Calculation of Internal Electric Fields Induced in Human Models by ELF and Intermediate Frequency Uniform Magnetic Fields

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***Abstract*— In this study, the internal (in-situ) electric field induced in human tissues by ELF and intermediate frequency uniform magnetic fields has been determined using the scalar potential finite difference (SPFD) method. These calculations were conducted on adult Japanese numerical models and the calculation results were compared with the basic restrictions provided in the IEEE safety standard. Under the maximum permissible exposure condition defined in the IEEE C95.6 standard, the calculated internal electric fields exceeded the basic restriction in the cases for certain body parts and conditions.**

Keywords—magnetic field; ELF; intermediate frequency; guidelines for human protection; IEEE C95.6 standard; dosimetry; detailed anatomical human model; SPFD method;

I. Introduction

There are public concerns regarding possible adverse health effects related to electromagnetic field exposure. There are international guidelines such as the International Commission on No-Ionizing Radiation Protection (ICNIRP) [1], [2] and IEEE [3], [4] that are used for the safety evaluation of exposure to extremely-low-frequency (ELF) and intermediate frequency electromagnetic fields. According to these guidelines, induced electric fields (*in-situ* electric fields) in the human body contribute to the index of the internal quantity in the case of exposure to ELF or intermediate frequency magnetic fields. The limit of induced (*in-situ*) electric fields is referred to as the “basic restriction”. In addition, the “reference level” (ICNIRP) or “MPE (maximum permissible exposure)” (IEEE) is defined as the external electric/magnetic field that corresponds to the basic restriction, as it is difficult to access internal quantities in order to make practical assessments. In the case of the ICNIRP guidelines, the results of numerical calculations using detailed anatomical human models were used to derive reference levels from the basic restrictions [1]. However, to convert basic restrictions into MPEs, the IEEE standard uses analytical solutions to determine the electric field produced due to magnetic induction. An elliptical cross-sectional model with homogeneous conductivity that simulates each part of the human body was employed [3]. Recently, a new IEEE working group (IEEE/ICES/TC95/WG6) has been founded in order to investigate the applicability of calculations using anatomical human models in the derivation of MPE levels. The calculation results of five different research groups were compared for electric fields induced by uniform magnetic fields of 50 Hz − 1 MHz. Consistent results were observed across all laboratories [5].

In this study, we conducted numerical calculations using detailed numerical human models of Japanese adults in order to determine the internal electric fields that were induced by uniform magnetic fields, ranging from ELF to intermediate frequencies (0.153 Hz – 5 MHz). This study extends the previous, similar investigation by inspecting a wider range of frequencies and greater variety of magnetic fields orientations [5]. These calculation results were then converted for comparison with levels of MPE exposure and compared with the basic restrictions in the IEEE safety standard.

II. Models and Computational Method

A. Numerical Human Models

In the numerical calculations, the Japanese adult male model “TARO” and female model “HANAKO” developed by NICT (National Institute of Information and Communications Technology, Japan) [6] were used to determine the internal electric fields induced by magnetic fields. In these models, 54 types of tissue are identified. The voxel resolution of the models is 2 mm.

B. Electrical Conductivities of Tissues

The electrical conductivities of each tissue type in the human body at 50 Hz and 1 MHz are listed in Table 1. These are based on the electrical constants database developed by IFAC (Institute of Applied Physics, a part of the Italian National Research Council, Italy) [7]. Values of 0.1 S/m (0.153 Hz−167 Hz), 0.2 S/m (3350 Hz), 0.5 S/m (1 MHz), and 0.6 S/m (5 MHz) were assigned for skin.

C. Computational Method

The internal electric fields induced in the human body were calculated using the SPFD (Scalar Potential Finite Difference) method [8]. Under the quasi-static condition, electric fields can be represented as

