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Article *in* Physics in Medicine and Biology · March 2007

DOI: 10.1088/0031-9155/52/4/001 · Source: PubMed

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Phys. Med. Biol. **52** (2007) 879–888 doi:10.1088/0031-9155/52/4/001

Fetal exposure to low frequency electric and magnetic fields

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Received 16 August 2006, in final form 28 November 2006
Published 17 January 2007
Online at stacks.iop.org/PMB/52/879

Abstract

To investigate the interaction of low frequency electric and magnetic fields with pregnant women and in particular with the fetus, an anatomical voxel model of an 89 kg woman at week 30 of pregnancy was developed. Intracorporal electric current density distributions due to exposure to homogeneous 50 Hz electric and magnetic fields were calculated and results were compared with basic restrictions recommended by ICNIRP guidelines. It could be shown that the basic restriction is met within the central nervous system (CNS) of the mother at exposure to reference level of either electric or magnetic fields. However, within the fetus the basic restriction is considerably exceeded. Revision of reference levels might be necessary.

1. Introduction

In the low frequency range electric and magnetic fields cause intracorporal electric current densities, although ruled by different physical laws and hence with different intracorporal orientation and pathways. Existing guidelines (ICNIRP 1998) contain reference levels for external electric and magnetic field quantities associated with basic limits to prevent adverse health effects. For frequencies up to 10 MHz the 'basic restriction' is based on intracorporal electric current densities within the central nervous system (CNS) averaged over 1 cm^2 perpendicular to the current flow. At 50 Hz, basic restrictions for the general public are set to 2 mA m^{-2}. By numerical simulations the corresponding reference levels of external field quantities were determined for sole exposure to either electric or magnetic fields. For worst case exposure conditions to homogeneous fields numerical simulation resulted in an electric field strength of 5 kV m^{-1} and a magnetic flux density of 100 μT, respectively.

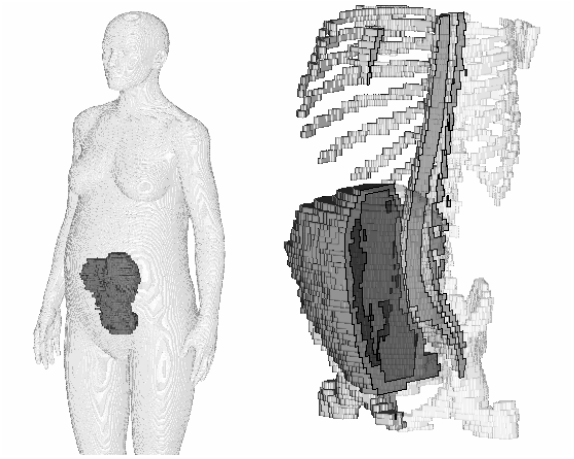
However, this relationship was derived concentrating on adults, in particular on male subjects only. Induction by 60 Hz *magnetic* fields was studied by Xi *et al* (1994) who calculated current densities within a homogeneous and a heterogeneous 13 mm cubical anatomical voxel model of a 70 kg/177 cm man, a rat and a mouse. Dimbylow (1998) presented calculations of current densities in a more realistic 2 mm male voxel model NORMAN (73 kg/176 cm) for uniform magnetic fields at 1 T incident from front, side and top of the body for frequencies from 50 Hz to 10 MHz. Dawson and Stuchly (1998) applied a modified Yale phantom (76 kg/177 cm) with a voxel resolution of 3.6 mm to 60 Hz uniform magnetic fields in three orthogonal orientations. Gandhi *et al* (2001) concentrated on the calculation of current densities in the CNS as averages over 1 cm^2 perpendicular to the current direction as recommended by ICNIRP (1998). A 6 mm resolution male model of the human body (71 kg/176 cm) was first used to investigate the induced current density distribution caused by uniform magnetic fields of various orientations and magnitudes. In a second step, regions around the spinal cord were refined to the original model dimensions of $2 \times 2 \times 3$ mm.

