

Dosimetry in Japanese Male and Female Models for Low-Frequency Electric Field

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Abstract

The present study quantified induced current in anatomically-based Japanese male and female models for exposure to low-frequency electric fields. A quasi-static FDTD method was applied to analyze this problem. For our computational results, the difference of the induced current density averaged over an area of 1 cm^2 between Japanese male and female models was less than 30% for each nerve tissue. The difference of induced current density between the present study and earlier works was less than 50% for the same conductivities, despite the different morphology. Particularly, maximum current density in central nerve tissues appeared in the retina of Japanese models, the same as in the earlier works.

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1. Introduction

There has been increasing public concern about adverse health effects due to electromagnetic fields. Safety guidelines for electromagnetic field exposure have been established by different public organizations. One of the most influential guidelines has been published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (1998). According to the ICNIRP guidelines, the dominant effect of extremely-low frequency (ELF) fields on humans is induced current in the central nerve system (Matthes 1998). Current density averaged over an area of 1 cm^2 is used as a measure of basic restriction. The limit is 10 mA/m^2 for occupational exposure and 2 mA/m^2 for the general public (ICNIRP 1998). An incident electric /magnetic field or power density, which does not produce induced current exceeding the above basic restriction, is used as a reference level. The

The current density induced by electric fields has been calculated in the American male (De Moerloose *et al* 1997) and corresponding child model (Hirata *et al* 2001), and standard male and female models (Dimbylow 2000, 2005). No study has been conducted to date on realistic models of Asians. Further studies must compensate for this oversight, since the human morphology would depend on race, gender, age, and so forth.

The purpose of the present study is to investigate current density in Japanese male and female models named TARO and HANAKO, respectively (Nagaoka *et al* 2004) by ELF electric fields. In particular, we calculated current density in the central nerve system averaged over 1 cm^2 in order to compare with the earlier works (Dimbylow 2000, 2005, Hirata *et al* 2001), in which human models with different races and gender were used.

2. Model and Methods

Whole-body numeric models for Japanese male and female named TARO and HANAKO, respectively, were developed by Nagaoka *et al* (2004). The resolution of this model is 2 mm and segmented into 51 anatomic regions. The height and weight of TARO are 1.73 m and 65 kg, respectively, while those of HANAKO are 1.61 m and 53 kg, respectively. Note that the retina is not classified in these models, so proper comparison with the results of Dimbylow (2000, 2005) is not feasible. Thus, the retina was manually re-assigned at the outer surface of the eyeball except for the cornea. The eyes are closed in the original TARO and HANAKO, and thus we removed the eyelids manually.

In order to investigate the induced current in the anatomic Japanese model, the quasi-static FDTD method was used (De Moerloose *et al* 1997). This is a scheme that extends the FDTD method (Taflove and Hagness 2005) to solve quasi-static problems by choosing incident waveforms appropriately. Under quasi-static approximation, fields exterior to conductors have the same phase as the incident field. The interior fields, on the other hand, are first-order fields

that are proportional to the time derivative of the incident field. Then, the incident field is chosen as a ramp function, just as in De Moerloose *et al* (1997). For generating proper electric fields or canceling out magnetic fields, two plane waves in opposite directions were excited.

The human was assumed to be standing on perfect ground. The remaining boundary is truncated by perfectly matched layers. The conductivities of tissues were chosen so as to coincide with those in Dimbylow (2005).

In the ICNIRP guidelines, current densities must be averaged over a cross-sectional area of 1 cm^2 perpendicular to the current direction. The procedure for calculating average current density is not defined in the guidelines. In addition, a complex procedure is required to define the current direction and calculate the average current density on the plane perpendicular to that direction. In the present study, we used the following procedures to calculate the average current density. First, at each voxel, we calculated three components of current density in the Cartesian coordinate, which were obtained by the FDTD method. Next, the current density perpendicular to three Cartesian planes is averaged over 5×5 cells (1 cm^2), as shown in figure 1. Then, the magnitude of the current density is obtained using three components of the 1-cm^2 -average current density. When air voxel and/or other tissues are included in the averaging region, we simply set the current density in these voxels to 0, while the same area was considered in the averaging process. Hence, no voxel was added to compensate the averaging area due to the inclusion of air and/or other tissues.

