A Formula for Predicting Whole-Body Average SAR in Japanese Models for Far-field Exposures

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Abstract

Electromagnetic absorption of the human body at the ICNIRP reference level shows the double-humped frequency characteristics: the first peak appears at several tens megahertz where whole-body resonance occurs and the second at 2 GHz, which is caused by an increase of the reference level. The frequency characteristic of whole-body average SAR has not been discussed for realistic models of children. In this study, first, we calculated the whole-body average SAR in Japanese adult and child models for far-field exposure. As a result, we found that calculated peak whole-body average SARs appeared at 2 GHz under the ICNIRP reference level. Whole-body average SAR for the child models were larger than those for the adult models, and exceeded the ICNIRP limit by 30%. Then, we developed a formula for predicting whole-body average SAR from the height and weight of the human models. This formula is based on our finding that the absorption cross-section and body surface area are in excellent correlation.

1. INTRODUCTION

There has been increasing public concern about adverse health effects of human exposure to electromagnetic (EM) waves. According to the ICNIRP (International Commission on Non-Ionizing Radiation Protection) safety guidelines [1], whole-body average specific-absorption-rate (SAR) is being used as a measure of basic limit for radio frequency far-field exposure. The limit is 0.4 W/kg for occupational exposure or 0.08 W/kg for public exposure [1, 2]. An incident electric /magnetic field or power density, which does not produce the EM absorption exceeding the above basic limit, is used as a reference level [1].

It is well known that whole-body average SAR is largely dependent on the frequency of the incident wave despite the same power density, and its peaks appear at several tens megahertz for adults. This is attributed to a standing wave over the whole body. This frequency is called as a "resonant frequency" in this research field. At this frequency, the human height is approximately 0.4 wavelengths of EM waves in free space [3]. Additionally, the whole-body average SAR has another peak around 2 GHz which is caused by the increase of the reference level. This double-humped frequency characteristic has been confirmed not only for adult male model but also for child models [4, 5]. One of the main findings in these studies was that the whole-body average SARs in the child models were larger than that of the adult model, and then exceeded the basic limits in the ICNIRP guidelines by up to 20% at the whole-body resonance frequency and GHz regions under the ICNIRP reference level. In these works, the models for children were developed by simply scaling down the dimension of adult linearly. Then, the whole-body average SAR in thin human model exceeded the ICNIRP limit. However, the ratios of organ weights to the whole-body weight are dependent on the age. In addition, similar results were reported in comparison of the original human body model developed at Brooks Air Force Base (Texas, USA) and its linearly-modified model [6]. These findings necessitate us to re-examine the frequency characteristics of whole-body average SAR in different human body models, especially in more realistic child models.

In the present study, the EM absorption in the models for children is investigated in the frequency range from 30 MHz to 3 GHz, which covers the whole-body resonance frequency and GHz regions. Particular attention is paid to how to predict a whole-body average SAR in different human body models. Anatomically-based models for children [7] were developed by transforming the adult male model [8] using a free form deformation algorithm [9]. The FDTD method is used for investigating the human-wave interaction.

2. MODELS AND METHODS

Figure 1 illustrates numeric Japanese child models, together with an adult male model. Whole-body voxel models for the adult male and female (not shown here) were developed by Nagaoka et al [7]. The resolution of these models was 2mm

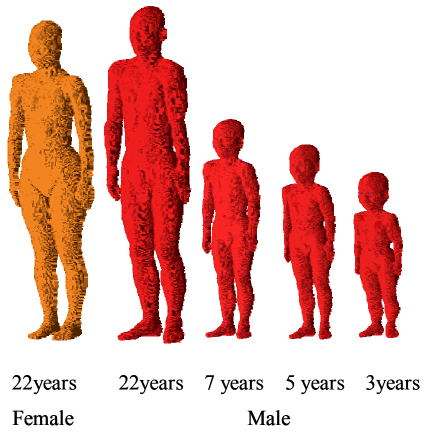

Figure1: Human body models for adult and children.

Table 1. Body parameters for adult and children models.