The interaction of low frequency *electric* fields with anatomical models of the human body was studied by Furse and Gandhi (1998). For external electric field exposure of 10 kV m^{-1} induced current densities were investigated in an MRI-based grounded male 6 mm voxel model (71 kg/176 cm). Dimbylow (1999) used NORMAN (73 kg/176 cm) for calculations of current density distributions induced by uniform, low frequency vertically oriented electric fields for grounded and isolated conditions from 50 Hz to 1 MHz. Hirata *et al* (2001) calculated electric field strength and current densities in a model of an adult (76 kg/177 cm) and a model of a 5-year-old child (18.7 kg/110 cm) caused by a uniform vertical electric field for both grounded and isolated conditions. Dimbylow (2005) described the development of a 2 mm female voxel model NAOMI (163 cm, 60 kg) and the calculation of current densities and electric fields induced by low frequency electric and magnetic fields. Comparisons were made to values from NORMAN. The calculations were performed from 50 Hz to 1 MHz for magnetic and electric field exposures. For external electric and magnetic fields at reference levels, induced current densities in the CNS lay below values gained with NORMAN and also below the recommended basic restriction.

Nagoka *et al* (2004) developed a 2 mm resolution, whole-body model of a Japanese adult male and a female, TARO and HANAKO, for calculations in radiofrequency electromagnetic-field dosimetry. The models with averaged height and mass differ between Japanese and Caucasians. Shi and Xu (2004) described the development of a torso model of a pregnant woman based on computed tomography (CT) images and its application to Monte Carlo organ dose calculations in the radiofrequency range only.

So far, reported results confirmed that for low frequency electric or magnetic field exposures at reference levels the basic restrictions are met even when applying different simulation methods using models with different size, mass and resolution. However, if a fetus within a pregnant woman is taken into account, the region of interest is enlarged to its CNS. Unfortunately, there were no numerical and high-resolution anatomical whole-body models of a pregnant woman available yet. Hence, it remains unclear whether existing basic restrictions also protect the fetus.

To fill the gap, the high-resolution model of a pregnant woman SILVY was developed and exposures to either low frequency electric or magnetic fields were studied. Results were compared with ICNIRP guidelines (1998). For 50 Hz reference level 5 kV m^{-1} electric and 100 μT magnetic fields at different orientations, the maximum 1 cm^2-averaged current densities were calculated and values within the central nervous systems of mother and fetus were compared to the basic restriction of 2 mA m^{-2}.



(a) (b)

Figure 1. (a) Fetal soft tissue inside the full body model and (b) the fetal soft tissue and skeleton, the placenta and the uterus.

2. Method

2.1. Development of pregnant voxel model, SILVY

The development of the pregnant voxel model SILVY was based on own MR images of a pregnant women with a malformed fetus, which were taken during a routine diagnostic examination in the beginning of the third trimenon. These data were modified based on CT-images of a woman in the 30th week of pregnancy presented by Shi and Xu (2004) on the internet[1].

The anatomical images cover the portion of the body between the lower breast and the upper thigh in 70 slices, each 7 mm thick. The image resolution was 512 × 512 pixels. Therefore, the size of each pixel of the anatomical cross-sectional images was 0.938 mm and the height of the associated voxels was 7 mm. The MRI and CT data were carefully segmented to identify 37 different organs and tissues. The spinal cord was manually inserted inside the backbone in a post-processing step (figure 1(b)).

Subsequently, this trunk model was inserted into a homogeneous whole-body 3D computer model of a woman, which was generated by laser scan imaging. By combined linear and nonlinear scaling, this female CAD-model was adapted to the trunk of the anatomical pregnant model after removing its superficial fat and skin layers.

To account for the region of interest restricted to the CNS, the brain and spinal cord were taken from the male model NORMAN and fitted into SILVY. This allowed identification of the proper region of interest also outside the anatomical torso part where the spinal cord was given the same conductivity to keep this part homogeneous (figure 2).

In order to get overall model compatibility, the pregnant part of the voxel model was redissolved by an image processing algorithm based on the nearest neighbour interpolation. By this, the whole-body pregnant voxel model SILVY with a voxel resolution of 2 mm could be generated (figure 1(a)). The total mass of the model was 89 kg, which is in quite good agreement with the known weight of the pregnant patient.

[1] http://www.rpi.edu/dept/radsafe/public_html/Projects/pregnant%20woman.htm

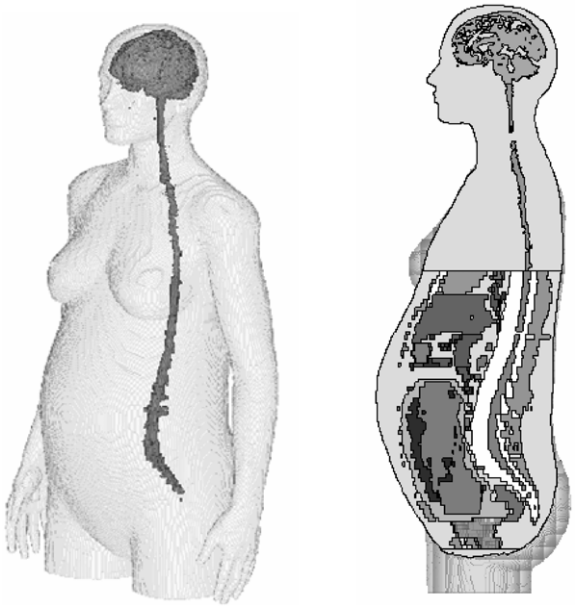


Figure 2. The position of the 'virtual CNS' inside the pregnant model SILVY.

