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Estimation of variability of specific absorption rate with physical description of children exposed to electromagnetic field in the VHF band

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Abstract—**Recently, there has been an increasing concern regarding the effects of electromagnetic waves on the health of humans. The safety of radio frequency electromagnetic fields (RF-EMFs) is evaluated by the specific absorption rate (SAR). In recent years, SAR has been estimated by numerical simulation using fine-resolution and anatomically realistic reference whole-body voxel models of people of various ages. The variation in SAR with a change in the physical features of a real person is hardly studied, although every person has different physical features. In this study, in order to estimate the individual variability in SAR of persons, we obtained considerable 3D body shape data from actual three-year-old children and developed several homogeneous models of these children. The variability in SAR of the homogeneous models of three-year-old children for whole-body exposure to RF electromagnetic fields in the very high frequency (VHF) band calculated using the finite-difference time-domain method has been described.**

I. Introduction

The increasing use of radio frequency (RF) applications has led to the growing presence of electromagnetic waves in various locations. There is an increasing concern regarding the effects of electromagnetic waves emanating from wireless communication devices on the health of humans. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] and the Institute of Electrical and Electronics Engineers (IEEE) [2] have issued guidelines that specify safe limits of exposure to electromagnetic fields (EMFs). According to these guidelines, the safety of the RF-EMF is evaluated by the specific absorption rate (SAR), which is the amount of RF energy absorbed per unit weight of the body and is used as a measure of the thermal effects in the body that are caused by the absorption of electromagnetic energy. SAR is defined by the following equation:

$$\mathrm{SAR} = \frac{\sigma}{\rho} E^2 \quad \mathrm{[W/kg]} \tag{1}$$

where σ is the conductivity of the tissue [S/m]; ρ, the density of the tissue [kg/m^3]; and E, the electric field strength (r.m.s.) inside the tissue [V/m]. The SAR of a human body exposed to RF-EMF is, however, very difficult to measure directly because SAR includes the internal electric field strength and conductivity of the body, as shown in Eq. (1). Therefore, SAR has been estimated by numerical methods using voxel-based models of humans.

Recently, the fine-resolution and anatomically realistic whole-body voxel models of adult males and females, pregnant women, and children have been developed on the basis of medical imaging devices or anatomical photographs of humans [3]–[13]. These models represent the anatomical structure (tissues and organs) of the human body as a set of minute elements. Researchers have also carried out a detailed SAR estimation by numerical simulation using these fine-resolution and anatomically realistic human voxel models. Most of the human voxel models are reference (average) models of adults or children [4]–[10]. In contrast, studies on the variations in SAR due to the difference in the physical features of real people are scarce; every person has different physical features, i.e., height, weight, and body shape, even if these people are of the same age. Therefore, it is desirable to use several fine-resolution and anatomically realistic models that are based on real persons for studying the variations in the SAR. However, developing several new fine-resolution and anatomically realistic voxel models is expensive and time consuming.

In this study, in order to estimate the variability in SAR of humans, we obtained considerable three-dimensional (3D) body shape data from actual three-year-old children, and developed several homogeneous models of these children. We calculated the SARs of the models of three-year-old children exposed to vertically polarized EMFs in a very high frequency (VHF) band (range: 30 MHz–300 MHz), and estimated the variation in SAR with the physical description of children.

II. Shape Data of Human Body

A. Subjects

The subjects were 30 Japanese children (14 boys and 16 girls) belonging to the age group 3–4. Fig. 1 shows the relationship between the height and weight of the subjects. The average height ± standard deviation (SD) and the average weight ± SD of the subjects were 94.5 ± 4.9 cm and 14.0 ± 1.6 kg, respectively.

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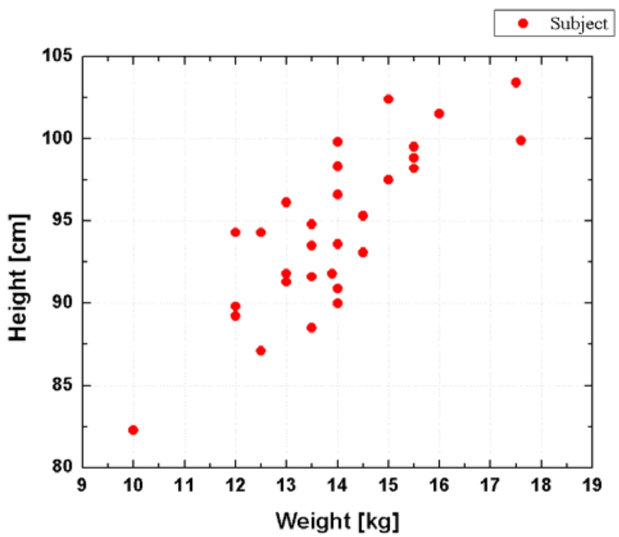

Fig. 1. Relationship between the height and weight of the subjects.

