Quandaries in the application of the ICNIRP low frequency basic restriction on current density

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Quantify 3D Geometric Distortion in MR Images
Verify the accuracy of target delineation and treatment efficacy for MRgRT
Quandaries in the application of the ICNIRP low frequency basic restriction on current density

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Abstract
This paper identifies uncertainties and problems in the practical application of the ICNIRP low frequency basic restriction on current density. This quantity should be averaged over a cross-section of 1 cm² perpendicular to the current direction. The rationale and the sensitivity of the current density average are investigated. There are difficulties in finding a square centimetre of spinal cord over which to average. The consequences of including neighbouring tissues in the averages are investigated in the male and female voxel models NORMAN and NAOMI for applied uniform electric and magnetic fields at 50 Hz. Also the case of the non-uniform magnetic field from a horizontal current carrying conductor adjacent to the back of the body is investigated. The maximum and 99th percentile current density values are compared with the 1 cm² average in the derivation of external field reference levels.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

An aim of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is to disseminate information and advice on the potential health hazards of exposure to non-ionizing radiation through the publication of exposure guidelines. The ICNIRP (1998a) basic restrictions on induced current density up to 10 MHz are provided to prevent effects on functions of the nervous system such as the control of movement and posture, memory, reasoning and visual processing. At 50 Hz the basic restriction is 10 mA m⁻² for occupational exposure and is 2 mA m⁻² for general public exposure. In a response to questions and comments on the guidelines, the ICNIRP (1998b) clarified that the basic restriction was based only on the threshold for acute effects in the central nervous system tissues in the head and trunk of the body. This basic restriction may permit higher current tissues in body tissues other than the central nervous system under the same exposure conditions. This confines the application of the current density restriction to the brain, retina and spinal cord. A footnote
to the table on basic restrictions states that ‘because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm² perpendicular to the current direction’.

The area of 1 cm² is somewhat arbitrary and seems large in comparison with possible sensitive structures in the central nervous system. Why is the inhomogeneity of the body an argument for using a relatively large area over which to average the current density? The opposing conclusion is that one should strive to avoid averaging over other non-central nervous system tissues, such as the high conductivity cerebrospinal fluid (CSF), by employing an area small enough to be wholly located within brain, spinal cord or the retina. ICNIRP (1999) in a response to CENELEC have suggested that for simplification it is acceptable to assume that the 1 cm² sections are composed entirely of nerve tissue. The implication is that voxels around the target tissue can be assigned electrical properties of the target tissue to make up the appropriate averaging area. However, this procedure will not produce the correct induced field distributions and this artificial physiology seems a makeshift way to resolve a problem that is inherent within the definition of the basic restriction.

The mean cross-sectional area of the spinal cord from data in the International Commission on Radiological Protection (ICRP) Publication 23 (1975) is about 0.6 cm². Therefore, for most of its length it is not possible to average over 1 cm² of the spinal cord. For uniform magnetic and also electric field exposure (Dimbylow 2005), this may not be too important because the maximum current densities occur in the higher conductivity retina and brain. However, for non-uniform exposures such as the magnetic fields encountered by live-line workers with the conductors adjacent to the lower back or by operational staff near to high gradient field MRI systems, then one might expect the maximum current density to occur in the spinal cord. Crozier et al (2007) have investigated occupational exposure for personnel working with and around magnetic resonance imaging equipment. This study was aimed to determine the worst case scenarios and so used a ‘full averaging algorithm’ which includes the current flowing in neighbouring dissimilar tissues. This method will overestimate the average values in low conductivity tissues and overestimate the averages in high conductivity tissues.

This paper investigates the effects on the average current density of using squares of varying area and the consequences of including neighbouring tissues in these averages. The induced current density distributions presented in Dimbylow (2005) using both male and female voxel models for applied uniform electric and magnetic fields at 50 Hz are analysed. Also the case of the non-uniform magnetic field from a horizontal current carrying conductor adjacent to the back of the body is investigated.