Table 1. Conductivities of various tissues assumed for 50 Hz.

Tissue	Conductivity σ (S m^{-1})
Bone	0.0201
Fat	0.0196
Heart	0.0827
Homogeneous tissue	0.216
Muscle	0.233
Skeleton of fetus	0.0201
Soft tissue of fetus	0.216 (+10%)
Spinal cord	0.0274
Uterus	0.229

The dielectric properties of body tissues were obtained from Gabriel *et al* (1996), which is almost in agreement with CENELEC (2004). For the homogeneous parts of the mother model, such as head, arms and legs, an electric conductivity of $\sigma = 0.216$ S m^{-1} was chosen, which equals the average properties of human tissue at 50 Hz, obtained by averaging conductivity values of all tissues over all parts of the body. Since data for the electric properties of fetal tissues at low frequency are still lacking, the conductivity of average body tissues was taken also for the fetal soft tissue. In a second calculation step they were increased by 10% to account for the higher water content of fetal tissue. Lu *et al* (1996) measured the *in vitro* dielectric properties of human fetal organ tissues in the frequency range from 100 kHz to 500 MHz. However, these data were not applicable to 50 Hz. For the fetal skeleton the electric conductivity was taken from the adult, i.e. 0.02 S m^{-1}. Table 1 gives the values of the electric conductivity of the most relevant tissues at 50 Hz.

2.2. Numerical method

The calculations were performed with the software package CST Studio® Suite[2] which has been developed for general purpose electromagnetic simulations based on the finite integration technique (FIT) (Weiland 1977). This numerical method provides a universal spatial discretization scheme applicable to various electromagnetic problems ranging from static field calculations to high frequency applications in time or frequency domain. Unlike most numerical methods, FIT discretizes the integral rather than the differential form of Maxwell's equations. Magnetic field interaction was calculated by the CST Low-Frequency Solver® which is based on Maxwell's grid equations for the time harmonic case. The simulation of the interaction of low frequency electric fields was more complicated. This was done with the CST Transient Solver®. This time domain solver is similar to FDTD with a different stability criterion and is not directly applicable to solve low frequency problems because the number of required time steps is proportional to the inverse of the frequency. To preclude the huge number of time steps that would be needed in these simulations the frequency scaling approach was used (Furse and Gandhi 1998), which relies on the quasi-static nature of the problem. This allowed calculations at a higher quasi-static frequency, e.g. 10 MHz, with the results scaled back to the low frequency of interest, e.g. 50 Hz. The validity of this method could be shown in Furse and Gandhi (1998). The exposure to electric and magnetic fields was simulated for worst case conditions of a well grounded model. Calculations were done with frontal, sagittal or vertical orientation of the magnetic field and vertical orientation of the electric field.

3. Results

The dependence on the height of the calculated total current induced in the pregnant woman model SILVY by a vertical electric field is shown in figure 3. The current increases from head to the feet of the grounded model and finally reaches 16.8 μA per kV m^{-1}. For comparison with the literature data this result was scaled to account for the differences in size and volume. The resulting 14.5 μA per kV m^{-1} of the downscaled SILVY are in good agreement with the value already published by Dimbylow (1998) which was 14.8 μA per kV m^{-1} for the calculated total current of NORMAN. Also, good agreement could be found with 14.7 μA (linearly scaled from 17.6 μA at 60 Hz) obtained by Dawson *et al* (Dimbylow 1998) for a 177 cm, 76 kg phantom and 14.3 μA similarly scaled from Furse and Gandhi (1998) for a 176 cm, 72 kg phantom.

For further comparison an own simulation with the NORMAN model resulted in a total current of 13.2 μA per kV m^{-1}, which is only about 10% lower than the published value from Dimbylow (1998) with the same model which can be considered to be a fairly good agreement of different calculation and meshing methods.