TABLE I. ELECTRICAL CONDUCTIVITIES OF TISSUES

Tissues	50 Hz	1 MHz	Tissues	50 Hz	1 MHz
Cerebellum	0.0953	0.185	Ovary	0.321	0.358
CSF	2.00	2.00	Pancreas	0.521	0.603
Cornea	0.421	0.656	Prostate	0.421	0.562
Eye tissue (Sclera)	1.50	1.50	Small Intestine	0.522	0.865
Grey Matter	0.0753	0.163	Spleen	0.0857	0.182
Hypothalamus	0.0753	0.163	Stomach	0.521	0.584
Lens	0.321	0.375	Stomach Contents	0.233	0.503
Pineal Gland	0.0753	0.163	Tendon	0.270	0.392
Pituitary	0.0753	0.163	Testis	0.421	0.562
Salivary Gland	0.233	0.503	Thyroid	0.521	0.603
Thalamus	0.0753	0.163	Trachea	0.301	0.373
Tongue	0.271	0.388	Urine	0.700	0.822
White Matter	0.0533	0.102	Uterus	0.229	0.564
Adrenals	0.233	0.503	Blood	0.700	0.822
Bladder	0.205	0.236	Cortical Bone	0.0201	0.0244
Breast Fat	0.0226	0.0258	Bone Marrow	0.0412	0.0473
Large Intestine	0.0545	0.314	Cartilage	0.171	0.233
Large Intestine Contents	0.233	0.503	Fat	0.0196	0.0251
Duodenum	0.521	0.584	Muscle	0.233	0.503
Esophagus	0.521	0.584	Nerve (Spinal Cord)	0.0274	0.130
Bile	1.40	1.40	Skin	0.100	0.500
Gall Bladder	0.900	0.90	Tooth	0.0201	0.0244
Heart	0.0827	0.328	Ligament	0.270	0.392
Kidney	0.0892	0.278	Small Intestine Contents	0.233	0.503
Liver	0.0367	0.187	Diaphragm	0.233	0.503
Lung	0.137	0.235	Seminal Vesicle	0.233	0.503

$$\boldsymbol{E}(\boldsymbol{r}) = -j\omega\boldsymbol{A}(\boldsymbol{r}) - \nabla\phi(\boldsymbol{r}) \tag{1}$$

where $\boldsymbol{E}$, ω, $\boldsymbol{A}$, and ϕ are the internal electric field, angular frequency, magnetic vector potential, and electric scalar potential, respectively. Assuming a continuity condition for the current density $\boldsymbol{J} = \sigma\boldsymbol{E}$, eq. (1) is reduced to the differential equation

$$-\nabla\cdot\left[\sigma(\boldsymbol{r})\nabla\phi(\boldsymbol{r})\right] = \nabla\cdot\left[j\omega\sigma(\boldsymbol{r})\boldsymbol{A}(\boldsymbol{r})\right] \tag{2}$$

and subject to the boundary condition

$$\sigma(\boldsymbol{r})\boldsymbol{E}(\boldsymbol{r})\cdot\boldsymbol{n}(\boldsymbol{r}) = 0 \tag{3}$$

where σ is the electrical conductivity of the body tissue and $\boldsymbol{n}$ is the normal vector at the body surface. Integrating eq. (2) with respect to the volume of a voxel and choosing the node of the voxel as the collocation, we obtain the discretized form of the dominant equation

$$\sum_{n=1}^{6} s_n\phi_n - \left(\sum_{n=1}^{6} s_n\right)\phi_0 = j\omega\sum_{n=1}^{6}(-1)^n s_n l_n A_{0n} \tag{4}$$

where n denotes the index of 6 voxel nodes around the subjected node, and s_n, ϕ_n, l, and A_{0n} are the voxel edge conductance, electric scalar potential at a node, voxel edge length, and magnetic vector potential at the voxel edge center, respectively. The unknown electric scalar potentials at all the nodes are obtained by solving the simultaneous equation that is formed by imposing eq. (4) on all nodes. A numerical solution of this simultaneous equation was obtained using the Bi-CGSTAB method [9]. Induced internal electric fields are derived from the gradient of the electric scalar potential by taking the difference between values at two adjacent nodes on the voxel edge. The electric field value at the voxel center was obtained by taking the average of the values at four parallel edge centers. To evaluate the induced internal electric field in each body part, the 99th percentile value of the electric field value at the voxel center was obtained.

D. Calculation Conditions

Three orientations were assumed for the magnetic field; LAT (side-to-side), AP (front-to-back), and TOP (top-to-top). The numerical human models were considered to be standing in free space. Magnetic flux intensity was set to 0.1 mT and considered to be spatially uniform. The frequencies of the magnetic field were chosen to be 0.153 Hz, 20 Hz, 50 Hz, 167 Hz, 3350 Hz, 1 MHz, and 5 MHz which are relevant to the boundary values of MPE in the IEEE standard [3]. The stopping criteria of the Bi-CGSTAB iterative procedure was set to 10^{-8} in terms of the relative residual norm of the equation solution.

Note that the SPFD method is applicable under quasi static conditions for which the displacement current is negligible, and the phases of the internal quantities are considered to be spatially constant. These conditions are met for uniform magnetic fields below 10 MHz [10].