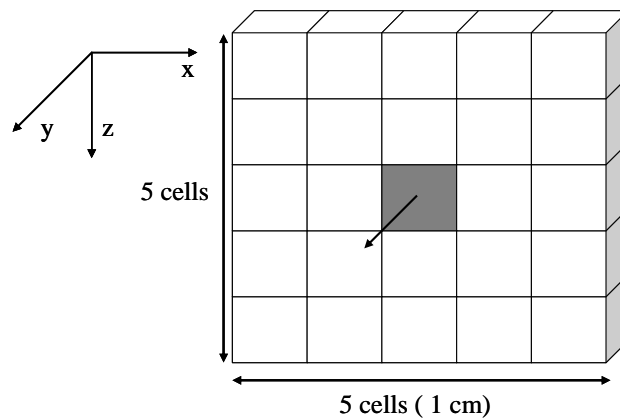


Figure 1. Region for calculating current density averaged over the area of 1 cm^2 . This is an example of current density in the y direction. The current densities in the x and z directions are calculated in the same manner.

3. Computational Results

We calculated vertical current induced in the human body for exposure to an electric field. The frequency and strength of the electric field are 60 Hz and 1 kV/m, respectively. The vertical

current in TARO and HANAKO was 16.9 μA and 14.3 μA , respectively. The induced current is approximately proportional to the square of the height ratio (Deno and Zaffanell 1982). This factor between TARO and HANAKO is $(1.73/1.61)^2=1.15$, which is in reasonably good agreement with the ratio of induced current between the two models. It should be noted that the vertical current in the American male model (1.77 m) (Hirata *et al* 2001) and European male model NORMAN (1.76 m) (Dimbylow 2000) was 18.0 μA and 16.8 μA , respectively, showing good agreement with that of TARO when the above scaling factor is taken into account. Similarly, the result for HANAKO is in good agreement with that of the European female model NAOMI (Dimbylow 2005) of 15.5 μA .

Figure 2 shows the current density on the vertical cross-sectional area across the center of the male and female models. As seen from this figure, the current density around the brain and backbone is high. The cerebrospinal fluid (CSF) exists around these areas. For electric field exposure, the positive charge is accumulated around the top of the head and shoulders, and the negative charge is around the soles of the feet. Then, short-circuit current flows from the top of the head to the soles (Stuchly and Dawson 2001). The CSF behaves as one of the main paths for current due to its higher conductivity (1.5 S/m) than that of other tissues.

Next, we note that the induced current density in nerve tissues averaged over 1 cm^2 . According to Matthes (1998), the current density should be calculated for central nerve tissues, which in the present study consisted of the spinal cord, brain, and retina. The induced current densities in the eye (combination of cornea, lens, retina, and vitreous) and heart are also calculated in TARO and HANAKO for comparison with the results for NORMAN and NAOMI in Dimbylow (2000, 2005) and for the American male in Hirata *et al* (2001). Note that the current density for NORMAN and NAOMI is scaled by a factor of (60/50) in order to compensate for the difference in the frequency of the applied electric field.

As seen from table 1, the current density in the retina was 0.204 mA/m^2 and 0.216 mA/m^2 in TARO and HANAKO, respectively. These values are maxima in induced current density for nerve tissues. The allowable external electric field at 60 Hz for complying with the ICNIR basic limit is 46.3 kV for occupational exposure and 9.26 kV for the general public. The difference of these values and those in Dimbylow (2005) is 20%. When considering the models with the eyes closed, these values were reduced to 0.087 mA/m^2 and 0.092 mA/m^2 for TARO and HANAKO, respectively. Thus, the effect of eyelids on the induced current density is much larger than that due to different race and gender.