Figure 4 shows the results of cross-section-averaged values of the intracorporal electric current densities in 2 mm thick horizontal slices of SILVY associated with different exposure situations (100 μT homogeneous magnetic field in frontal, sagittal or vertical orientation and a vertical 5 kV m^{-1} electric field in vertical orientation) with the lower electric conductivity chosen for the fetal soft tissue. The vertically oriented electric field at reference level causes higher current densities than the magnetic field at any orientation. E-field related hot spots occur in the neck, the knees and ankles (absolute maximum) as a result of the reduced cross sections. For magnetic fields the frontal orientation led to the highest current density values, this time in the trunk, but not in the extremities. In the head and trunk region the maximum

[2] CST Studio® Suite 2006 CST GmbH, Bad Nauheimer Straße 19, D-64289, Darmstadt, Germany, www.cst.com.

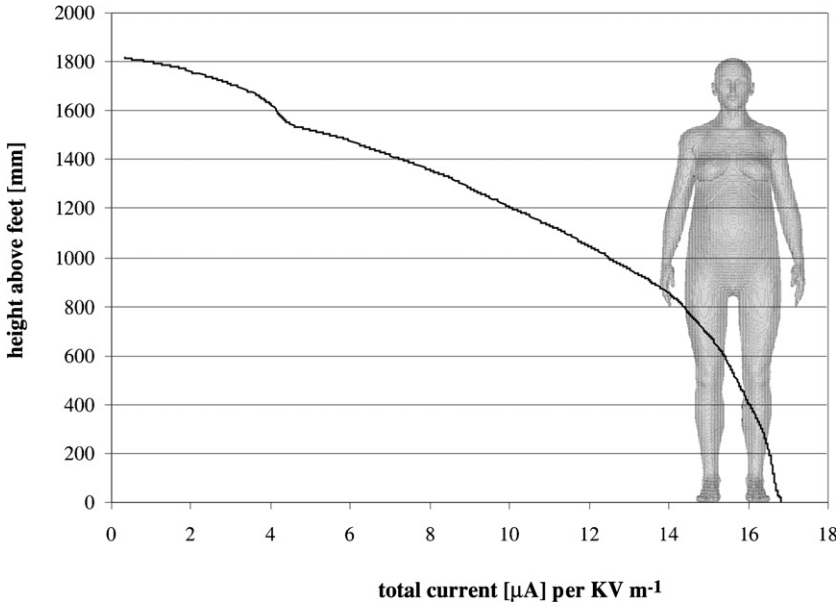


Figure 3. Vertical total current per kV m^{-1} at 50 Hz in the pregnant woman model SILVY in a vertical electric field in a grounded condition.

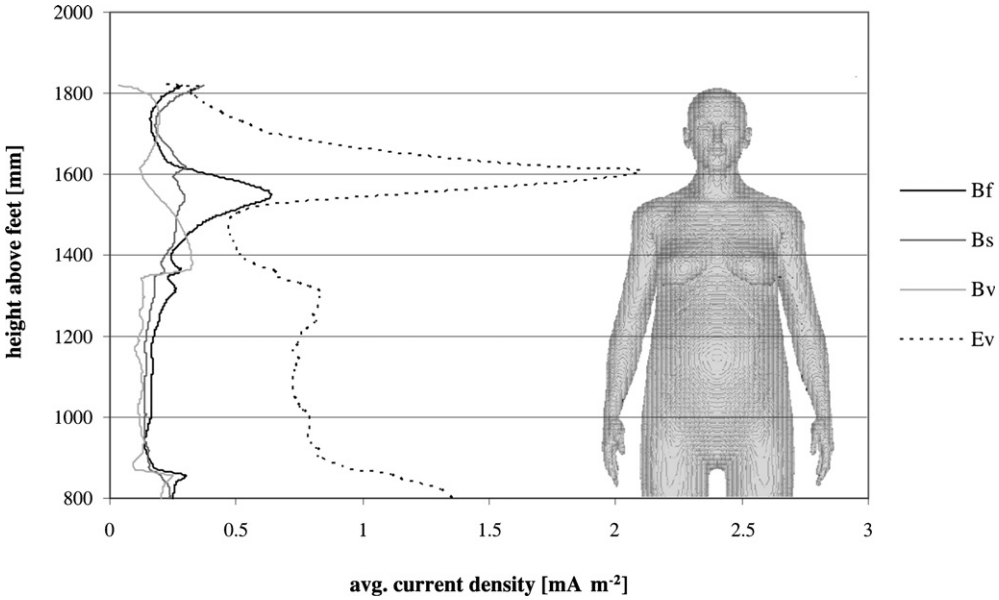


Figure 4. Individual cross-section averages of the intracorporal electric current densities at 50 Hz in mA m^{-2} in each 2 mm thick horizontal slice in the pregnant human model SILVY caused by a homogeneous 100 μT magnetic field with frontal (B_f), sagittal (B_s) and vertical (B_v) orientation, respectively, and by a vertical 5 kV m^{-1} electric field (E_v). For clarity the results are restricted to the upper part of the body.

cross-sectional average values for worst case electric and magnetic field orientations are found at the neck with 2.10 mA m^{-2} and 0.63 mA m^{-2}, respectively.