III. CALCULATION RESULTS

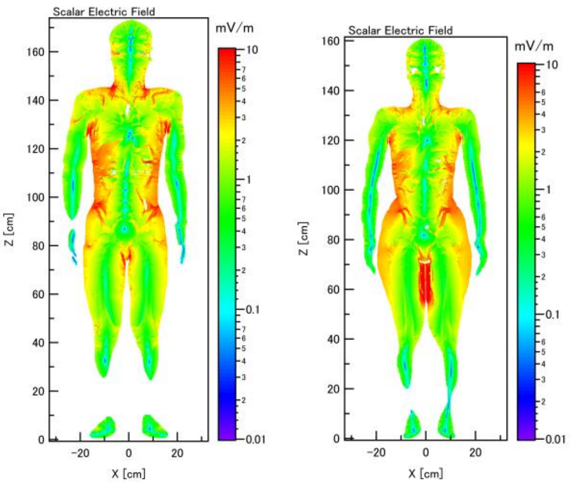
Figure 1 shows the distribution of the internal electric field in terms of AP direction exposure (results for 50 Hz and 1 MHz are shown as representative cases) in TARO and HANAKO. In both cases, the electric field intensity is relatively high around the periphery of the torso, where the body cross section is the largest. On the contrary, electric field intensity reduces around the ends of limbs where the cross sections are smaller. This is a common qualitative feature, regardless of frequency or male/female differences. However, there is a significant difference between the results for TARO and HANAKO in that the electric field intensity around the inner thighs of HANAKO is significantly higher than that of TARO. This is because the inner thighs are in contact with each other in the case of HANAKO, which produces a local circulating current, as discussed in a previous study by Aga *et al.* [5].

Figure 2 shows the 99th percentile values of induced internal electric fields for each body part ("Brain", "Heart", "Limbs", and "Other Tissues") as functions of frequency. These were obtained by converting the calculation results for a magnetic field of 0.1 mT into the MPE conditions for controlled environments in the IEEE standard.

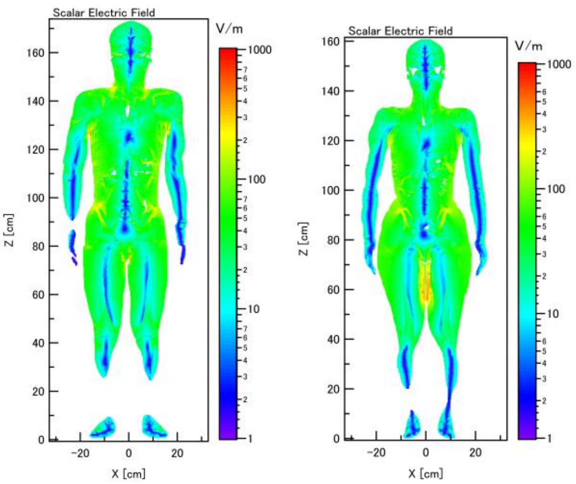
Together with these results, the analytical solutions for magnetic induction of the homogeneous elliptical cross-sectional model in IEEE standard [3]

$$E = 2\pi f B \frac{\sqrt{(a^2 u)^2 + (b^2 v)^2}}{a^2 + b^2} \tag{5}$$

are plotted, where f, B, a and b, u, and v are the frequency, magnetic flux density, semi-major and semi-minor diameter of the ellipse, and the electric field evaluation point in the ellipse, respectively.