Furthermore, current densities in the brain and spinal cord calculated in this study were compared with those in the earlier study by Hirata *et al* (2001). As seen from the table, the current density in the spinal cord is 50-65% smaller than in Hirata *et al* (2001), but in reasonable agreement with that in the brain. One of the main reasons for this is the difference in

conductivity; the spinal cord conductivity was different from that in Hirata *et al* (2001), while those of the brain tissues were the same in both studies. For numerical comparison, the conductivity of the spinal cord only was changed from 0.1 S/m (Hirata *et al* 2001) to 0.03 S/m (Dimbylow 2005). From the table, a reasonable agreement is observed in the induced current density in the spinal cord with the same conductivity. Since the maximum current density in the brain is larger than in the spinal cord, the former is compared with that calculated by Dimbylow (2005). Our calculated values were 20-35% smaller than those by Dimbylow. A difference of the same order is also observed in the heart. From these results, we may conclude that current densities in nerve tissues are not so sensitive to gender and/or race. One of the main reasons for this is that the tissue with high conductivity (CSF and eye humor) exists in the vicinity of nerve tissues. Current densities around the nerve tissues would be rather sensitive to the human anatomy. One of the rationales for this is that the 99%ile value of current density in the spinal cord and brain for TARO was 32 % and 51% smaller than their maximum values, respectively, the same tendency was observed in Hirata *et al* (2001).

The current densities in Hirata *et al* (2001) are slightly smaller than those in the other models. These values may be partially attributed to different voxel resolution. The resolution of the American male model is 3.6 mm against 2 mm in the other models. Then, in Hirata *et al* (2001), the average area ($10.8 \text{ mm} \times 10.8 \text{ mm}$) was 16% larger than in the other models: Additional discussion on the effect of cell resolution and conductivity contrast on induced current density can be found in Dawson *et al* (2001).

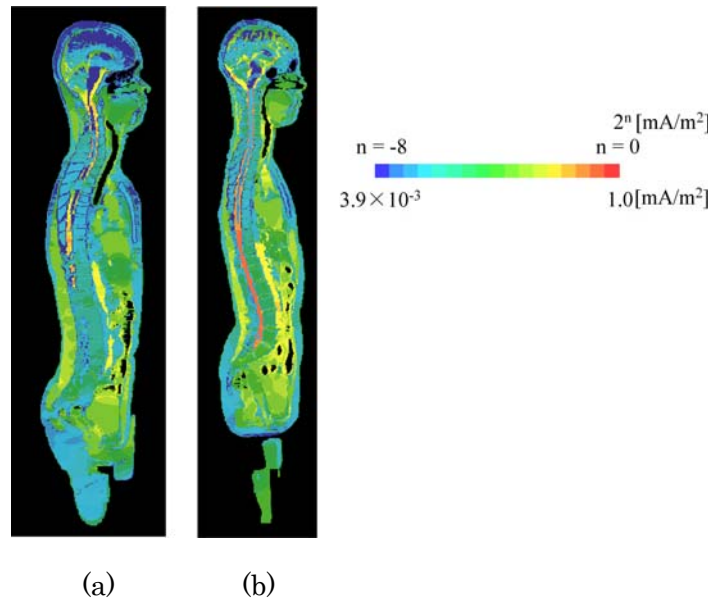


Figure 2. Current density distribution exposed to 1 kV/m electric field at 60 Hz: mid-sagittal sections in TARO (a) and HANAKO (b).

4. Summary

The present study computed induced current in the Japanese male and female models, TARO and HANAKO for exposure to ELF electric fields. Computational results show that the difference in the induced current density between TARO and HANAKO was less than 20%, which depends on the tissues/organs. This value would be reasonable since a difference of the same magnitude was observed between NORMAN and NAOMI (Dimbylow 2005). Additionally, one of the main reasons for the difference in current density between different studies was confirmed to be the different conductivities of tissues used in the calculation, as pointed out by earlier works (e.g., Stuchly and Dawson 2001). From these results, the effect of gender and/or race on induced current density is comparable or smaller than that caused in the process of computational modeling.

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Table 1. Current density (mA/m²) averaged over 1 cm² area for nerve tissue in ELF electric field parallel to the human height direction (1 kV/m and 60Hz).

	retina	brain& spinal cord	spinal cord	brain	eye	heart
TARO	0.204/0.087 ^a	0.178	0.110/0.354 ^b	0.178	0.185/0.152 ^a	0.297
HANAKO	0.216/0.092 ^a	0.154	0.081/0.237 ^b	0.154	0.245/0.194 ^a	0.314
NORMAN	0.253	0.214	-	-	-	0.300
NAOMI	0.260	0.221	-	-	-	0.455
American	-	-	0.223 ^b	0.144	0.235	0.253

a: original Japanese model with eyelid.

b: conductivity of spinal cord =0.1 S/m as in Hirata *et al* (2001).