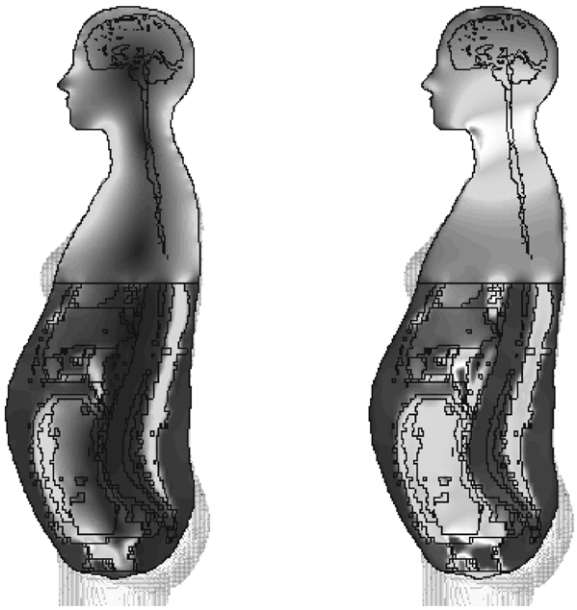
Table 2. Maximum 1 cm^2 area-averaged current densities at 50 Hz in maternal spinal cord, fetal soft tissue, uterus, placenta and in the whole body induced by frontally (B_f), sagittally (B_s), vertically (B_v) oriented 100 μT magnetic and 5 kV m^{-1} vertically oriented (E_v) electric field. Values in brackets were calculated with a 10% higher conductivity of fetal soft tissue. Non-compliance with the recommended basic restriction of 2 mA m^{-2} is highlighted by bold values.

	1 cm^2-averaged current density J (mA m^{-2})			
Tissue	B_f	B_s	B_v	E_v
Soft tissue of fetus	0.604	0.652	0.424	**3.30**
	(0.617)	(0.652)	(0.430)	**(3.32)**
Spinal cord of mother	0.160	0.247	0.419	1.13
	(0.160)	(0.248)	(0.423)	(1.13)
'Virtual CNS' of mother	0.413	0.362	0.419	1.980
	(0.412)	(0.360)	(0.423)	(1.980)
Uterus	0.791	1.21	0.627	5.20
	(0.795)	(1.20)	(0.634)	(5.20)
Placenta	0.596	0.651	0.552	**(2.33)**
	(0.600)	(0.666)	(0.555)	**(2.33)**
Heart	0.462	0.711	0.308	1.70
	(0.463)	(0.714)	(0.308)	(1.70)
Kidneys	0.475	0.351	0.222	1.93
	(0.477)	(0.352)	(0.223)	(1.92)
Liver	0.868	0.770	0.315	**2.85**
	(0.869)	(0.774)	(0.312)	**(2.85)**
Bladder	1.48	1.28	0.773	**5.94**
	(1.49)	(1.28)	(0.782)	**(5.96)**
Body	**2.26**	1.18	0.905	**10.10**
	(2.27)	(1.18)	(0.919)	**(10.10)**

Table 2 shows the results of the maximum 1 cm^2-averaged electric current densities within the spinal cord, uterus, placenta and several other abdominal organs of the mother and the fetal soft tissue for the vertically oriented electric field, and frontally, sagittally and vertically oriented magnetic fields. The values in brackets refer to a second calculation pass with the electric conductivity of fetal soft tissue increased by 10%. The highest value in the trunk of the model occurs in the bladder, which has a high conductivity (up to 1.28 mA m^{-2} for frontally oriented magnetic field and 5.94 mA m^{-2} for vertical electric field). The overall maximum current density of 10.1 mA m^{-2} was found at the ankles of the grounded model with vertical electric field exposure. Figure 5 shows the intracorporal electric current density distribution in a cross-sectional plane for the worst case exposure condition.