2. Voxel model calculations

2.1. Male and female voxel models: NORMAN and NAOMI

NORMAN and NAOMI are the Health Protection Agency (HPA) male and female voxel models designed to be representative of the average adult. A description of their construction, the acquisition of the medical imaging data and its segmentation into tissue types can be found in Dimbylow (1997, 2005), respectively. NORMAN was normalized to be 1.76 m tall and to have a mass of 73 kg, the values for ICRP (2002) reference man. The height fixes the vertical voxel dimension, 2.021 mm, and the horizontal dimensions, 2.077 mm, are then fixed by the mass. There are 8.3 million voxels in the body differentiated into 38 different tissue types. Likewise, NAOMI was rescaled to the reference adult female height of 1.63 m and a mass of 60 kg. The voxel dimensions are 2.061 mm in the vertical direction (z) and 1.948 mm in the horizontal directions (x from front to back and y from side to side). A 5 × 5 square will have
nominal dimensions of 1 cm\(^2\). In NORMAN, the exact areas will be 1.08 cm\(^2\) in the \(x\)-\(y\) plane and 1.05 cm\(^2\) in the \(x\)-\(z\) and \(y\)-\(z\) planes. In NAOMI these will be 0.95 cm\(^2\) in the \(x\)-\(y\) plane and 1.00 cm\(^2\) in the \(x\)-\(z\) and \(y\)-\(z\) planes.

2.2. Spinal cord anatomy

ICRP Publication 23 (1975) gives reference masses for the spinal cord of 30 g for the adult male and 28 g for the female. Table 96 gives a mean length of 45 cm for the male and 42–43 cm for the female. The specific gravity is 1.0387 for the male and 1.0348 for the female. Assuming a cylindrical structure gives a mean cross-sectional area of 0.64 cm\(^2\) in both the male and female. Figures 1 and 2 show the number of spinal cord voxels in a horizontal cross-section as a function of height in NORMAN and NAOMI. The dashed line is at 25 voxels representing a nominal cross-section of 1 cm\(^2\). In many sections in NORMAN and nearly entirely in NAOMI the spinal cord cross-sectional area is less than 1 cm\(^2\). In NORMAN the average cross-sectional area is 1.30 cm\(^2\) whilst in NAOMI it is 0.50 cm\(^2\).

3. Calculations of average induced current density

3.1. Numerical methods

The numerical methods used to calculate the induced current densities for applied magnetic and electric fields are outlined in Dimbylow (2005). The SPFD method (Dawson et al. 1996, Dawson and Stuchly 1997, Dimbylow 1998, Caputa et al. 2002) has been used for applied magnetic fields. A nested sub-grid technique (Dimbylow 2000) was used for applied electric fields. The outer region of the domain extended sufficiently so that the perturbation in the applied field, due to the phantom, was small at the periphery whilst the grid near and in
the phantom was matched to the voxel resolution. An evaluated review of the dielectric properties of all the tissue types in the models was performed by Gabriel et al (1995, 1996a, 1996b, 1996c). A 4-Cole-Cole dispersion model was fitted to the data for each tissue type to parameterize the conductivity and permittivity as a function of frequency. Other recent examples of induced current density calculations can be found inter alia in Cech et al (2007), Bencsik et al (2007) and Dimbylow (2006).

The induced current densities in both models were analysed at 50 Hz for uniform magnetic fields aligned from front to back of the body (AP) and from side to side (LAT), for a uniform electric field under grounded conditions and for a non-uniform magnetic field from a horizontal current carrying conductor adjacent to the back of the body.

3.2. Applied uniform magnetic and electric fields

Figure 3 shows the current density in NORMAN for the three rectilinear directions averaged over squares of brain tissue for a LAT uniform magnetic field. The squares of side from 1 to 10 only comprise brain voxels. The x-direction is from the front to the back of the body, y is from side to side and z is the vertical direction. A side length of 5 voxels gives an averaging area of 1 cm², whilst a side of 10 voxels gives an area of 4 cm² and a side of 1 voxel gives an area of 0.04 cm². The z-component gives the highest current densities in squares of brain, 3.32 A m⁻² per T for the 5-square (square with a 5 voxel side). Averaging over a 1-square yields values about two to three times that of the 5-square and the 10-square gives values about half the 5-square. Figure 4 gives a similar plot for the spinal cord. In this case, the maximum side lengths of square that comprise totally spinal cord are 9 normal to the x-direction, 7 normal to y and 6 normal to z. The z-component gives the highest current densities in squares of spinal cord, 1.34 A m⁻² per T for a 5-square. For a 1-square the value is a factor
Figure 3. Current density averaged over brain squares of varying side for a LAT uniform magnetic field of 1 mT. The $x$-direction is from the front to the back of the body, $y$ is from side to side and $z$ is the vertical direction.

Figure 4. Current density averaged over spinal squares of varying side for a LAT uniform magnetic field of 1 mT. The $x$-direction is from the front to the back of the body, $y$ is from side to side and $z$ is the vertical direction.
Figure 5. The number of squares, normal to the z-direction, consisting entirely of brain as a function of the number of voxels per side.

of 2.3 times higher than the 5-square. Figures 5 and 6 display the number of possible squares consisting entirely of brain and spinal cord respectively as a function of the number of voxels per side. In brain the number of squares for a particular side decrease smoothly from around 170 000 for a 1-square to 50 000 for a 10-square. In the spinal cord, the number of squares for a particular side drops off dramatically with the increasing area. Indeed there are no squares of side 5 over which to average 1 cm² in NAOMI.

