
</tr>
<tr>
<td>Other tissues (excluding hands, wrists, feet and ankles)</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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The RMS current density spatially averaged over 1 cm$^2$ in the plane normal to the direction of current flow.

$$J \leq 10 \text{ mA/m}^2 \text{ for } 1 \text{ kHz}$$

They are intended to protect against effects of acute exposure to CNS tissues in the head and trunk.

Higher current densities in body tissues other than the CNS under the same exposure conditions may be permitted.
Max RMS J Value Averaged over 1 cm² (for Gradient of 10mT/m)

Position 1: 15.4 mA/m² close to thoracic vertebrae
Position 2: 10.9 mA/m² close to thoracic vertebrae
Position 3: 20.4 mA/m² in head

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Compliance when gradient is 10mT/m

<table>
<thead>
<tr>
<th>Position</th>
<th>IEEE C95.6 2002</th>
<th>Directive 2004/40/EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>✗ 4.1 V/m (skin of inner right leg close to groin) 2.7 V/m (skin of the tip of the nose).</td>
<td>✗ ( J_{\text{max}} = 15.4 \text{ mA/m}^2 )</td>
</tr>
<tr>
<td>Position 2</td>
<td>✓ Complies (&lt; 2.1 V/m)</td>
<td>✗ ( J_{\text{max}} = 10.9 \text{ mA/m}^2 )</td>
</tr>
<tr>
<td>Position 3</td>
<td>✓ Complies (&lt; 2.1 V/m)</td>
<td>✗ ( J_{\text{max}} = 20.6 \text{ mA/m}^2 )</td>
</tr>
</tbody>
</table>
Summary

Electric field $E$ and current density $J$ at 1 kHz within an anatomically realistic human body model located 0.19-0.44 m from the end of a generic z-gradient coil were described.

E-field hot spots in the groin and at the tip of the nose did not comply with the basic restrictions in the case of Position 1.

The maximum values of spatially averaged RMS current density exceeded the exposure limits values set in Directive 2004/40/EC for all three positions considered.
Acknowledgements

This work was funded by:

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Gradient: 10 mT/m.
Maximum amplitude 2.31 mT at $z = +/- 0.325$ m in agreement with Tas (2005)$^2$. 

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Homogeneous sphere, $\sigma = 0.2 \text{ S/m}$, radius 0.25 m, placed symmetrically with respect to a Helmholtz pair (radii and centre-centre separation 0.35 m)

A sinusoidal current of peak amplitude 1 A was injected at each of the ports of the current loops

Model was meshed to $\sim 5.5 \times 10^6$ cells.
Verification against analytical data

The B-field from the Helmholtz pair at a distance $r$ off axis in the mid-plane, $B_{Hz}$

$$B_{Hz} = \frac{I\mu_0}{\pi a \sqrt{((1+\alpha)^2 + \beta^2)}} \left[ E(k) \frac{1 - \alpha^2 - \beta^2}{(1 + \alpha)^2 + \beta^2 - 4\alpha} + K(k) \right]$$

$a$ is the radius and $2d$ is the separation of the loops  
$r$ is the radial distance from the axis to the measurement point  
$\alpha = \frac{r}{a}$  
$\beta = \frac{d}{a}$  
$E(k)$ and $K(k)$ are the complete elliptical integrals of the first and second kind
Verification against analytical data

Current density within a homogeneous sphere exposed to a time-varying uniform B-field is given by:

\[ J(r) = \pi f \sigma B r \]

Take \( \sigma = 0.2 \) S/m, \( B = 2.569 \) µT and \( f = 1 \) kHz
## Verification against analytical data

<table>
<thead>
<tr>
<th>$r$ (m)</th>
<th>$B$ (μT)</th>
<th>$J$ (μA/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical</td>
<td>Numerical</td>
</tr>
<tr>
<td>0</td>
<td>2.569</td>
<td>2.567</td>
</tr>
<tr>
<td>0.1</td>
<td>2.561</td>
<td>2.558</td>
</tr>
<tr>
<td>0.15</td>
<td>2.525</td>
<td>2.521</td>
</tr>
</tbody>
</table>

$\text{r} < 0.7\%$ $\text{J} < 0.7\%$
Verification against analytical data

$r = 0.15 \text{ m}$

$r = 0.1 \text{ m}$

Simulated

Analytical