Electric current densities calculated within the CNS of the mother met the basic requirements at reference level exposure conditions. The maximum was found for vertical electric field exposure almost at reference level. It was 1.98 mA m^{-2} which in fact is more than 4.6 times higher than the maximum induced by a vertical magnetic field (0.432 mA m^{-2}), but still meets the basic restriction of 2 mA m^{-2}. The magnetic field induced maximum is located in the spinal cord of the heterogeneous part of the model; the maximum current density induced by the electric field could be found in the virtual position of the spinal cord in the neck.

The situation changed dramatically when analysing the fetus. Due to the possible movement of the fetus, the location of the CNS cannot be considered fixed like the spinal cord of the mother. Therefore, any position of the fetal body needs to be considered. Therefore, to check for compliance the maximum electric current density was determined within the



(a) (b)

Figure 5. Electric current density distributions in a medial sagittal cross-sectional plane caused by (a) a sagittally oriented magnetic field and (b) a vertically oriented electric field. All plots are scaled to a maximum range of 2 mA m^{-2}.

whole fetal body region. It could be shown that exposure to magnetic fields at reference level remained in compliance with the basic restrictions, although the values were about 50% higher than in the spinal cord of the mother for the vertically and up to 3.8 times higher for the frontally oriented field. Differences became lower when current densities within the fetal soft tissue were compared to values within any virtual position of the maternal CNS (2% higher for vertically and 1.8 times higher for sagitally oriented magnetic fields).

However, the exposure to the homogeneous electric field caused an excess of the basic restriction by more than two thirds (3.32 mA m^{-2}). The increase of the average fetal tissue conductivity by 10% did not change much. It increased the maximum induced current densities only by less than 2%, indicating that the choice of this value is not critical.

It could be shown that values for the worst case single exposure conditions of electric and magnetic fields lie below the basic restriction when considering the CNS of the mother. However, within the fetus the simulated maximum 1 cm^2 area-averaged current density increased the recommended basic restriction of 2 mA m^{-2} by a factor of 1.65 (3.32 mA m^{-2}).

4. Discussion

Compliance with the basic restriction within the CNS of the mother for electric and magnetic field exposures could be shown by calculation of the maximum current density within the spinal cord: for electric field exposure the hot spot was found in the virtual spinal cord in the neck within the homogeneous part of SILVY. Considering the restricted electric conductive area due to the oesophagus, trachea and the backbone, even higher values can be expected in the CNS part of the neck. Considering, on the one hand, that the maximum induced current

density inside the spinal cord almost reaches the basic restriction of 2 mA m^{-2}, and on the other hand, that assessment uncertainties should be subtracted prior to comparison, reference levels of electric fields do not comply any longer with basic restrictions. Finally, the used SILVY model, although above-average-sized, does not represent the anatomical worst case and even higher values for the induced current densities can be expected for taller and corpulent persons.

Similar arguments apply to the non-compliance found within the fetus. Although the anatomical structures of the fetus were not modelled in detail, the conclusions are not compromised. On the one hand, the calculation uncertainties are much lower than the excess of the basic restrictions (and should be subtracted prior to comparison, anyway). On the other hand, the fetus model represents week 30 of pregnancy. It can be expected that the non-compliance would be even more pronounced close to birth. The excess of the basic restriction was calculated for the worst case which is a barefooted well-grounded mother exposed to homogeneous reference level electric or magnetic fields at worst case orientation. This might not reflect the usual situation. If the isolating abilities of shoes were considered, the exposure to electric-field-related current densities would drop considerably.

However, in this investigation both electric and magnetic fields were assessed separately and synergistic effects neglected. Already the exposure to the homogeneous electric field caused an excess of the basic restriction within the fetus by more than two thirds. It should be expected that this situation becomes even worse when simultaneous exposure to electric and magnetic fields is considered. It needs to be mentioned that averaging over 1 cm^2 of contiguous CNS tissue perpendicular to the current flow might not be possible in the fetal spinal cord, because the spinal cord of a 30-week-old fetus is less than 1 cm^2 in cross section.

5. Conclusion

By analysing the exposure situation of a pregnant woman, the association of reference level electric and magnetic fields in the spinal cord of the mother with basic limits was confirmed. However, the results show that this is not the case for fetal exposure. Further investigations with detailed anatomical fetal models at different stages of pregnancy and fetal tissue parameters are required. Revision of reference levels might be necessary.

Acknowledgments

The authors would like to thank Dr Peter Dimbylow from the Health Protection Agency for assisting our research by committing NORMAN to our institute.

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