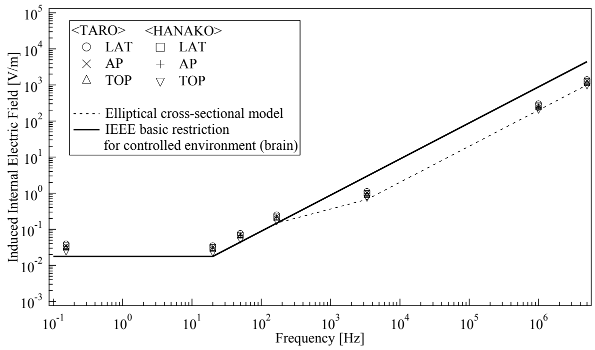


(a) 50 Hz

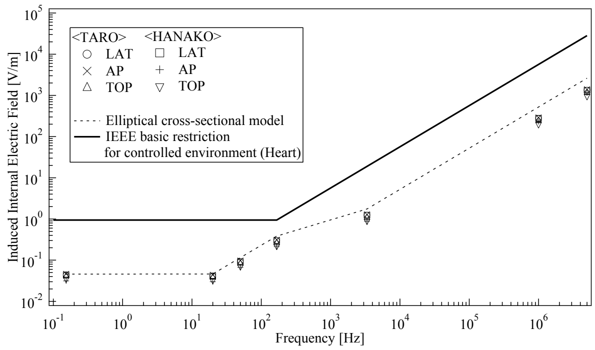


(b) 1 MHz

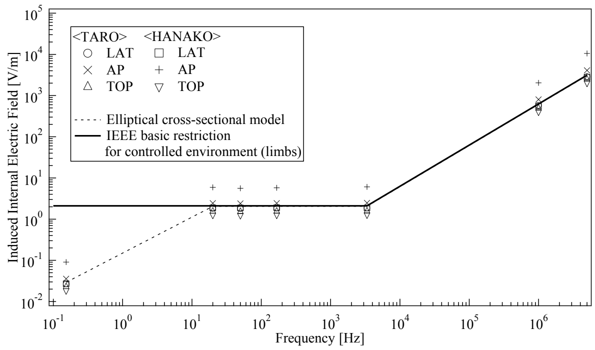
Fig. 1. Distribution of the internal electric field induced by the time-varying uniform magnetic field (0.1 mT, (a) 50Hz, and (b) 1 MHz) for AP-direction exposure in a Japanese male (TARO) and female (HANAKO) model.



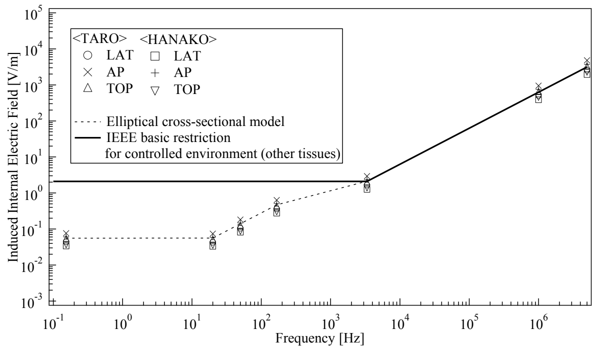
(a) Brain



(b) Heart



(c) Limbs



(d) Other Tissues

Fig. 2. Internal electric fields in body parts induced by uniform magnetic fields of maximum permissible exposure levels in a controlled environment (IEEE standard). Analytical solutions for magnetic induction obtained using the homogeneous elliptical cross-sectional model are also provided.

Note that a, b, u, and v adopt different values depending on the exposure scenario (e.g. sagittal or coronal direction exposure) in the IEEE standard [3]. The severest condition value (i.e. that for which the induced electric fields is largest) was chosen for each body part. The parameters applied to the homogeneous elliptical cross-sectional model for each body part are listed in Table 2 Among the three different magnetic field orientation cases, maximum values are shown in the AP direction exposure case at the majority of frequencies for "Limbs" and "Other Tissues". It is assumed that the magnetic flux which passes through the exposed area (thus, also the induced electric field) tends to be larger in the AP direction for these body parts. The analytical solutions of the elliptical cross-sectional model are in good qualitative agreement with the calculated internal electric field, though not in quantitative agreement. For certain body parts, the calculated internal electric fields exceed those of the elliptical cross-sectional model (most cases for "Brain", AP direction exposure cases for "Limbs" and "Other Tissues"). Consequently, for "Brain", "Limbs", and "Other Tissues", the electric field intensities exceed the basic restrictions in certain magnetic field orientations and frequency cases. On the other hand, electric field intensities are lower than the basic restriction for "Heart" in all cases. Such discrepancies between the results obtained using the numerical human model and those in elliptical cross-sectional model may result from the complex structure of the anatomical human models used. This has been suggested by several previous studies concerning dosimetry that employed anatomical human models. In the derivation of basic restrictions in the IEEE standard, each body part is simulated using isolated homogeneous elliptical cross-sectional models, while the inner organs such as the brain or heart are surrounded by other organs and are subject to injection currents from other organs. Additionally, the posture of the human model may affect the level difference between the human model and the homogeneous elliptical cross-sectional model. To clarify these concerns, further studies are needed.

TABLE II. PARAMETERS APPLIED TO HOMOGENEOUS ELLIPTICAL CROSS-SECTIONAL MODEL

	Parameters			
Body Part	a	b	u	v
Brain	10.5	90	42	90
Heart	9	17	9	17
Limbs	9	14	9	17
Other Tissues	0	18	0	0

IV. CONCLUSION

The internal electric fields that were induced by uniform magnetic fields from ELF to intermediate frequencies in various body parts were determined. Under the MPE conditions, the calculated internal electric fields exceeded the basic restrictions for certain body parts and conditions. This may result from the discrepancy between the anatomical human model and the isolated elliptical cross-sectional model. Further studies are required in order to investigate the applicability of calculation results using the anatomical human model to the derivation of MPE levels.

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