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IN-SITU ELECTRIC FIELD AND CURRENT DENSITY IN JAPANESE MALE AND FEMALE MODELS FOR UNIFORM MAGNETIC FIELD EXPOSURES

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The present study quantified the *in-situ* electric field and induced current density in anatomically-based numeric Japanese male and female models for exposure to extremely-low-frequency magnetic fields. A quasi-static FDTD method was applied to analyze this problem. The computational results obtained herein reveal that the 99th percentile value of the *in-situ* electric field in nerve tissue and the current density averaged over an area of 1 cm^2 of the nerve tissue (excluding non-nerve tissues in the averaging region) in the female models were less than 35% and 25%, respectively. These induced quantities in the Japanese models were smaller than those for European models reported in a previous study, which is mainly due to the difference in cross-sectional area of the body.

INTRODUCTION

There has been increasing public concern regarding the adverse health effects associated with electromagnetic fields. Safety guidelines/standards for electromagnetic field exposures have been established by different organizations [1][2]. One of the most influential guidelines has been published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2]. According to the ICNIRP guidelines, the dominant effect of extremely-low frequency (ELF) fields on humans is due to induced current in the central nerve system [3]. Current density averaged over an area of 1 cm^2 is used as a metric of basic restriction. The limit is 10 mA/m^2 for the occupational exposure and 2 mA/m^2 for the general public exposure [1]. Recently, the *in-situ* electric field has gained significant attention. One of the main reasons for this increasing attention is that the latest version of the IEEE standards used an *in-situ* electric field averaged over a straight-line segment of 5 mm as a metric for human protection. In addition, Dawson *et al* reported that the uncertainty of the *in-situ* electric field is less sensitive to tissue conductivity than that of induced current density [4].

The induced current density and/or *in-situ* electric field due to magnetic field exposure has been calculated in the American male [5, 6] and in standard male and female models based on the ICRP reference adults [7, 8], in addition to the model developed at Brooks Air Force Base [9] and the fetus model [10][11]. No study, however, has been conducted to date on realistic models of Asians. For radio-frequency whole-body exposures, the model morphology has been reported to influence the whole-body averaged specific absorption rate, which is a dosimetric measure in that frequency region [12]. Further studies must compensate for this oversight, because the human morphology would depend on race, gender, age, and so forth.

The purpose of the present study is to investigate the *in-situ* electric field and induced current density in the Japanese adult male and female models named TARO and HANAKO, respectively, [13] for uniform ELF magnetic field exposures. Then, we discuss the effect of gender and race on the induced quantities with the aid of the data published in a previous study [8].

MODELS AND METHODS

Human Models

Whole-body numeric models for the Japanese male (TARO) and the Japanese female (HANAKO) were developed by Nagaoka *et al* [13]. The average height and weight of Japanese 18 to 30 years old are 1.714 m and 63.3 kg for males, and 1.591 m and 52.6 kg for females. Volunteers were selected whose dimensions were close to the average values. The male volunteer

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was 22-years old, 1.728 m tall and weighed 65.0 kg; the female volunteer was 22-years old, 1.6 m tall and weighed 53.0 kg. A complete set of MRI 256 x 256 axial images with a 240 mm field-of view for a head and a 480 mm field-of view for other parts of the body was acquired at a slice thickness of 2 mm. The voxels were rescaled to 2 mm cubes and segmented to define 51 discrete organs.

Computational Methods

The quasistatic FDTD method was used to investigate the induced quantities in the anatomic Japanese models [5]. This scheme extends the conventional FDTD method [14] to solve quasistatic problems by choosing incident waveforms appropriately. Under quasistatic 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. The incident field is then chosen as a ramp function, as in De Moerloose *et al.* [5]. In order to generate a proper uniform magnetic field, two plane waves in opposite directions were excited so that the electric fields of the plane waves cancel each other. The computed *in-situ* electric field can be linearly scaled to 50 Hz.

Exposure Scenario

The human was considered to be standing in free space. Three orientations of magnetic fields were considered: AP (front-to-back), TOP (top-to-bottom), and LAT (side-to-side), which match those in other works (e.g., [8], [9]). The conductivities of tissues were chosen on the basis of [15]. The frequency and magnitude of the magnetic field are 50 Hz and 0.1 mT, respectively. The computational boundary is truncated by perfectly matched layers.

Averaging Scheme of Current Density

In [1], the current density 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 the present study, we calculate the average current density using two schemes. For both schemes, at each voxel of nerve tissue, we calculated three components of current density in Cartesian coordinates, which were obtained by the FDTD method. In the first scheme (labeled (I)), the current density perpendicular to the three Cartesian planes is averaged over 5×5 cells (1 cm^2) [16]. The magnitude of the current density is then obtained using the three components of the 1-cm^2-average current density. Even though the air voxel and/or other tissues are included in the averaging region, we simply averaged these components to obtain the overestimation. Note that the area of the air is taken into account in the average procedure. The rationale for this scheme is based on the response of ICNIRP [17] to CENELEC, which suggests that, for the purpose of simplification, it is acceptable to assume that the 1-cm^2 sections are composed entirely of nerve tissue.

In the second scheme (labeled (II)), the current density in non-nerve tissues is not taken into account and the current density is averaged over 5×5 square cells for the three Cartesian planes. When one or more voxels includes non-nerve tissue, the average current density was not calculated. The maximum value in these three components is considered as a measure. This scheme is the same as that of [18]. A thorough discussion on the effect of the inclusion of non-nerve tissues in the averaging area on the resultant spatial-average current density can be found in [18].