Because of this difficulty in defining a 1 square cm of spinal cord it may be useful to look at the ‘full averaging algorithm’ which includes the current flowing in neighbouring dissimilar tissues as suggested by Crozier et al (2007) to determine a worst case scenario. Figure 7 shows the current density in the x-direction, \( J(x) \) averaged over squares of varying side for a LAT uniform magnetic field of 1 mT in NORMAN. The average is over all tissue types that fill squares of side from 1 to 10, but the brain must provide more than \( p\% \) of the cells where \( p = 50, 60, 70, 80, 90 \) and 100. Obviously, as one allows more high conductivity non-target material, principally CSF into the average, the higher this will be. The conductivity values of retina, brain, spinal cord and CSF are 0.5, 0.08, 0.03 and 2.0 S m\(^{-1}\). The maximum \( J(x) \) averaged over a single voxel are 5.37 and 1.75 mA m\(^{-2}\) in the brain and spinal cord but 65.0 mA m\(^{-2}\) in CSF. For a 5-square insisting on only 50% of brain the inclusion of CSF increases the \( J(x) \) average over the standard single tissue average (\( p = 100 \)) by a factor of over 5. Moreover, it is higher than the average over a single brain voxel by a factor of 2.3. Figure 8 shows a similar plot for \( J(z) \) in the spinal cord. The effect of including CSF into the spinal cord average is more marked than for brain. For a 5-square insisting of only 50% of the spinal cord the inclusion of CSF increases the \( J(z) \) average over the single tissue average by a factor of 13 and it is higher than the average over a single spinal cord voxel by a factor of 5.3. Figure 9 displays spinal cord averages for NAOMI. There are no 5-squares comprising completely of spinal cord. The inclusion of other tissues in the averages does not produce such high values as for NORMAN because there is less high conductivity CSF surrounding
Figure 6. The number of squares, normal to the three orthogonal directions, consisting entirely of spinal cord as a function of the number of voxels per side.

Figure 7. Current density in the $x$-direction averaged over squares of varying side for a LAT uniform magnetic field of 1 mT in NORMAN. The average is over all tissue types that fill squares of side from 1 to 10, but brain must provide more than $p\%$ of the cells where $p = 50, 60, 70, 80, 90, 100$.

the spinal cord in NAOMI. A 5-square average consisting of at least 50% of the spinal cord is a factor of 2.3 times higher than the average over a single spinal cord voxel.
Figure 8. Current density in the $z$-direction averaged over squares of varying side for a LAT uniform magnetic field of 1 mT in NORMAN. The average is over all tissue types that fill squares of side from 1 to 10, but spinal cord must provide more than $p\%$ of the cells where $p = 50, 60, 70, 80, 90, 100$.

Figure 9. Current density in the $z$-direction averaged over squares of varying side for a LAT uniform magnetic field of 1 mT in NAOMI. The average is over all tissue types that fill squares of side from 1 to 10, but spinal cord must provide more than $p\%$ of the cells where $p = 50, 60, 70, 80, 90, 100$. 
Quandaries in the application of the ICNIRP low frequency basic restriction

Table 1. Comparison of the averaging strategies for applied magnetic and electric fields. The applied magnetic flux density is 1 mT and the applied electric field is 1 kV m⁻¹.

<table>
<thead>
<tr>
<th></th>
<th>Brain</th>
<th>Spinal cord</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brain Spinal cord</td>
<td>J((z)) for a single tissue</td>
</tr>
<tr>
<td></td>
<td>5 × 5 square (mA m⁻²)</td>
<td>(J((y))) 2.4</td>
</tr>
<tr>
<td></td>
<td>Ratio of single tissue to 1-square tissue</td>
<td>Ratio of 50% tissue to 5-square tissue</td>
</tr>
<tr>
<td>NORMAN AP</td>
<td>3.56</td>
<td>1.9</td>
</tr>
<tr>
<td>NORMAN LAT</td>
<td>3.32</td>
<td>2.1</td>
</tr>
<tr>
<td>NAOMI AP</td>
<td>2.98</td>
<td>2.3</td>
</tr>
<tr>
<td>NAOMI LAT</td>
<td>2.72</td>
<td>2.7</td>
</tr>
</tbody>
</table>

The analyses of the averaging procedures for applied electric fields exhibit similar characteristics. Table 1 summarizes the comparison of the various averaging strategies for applied magnetic and electric fields.