B. Three-dimensional shape data of human body

The 3D shape data of the standing position were obtained using the Bodyline Scanner (Hamamatsu Photonics K.K., Hamamatsu, Japan), which is a 3D surface laser scanner, as shown in

Fig. 2. The scan time for an entire body was approximately 3–5 s. For the scan, each subject wears a swimming cap as it is impossible to measure the body surface (head part) because the head hair absorbs the laser beam of the device. The scan was also performed while the subjects raised their arms slightly, as shown Fig. 3, because of certain limitations in the device. The body shape data obtained were mesh data. After scanning, the body shape data were modified to simulate the upright position of the subjects, as shown in Fig. 4. The areas where accurate measurement is difficult, such as fingers, armpits, and crotch, were also modified. Finally, the data of these models were converted from mesh data to voxel data.


Fig. 2. 3D surface laser scanner.

III. NUMERICAL SIMULATION

A. Calculation method and model

In this study, the finite-difference time-domain (FDTD) method [14] was used to estimate the whole-body averaged SARs, which are used as the basic restrictions in the RF human safety guidelines [1], [2], of three-year-old child models exposed to vertically polarized plane-wave EMFs with frequencies ranging from 30 MHz to 300 MHz. The incident waves were assumed to propagate from anterior to posterior (AP) and from left to right (LR) of the model. The incident power density was 1 mW/cm^2 (10 W/m^2), which is the reference level for the occupational exposure to electromagnetic fields in the VHF band [1]. The model was assumed to be in free space. The cell size of the calculation region was 2 × 2 × 2 mm^3. In addition, the absorbing boundary condition was set by perfectly matched layers (PML) (eight layers) [15]. The PML boundaries were set 30 cells (60 mm) away from all parts of the model. The models were homogeneous models with dielectric properties corresponding to 2/3 muscle tissue [16], which are often considered as the mixture of internal tissues of a human body [17].

The FDTD calculations were performed by the NEC SX-8R supercomputer using code written in-house.


Fig. 3. 3D body shape data.


Fig. 4. Model of upright position.

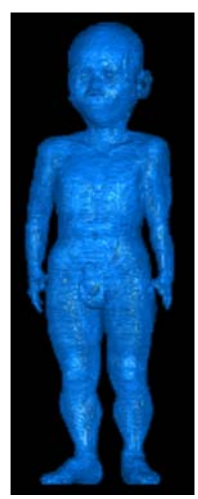
Fig. 5. Heterogeneous model of a three-year-old child.

B. Comparison of whole-body averaged SAR between homogeneous model and heterogeneous model

In this subsection, as preliminary study, a heterogeneous model of a three-year-old child is compared with a homogeneous model in order to study the difference in whole-body averaged SARs between the two models. Fig. 5 shows the heterogeneous model of a three-year-old child [10]. The model was constructed on the basis of the Japanese adult male model [7] by using the average body dimensions of three-year-old Japanese children; this model was fitted to the height, weight, and other dimensions of average three-year-old Japanese children. The model consisted of 2 × 2 × 2 mm^3 voxels and was segmented into 51 different types of tissues and organs. The homogenous model was constructed by replacing the tissues and organs in the heterogeneous model with 2/3 muscles. The dielectric properties of the tissues and organs of these child models were determined by Gabriel's report [16], which has been used in studies involving adult models [7], because sufficient data on the dielectric properties of the tissues and organs of children were not available.

We calculated the whole-body averaged SARs of these two models. The whole-body averaged SARs of the homogeneous model of a three-year-old child for AP and LR propagations when compared to those of the heterogeneous model are shown in Figs. 6 and 7, respectively. For both models and both propagations, the whole-body averaged SAR maxima were observed at ~150 MHz. This frequency corresponded to the whole-body resonant frequency of these models, where the height of the human body was approximately 0.4 times the wavelength [18]. The whole-body averaged SARs of the homogeneous model tended to become slightly higher than those of the heterogeneous model. However, the differences in the whole-body averaged SAR between the homogeneous model and the heterogeneous model were at most 14%. This result indicated that the energy absorption hardly depended on the anatomical structure of a human body. It was also suggested that the homogeneous model could be used for estimating the whole-body averaged SAR of three-year-old children exposed to a plane-wave EMF in the VHF band.

C. Variability in whole-body averaged SARs for three-year-old children

Figs. 8 and 9 show the frequency characteristics of the whole-body averaged SAR at AP and LR propagations estimated for 30 homogeneous models of three-year-old children, respectively. In these figures, we plotted the mean whole-body averaged SAR and ±2 SD of the whole-body averaged SARs. From the results, it could be concluded that the variation pattern of the whole-body averaged SAR was not significantly different between AP and LR propagations. The variations in the whole-body averaged SAR at around the whole-body resonant frequency (110–140 MHz) were smaller than those at other frequencies. The mean value of the coefficient of variation (CV) at around the whole-body resonant frequency was 6.5%. The range of the whole-body averaged SAR at around the whole-body resonant frequency that covered approximately 95% of three-year-old children was approximately ±13%. In contrast, the mean value of CV at other frequencies was 12%. This whole-body averaged SAR can be attributed specifically to the strong dependence on only the height and weight of the person, whereas the SAR depends on height, weight, body shape, posture, etc., in the VHF band.