	Female	Male			
	22years	22years	7years	5years	3years
H[m]	1.61	1.73	1.20	1.05	0.90
W[kg]	53	65	23	17	13
$S_M[m^2]$	2.08	2.45	1.24	0.98	0.79
$S_H[m^2]$	1.54	1.78	0.88	0.70	0.56
S_H / S_M	0.74	0.73	0.71	0.71	0.71

segmented into 51 anatomic regions. The models for 3-year, and 5-year, and 7-year children were developed by applying a free form deformation algorithm [7] to the male model, similar to the approach for developing head models for children in [9]. In our modelling, the total of 66 body dimensions was taken into account, and we made manual editing for keeping anatomical validity. The resolution of these models was kept to 2 mm. It is worth commenting that the whole-body models for children were developed by linear scaling and then used for dosimetry in [4, 5]. The parameters of these models are listed in Table I. The surface area of the human body models S_M was obtained by simply counting the surface area of the descretized model. The surface area S_H was estimated in terms of Du Bois formula [10], which is derived statistically:

$$S_H[m^2] = 71.84 \times 10^{-4} \times H[cm]^{0.725} \times W[kg]^{0.425} \qquad (1)$$

where H, and W denote the surface area, height, and weight of the human body models. From that table, empirically estimated value is 71-74 % of descritized human body surface. Note that the effectiveness of Eq.(1) is not certain, and the uncertainties may be up to 10 % from the comparison of other equations [11].

In this study, the whole-body average SAR in an anatomically-based human model was investigated with the FDTD method. Figure 2 illustrates computational conditions applied in this study. The separation between the human model and 12-layered uniaxial PML was kept to 60 mm (30 cells) on the basis of the computational verification [5]. As an incident wave, a plane wave with a vertical polarization is considered (see Fig.2). The electrical constants of tissues are taken from [12].

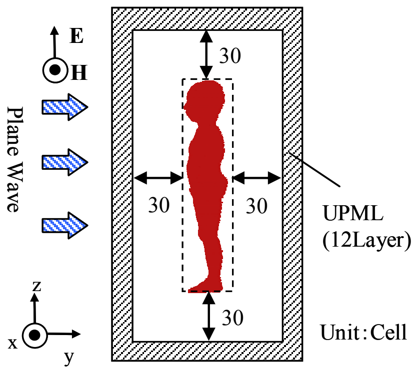

Fig. 2: Computational condition applied in this study.

3. COMPUTAIONAL RESULTS

Figure 3 shows the whole body average SAR in the child models at the incident power density of 1 mW/cm^2. Maximal whole-body average SAR appears at 100 MHz for 7-year child model, 120 MHz for 5-year child model and 130 MHz for 3-year child model. It was 60 MHz for the adult male model [6]. These frequencies correspond to electrical resonance. At these frequencies, the ratio of wavelength in free space to the model height is 0.4 for 7-year child, 0.42 for 5-year child, and 0.39 for 3-year child. This relation is reasonably coincident with the finding in [3].

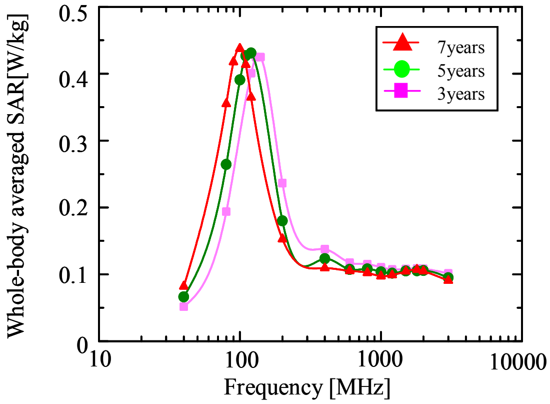

Fig.3 Whole-body average SAR in the model of children at the incident power density of 1 mW/cm^2.

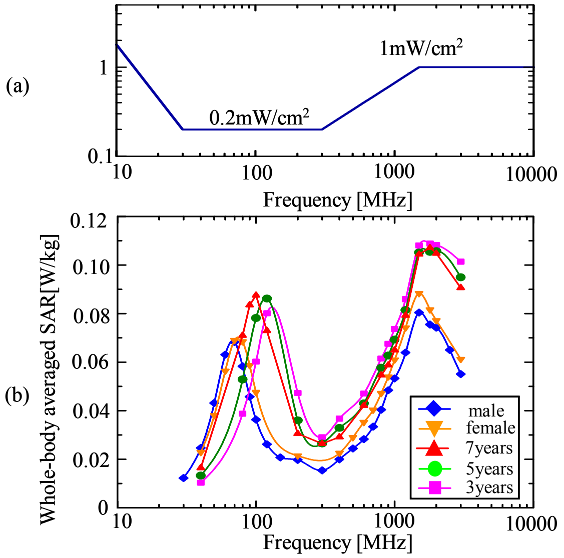

Fig.4. Whole-body average SAR in the model of adult and children at the ICNIRP reference level: (a) reference level and (b) whole body average SAR.