3.3. Non-uniform magnetic fields from a line current source

A non-uniform magnetic field with relatively high values at the spinal cord compared to the head was investigated. There is a minimum in the NORMAN spinal cord cross-section at the voxel height of 600 (figure 1). Calculations were performed at this height for a horizontal conductor aligned from side to side at the back of the models. This is the type of source geometry that could be encountered in, e.g., live-line working. Figure 10 shows current density averages for a line source of 1 kA at a voxel height of 600, 1 cm from the back. In this geometry the maximum current density is still higher in the brain (2.76 mA m⁻²) than in the spinal cord (2.23 mA m⁻²) but allowing CSF in the average makes the spinal cord average much higher than that in the brain. For a 5-square with only 50% of the spinal cord the inclusion of CSF increases the \(J(\(y\))\) average over the single tissue average by a factor of 22 and it is higher than the average over a single spinal cord voxel by a factor of 9.4. Gandhi et al (2001) in their work on currents induced by power frequency magnetic fields argue that an omission from the standard conductivity parameters is the lack of measured conductivity data for the spinal cord for which properties similar to nerve are recommended. They suggest that the spinal cord is similar to brain in texture and does not have connective tissue like nerve and so the conductivity for the brain should also be used for the spinal cord. This means increasing the conductivity for spinal cord from its low value of 0.03 to 0.08 S m⁻¹. Calculations with this spinal cord conductivity give higher values of current density when averaging over only spinal cord. Table 2 summarizes the comparison of averaging strategies for the magnetic field line source.

4. Reference levels based on different algorithms

When considering uniform applied fields the maximum current density occurs in the brain or retina and it is possible to average over 1 cm² of a single tissue. The retina is a curved surface and it is possible to define a set of 25 neighbouring cells, without any inclusions of other
Figure 10. Current density in the $y$-direction averaged over squares of varying side for a line source of 1 kA at a voxel height of 600, 1 cm from the back of NORMAN. The average is over all tissue types that fill squares of side from 1 to 10, but spinal cord must provide more than $p\%$ of the cells where $p = 50, 60, 70, 80, 90, 100$.

Table 2. Comparison of the averaging strategies for a horizontal line source of 1 kA. The source was placed at $\Delta x$ behind the back. $\sigma = 0.08$ denotes that the spinal cord conductivity has been set to that of the brain.

<table>
<thead>
<tr>
<th></th>
<th>Brain</th>
<th>Spinal cord</th>
<th>NORMAN</th>
<th>NAOMI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J(z)$ for a single tissue $5 \times 5$ square (mA m$^{-2}$)</td>
<td>Ratio of 1-square to 5-square tissue</td>
<td>Ratio of 50% of 5-square tissue to 100% tissue</td>
<td>$J$ for a single tissue $5 \times 5$ square (mA m$^{-2}$)</td>
</tr>
<tr>
<td>$\Delta x = 10$ cm</td>
<td>1.35</td>
<td>1.8</td>
<td>2.1</td>
<td>0.766</td>
</tr>
<tr>
<td>$\Delta x = 1$ cm</td>
<td>1.54</td>
<td>1.8</td>
<td>2.2</td>
<td>1.11</td>
</tr>
<tr>
<td>$\Delta x = 1$ cm $\sigma = 0.08$</td>
<td>1.54</td>
<td>1.8</td>
<td>2.2</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Tissue types, from which the maximum can be sought. The maximum current density from non-uniform fields may occur in the spinal cord and it is then difficult to define an averaging area of 1 cm$^2$ in NORMAN and not even possible in NAOMI. This section explores other averaging methods that could be applied consistently to the spinal cord as well as to the retina and brain.
An ad hoc expert group has reported (appendix A, McKinlay et al. 2004) on the potential health effects of physiologically weak electric fields, induced in the body by EMF exposure. They suggested that induced electric field rather than current density might be a more appropriate basic restriction quantity for effects based on voltage-gated ion channels. The averaging volume would be based on a minimum of 1000 interacting cells, approximately 1 mm$^3$ in most nerve tissues. This suggests that an appropriate average for induced electric fields and hence current density which is simply related to the electric field by the conductivity of the particular tissue should be the total field over a single voxel with a volume of at least 1 mm$^3$. The maximum current density, $J_{(\text{max})}$, in a particular tissue will depend upon the resolution of the calculations; the finer the resolution the higher will be the value of $J_{(\text{max})}$. The maximum single voxel value is also susceptible to boundary errors particularly when there is a large contrast in conductivity between neighbouring voxels and where single isolated voxels occur embedded in another tissue. Dawson et al. (2001, 2002) introduced the 99th percentile field value, $J_{(99)}$, i.e. the value exceeded in only 1% of the voxels of that organ. This value avoids to a degree errors introduced into the modelling by the voxel discretization and staircasing errors at sharp corners. Tables 3 and 4 provide relationships between external field values and induced current densities averaged over 1 cm$^2$ normal to the current flow, the maximum current density in a single 2 mm voxel and the 99th percentile value. The 99th percentile value in the retina occurs at about 70–90% of the maximum value. The brain has inclusions of CSF and so the 99th percentile value occurs at about 40% of the maximum value in brain.