COMPUTATIONAL RESULTS

Table 1 shows the induced current densities due to magnetic field with different exposure directions. We chose seven measures based upon which to compare the induced field and current density between different models: i) maximum value of induced current density in one voxel, ii) maximum value of current density averaged over an area of 1 cm^2 with scheme (I), iii) maximum value of current density averaged over an area of 1 cm^2 with scheme (II), iv) maximum value and v) 99th percentile value of the *in-situ* electric field in one voxel for all tissues and vi) the maximum value and vii) 99th percentile value of the *in-situ* electric field in one voxel for nerve tissues. In the following discussion, the relative difference *RD* between two values is defined as the following equation:

$$RD = \frac{2(E_1 - E_2)}{E_1 + E_2} \qquad (1)$$

where the subscripts 1 and 2 correspond to the two data sets obtained for the two different models.

As shown in Table 1, the relative difference of the maximum current density in one voxel between male and female models was less than 40%, which is much smaller than that reported in the intercomparison between three institutes [18]. The maximum current density appeared in the cerebro-spinal fluid (CSF), the conductivity of which is high. Note that good agreement was observed between the maximum current densities between TARO and NORMAN [19].

A significant difference was observed between the averaged current densities calculated with (I) and (II), as suggested by Bahr et al [8]. The latter is larger than the former by a factor of 5 to 12. Even for different schemes, the averaged current densities in the male model were larger by 25% than those in the female model (expect for LAT with scheme (II) for Japanese models). One of the main reasons for this difference is the larger circumference of the male model compared to the female model [7]. The results calculated using scheme (I) are 20-50% smaller than those reported by [7]. One reason for this difference is thought to be the larger circumference of European models compared to Japanese models. In addition, the average current density in nerve tissues is sensitive to the surrounding tissues. Japanese models are comprised of 52 tissues, whereas NORMAN and NAOMI are comprised of 38 and 41 tissues, respectively. In particular, white matter and gray matter are classified in the Japanese models but not in the European models. For this reason, the possibility of including other tissues in the averaging procedure with scheme (II) becomes higher, resulting in non-inclusion of the corresponding region.

Table 2 shows the *in-situ* electric fields in different models due to magnetic field exposures. This table reveals a similar tendency between male and female models with respect to the induced current density in the maximum and 99th percentile values of the *in-situ* electric field. In particular, the differences in the maximum and 99th percentile values of the nerve tissue between male and female models were at most 35%. The differences in the maximum values of nerve tissues between the male and female models are smaller than those for all of the tissues. The reason for this would be the contrast of conductivities between tissues. Dawson *et al* [18] showed that higher contrast results in a larger difference from the theoretical value. Except for exposure in case of LAT for NORMAN, good agreement was observed in the *in-situ* electric field between Japanese and European models as compared with averaged current density.

SUMMARY

The present study computed the *in-situ* electric field and induced current in TARO and HANAKO for exposure to uniform magnetic fields. Computational results show that the *in-situ* electric field and induced current density in HANAKO were 35% lower and 25% lower, respectively, than those in TARO, mainly due to the circumference of the models. The induced quantities in the Japanese models were smaller than those in the European model due to the difference in circumference of the models and the anatomical modeling.

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Table 1. (i) The maximum value of current density in one voxel, (ii) the current density averaged over an area of 1 cm^2 for nerve tissue with scheme (1), and (iii) that with scheme (2) for an applied 0.1 mT field at 50 Hz. The unit of current density is mAm^{-2}.

		TARO		HANAKO		NORMAN		NAOMI	
LAT	(i)	8.15	CSF	5.03	CSF	7.65	Dimbylow (1998)	–	–
	(ii)	2.24	gray matter	1.67	gray matter	–	–	–	–
	(iii)	0.186	grey matter	0.238	gray matter	0.332	brain and nerves	0.281	brain and nerves
AP	(i)	7.48	CSF	5.74	CSF	8.22	Dimbylow (1998)	–	–
	(ii)	1.56	gray matter	1.18	gray matter	–	–	–	–
	(iii)	0.226	spinal cord	0.225	nerve	0.356	brain and nerves	0.298	brain and nerves
TOP	(i)	5.09	CSF	4.95	CSF	5.20	Dimbylow (1998)	–	–
	(ii)	1.21	graty matter	0.802	gray matter	–	–	–	–
	(iii)	0.176	grey matter	0.145	gray matter	0.249	brain and nerves	0.185	brain and nerves

Table 2. (iv) The maximum and (v) 99th percentile values of the *in-situ* electric field for all tissues, and (vi) the maximum and (vii) 99th percentile values of the *in-situ* electric field for nerve tissues for an applied 0.1 mT field at 50 Hz. The unit of the *in-situ* electric field is mVm^{-1}.

		TARO		HANAKO		NORMAN		NAOMI	
LAT	(iv)	17.7	cartilage	9.77	skin	–	–	–	–
	(v)	3.35	–	2.77	–	–	–	–	–
	(vi)	8.91	spinal cord	6.51	gray matter	–	–	–	–
	(vii)	2.77	gray matter	2.68	gray matter	4.86	nerve	3.14	brain
AP	(iv)	31.2	skin	11.7	fat	–	–	–	–
	(v)	5.80	–	3.42	–	–	–	–	–
	(vi)	7.29	spinal cord	5.36	gray matter	–	–	–	–
	(vii)	2.77	spinal cord	2.59	gray matter	3.07	brain	2.57	brain
TOP	(iv)	16.2	fat	18.1	fat	–	–	–	–
	(v)	4.07	–	2.87	–	–	–	–	–
	(vi)	5.30	gray matter	5.30	gray matter	–	–	–	–
	(vii)	2.29	white matter	2.01	gray matter	2.30	spinal cord	2.51	brain