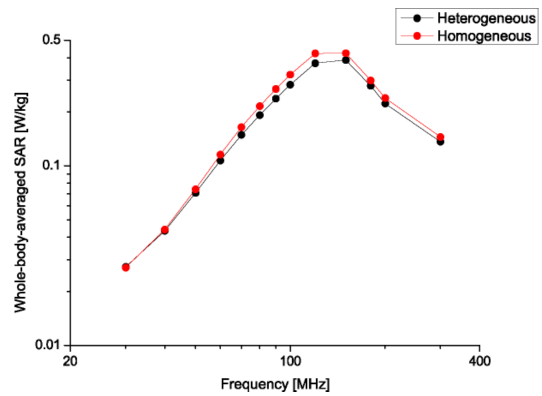

Fig. 6. Comparison of whole-body averaged SAR between the heterogeneous model and homogeneous model for AP propagation.

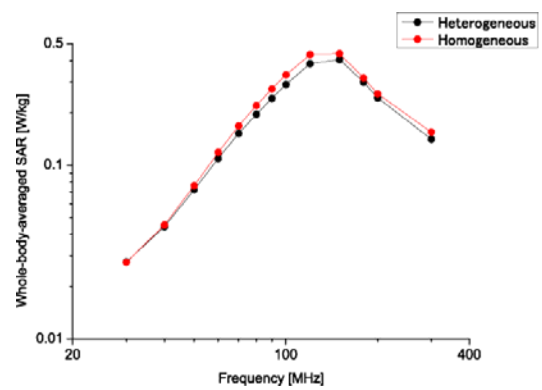

Fig. 7. Comparison of whole-body averaged SAR between the heterogeneous model and homogeneous model for LR propagation.

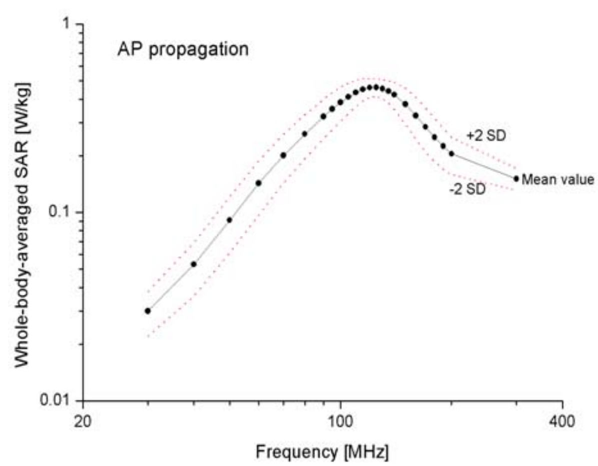

Fig. 8. Frequency characteristics of the whole-body averaged SAR of homogeneous models of three-year-old children for AP propagation.

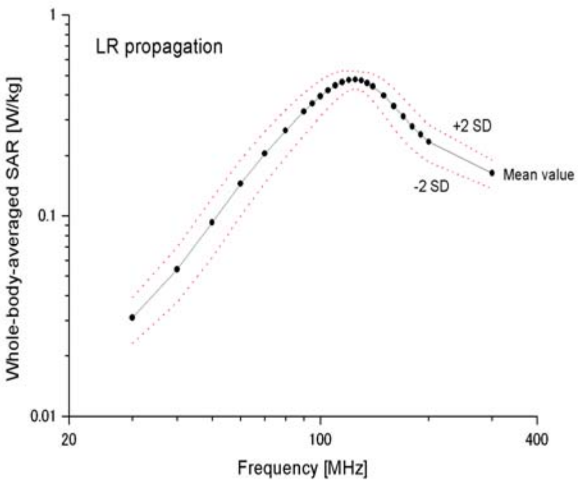

Fig. 9. Frequency characteristics of the whole-body averaged SAR of homogeneous models of three-year-old children for LR propagation.

IV. Conclusion

In order to estimate the variability in the whole-body averaged SAR of a person's exposure to EMF in the VHF band, 30 homogeneous models with dielectric properties corresponding to 2/3 muscle tissue were constructed on the basis of the 3D body surface data of three-year-old Japanese children obtained using the Bodyline Scanner. The models consisted of $2 \times 2 \times 2$ mm^3 voxels.

In this study, the whole-body averaged SARs of all the homogeneous models exposed to vertically polarized EMFs with frequencies ranging from 30 MHz to 300 MHz were estimated using an FDTD method. From the results, it was found that the variations in the whole-body averaged SAR at around the whole-body resonant frequency for three-year-old children were smaller than those at other frequencies. In addition, it was confirmed that the range of the whole-body averaged SAR at around the whole-body resonant frequency that covered approximately 95% of three-year-old children was approximately ±13%. In the future, we shall estimate the individual variability in SAR for people belonging to other age groups because variations in body height and weight and body shape for various ages are different from those in three-year-old children and for other frequencies

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