In the magnetic field case the maximum current densities occur for LAT alignment in NORMAN. They are 5.50, 7.88 and 10.2 mA m$^{-2}$ for $J_{(1 \text{ cm}^2)}$, $J_{(99)}$ and $J_{(\text{max})}$. The external magnetic flux densities required to produce the occupational basic restriction of 10 mA m$^{-2}$ for these quantities are 1.82, 1.37 and 0.98 mT, respectively. The ICNIRP reference level of 0.5 mT is conservative with respect to all three quantities.
In the electric field case the maximum current densities occur in NAOMI. They are 0.217, 0.276 and 0.485 mA m$^{-2}$ for $J(1 \text{ cm}^2)$, $J(99)$ and $J(\text{max})$. The external electric fields required to produce the occupational basic restriction of 10 mA m$^{-2}$ for these quantities are 46.1, 36.2 and 20.6 kV m$^{-1}$. The corresponding fields for the public exposure basic restriction of 2 mA m$^{-2}$ are 9.22, 7.25 and 4.12 kV m$^{-1}$.

The ICNIRP reference level of 10 kV m$^{-1}$ for occupational exposure is conservative with respect to all three quantities. However, the reference level of 5 kV m$^{-1}$ for public exposure is not conservative if the $J(\text{max})$ quantity is used.

5. Conclusions

The ICNIRP basic restrictions on induced current density in the brain, retina and spinal cord are provided to prevent effects on functions of the nervous system. The current densities should be averaged over a cross-section of 1 cm$^2$ perpendicular to the current direction. The area of 1 cm$^2$ is somewhat arbitrary and seems large in comparison with possible sensitive structures in the central nervous system. The induced current density is sensitive to the size of the averaging area. In brain, averaging over a 1-square gives values about two to three times that of the 5-square and the 10-square gives values about half the 5-square. The same observation can be made for the spinal cord in NORMAN. However, in NAOMI there are no squares of side 5 over which to average 1 cm$^2$.

Because of this difficulty in defining a 1 cm$^2$ of spinal cord, the ‘full averaging algorithm’ which includes the current flowing in neighbouring dissimilar tissues was investigated. Obviously, as one allows more high conductivity non-target material, principally CSF into the average, the higher this average will be. In NORMAN the case that the tissue of interest has to be only in the majority (i.e. 50%) increased the average value over 1 cm$^2$ by up to a factor of 4 in the brain and 20 in the spinal cord compared with the average over a single tissue (100%). The 50% averages over 1 cm$^2$ are even higher than the average over a single voxel by up to a factor of 2 in the brain and 9 in the spinal cord. As the basic restrictions apply to only brain, spinal cord and retina it seems judicious, if there is a difficulty in averaging over 1 cm$^2$ entirely in one tissue, to average over a discrete voxel of the target tissue rather than producing a too conservative value by including CSF into a 1 cm$^2$ average.

An ad hoc expert group has suggested that induced electric field rather than current density might be a more appropriate dose quantity for effects based on voltage-gated ion channels. The averaging volume would be based on a minimum of 1000 interacting cells, approximately 1 mm$^3$ in most nerve tissues. This argument indicates a similar averaging volume for the current density which is related to the electric field by the conductivity of the particular tissue. The maximum current density, $J(\text{max})$, in a particular tissue will depend upon the resolution of the calculations and is susceptible to boundary errors. The 99th percentile field value averts to a certain degree these problems. A comparison has been made between the average over 1 cm$^2$, the 99th percentile and the maximum value for uniform magnetic and electric fields. At 50 Hz the ICNIRP magnetic flux density occupational and public exposure reference levels are conservative with respect to all three quantities. Similarly, the electric field occupational exposure reference level is conservative with respect to all three quantities. However, the reference level of 5 kV m$^{-1}$ for public exposure is not conservative if the maximum current density is averaged over a single voxel.

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Quandaries in the application of the ICNIRP low frequency basic restriction

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