Next, the whole-body average SAR for the models of adult and children is scaled at the ICNIRP reference level, as shown in Fig. 4. In addition to the peak caused by whole- for the models considered in this study. These peaks are body resonance (see Fig. 3), another peak is found at 2.0 GHz caused by the relaxation of the ICNIRP reference level, as is evident from Fig. 4(a).

At whole-body resonance frequency, peak values of whole-body average SAR in the models of children were larger than that in adult model. Peak values for the models for children were 0.085 W/kg for the, which is marginally larger than the basic limit in the ICNIRP guidelines. At 2.0 GHz, peak values of whole-body average SAR were 0.105 W/kg for the models of children, which is larger than that for the adult model by 40%. This value is larger than the ICNIRP basic limit by 31.5%.

From the above discussion, it is worth evaluating the uncertainty of whole-body average SAR in the child models especially at 2.0 GHz where the SAR takes maxima. In [13], we revealed that a dominant factor for determining the whole-body average SAR is the surface area of the model rather than electrical constants in this frequency region. Then, in this study, we attempted to correlate the absorption cross section and surface area for the body models. The absorption cross section is defined as the ratio of incident power density to body surface area of S_M.

Figure 5 illustrates the correlation between the surface area S_M and absorption cross section for the body models. As is evident from this figure, excellent correlation is observed between them, suggesting the validity of our finding in [5].

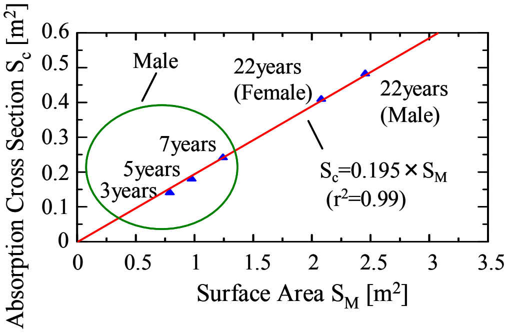

Fig.5. Correlation between absorption cross section and body surface area.

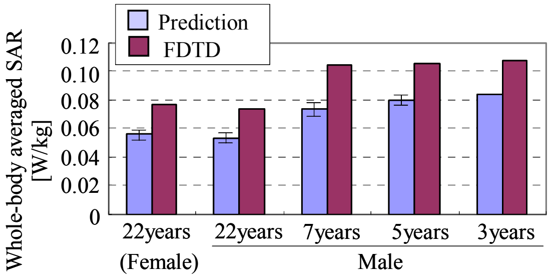

Fig.6. Comparison of FDTD-calculated and predicted whole-body average SAR.

The regression line was determined by the least mean square method, where the intercept of the line was set to 0. The rationale for this is that the absorption must be 0 in the condition where the body is nonexistent. The coefficient of determination was 0.99 and the slope of the regression line was 0.195. Thus, the whole-body average SAR can be estimated as

$$< SAR >_{whole-body} = \frac{P_i \times S_c}{W} = 0.195 \times \frac{P_i \times S_M}{W}. \qquad (2)$$

where Pi is the power density of incident wave. Provided that Eq. (2) is valid for actual human, the whole body SAR can be predicted from the following equation:

$$< SAR >_{whole-body} = 14 \times 10^{-4} \times P_i \times H^{0.725} \times W^{-0.575}. \qquad (3)$$

Figure 6 illustrates the comparison between FDTD-calculated and predicted whole-body SAR with the power density of 1mW/cm². The bars for prediction represents the results estimated from (3) for the body dimension with average value of Japanese at those ages, while uncertainties derived from standard deviation of Japanese are also given. In this figure, predicted values are smaller than those of the FDTD method by 30 %, since S_H was used instead of S_M.

4. SUMMARY

In this study, first, we calculated the whole-body average SAR in Japanese adult and child models for far-field exposure.

As a result, we found that calculated peak whole-body average SARs appeared at 2 GHz under the ICNIRP reference level. Whole-body average SAR in the child models were larger than those for the adult models, and exceeded the ICNIRP limit by 30%. Then, we attempted to formulate a equation for predicting whole-body average SAR from the height and weight of the human models. This formula was based on our finding that the absorption cross-section and body surface area are in excellent correlation. It is worth noting that the relation between absorption cross section and body surface remains applicable down to several hundreds megahertz. In future work, we will examine the applicability of the equation to different human body models.

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