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journal or publication title	IEEE transactions on electromagnetic compatibility
volume	48
number	1
page range	240-247
year	2006-02
URL	http://id.nii.ac.jp/1476/00005273/

doi: 10.1109/TEMC.2006.870816(<http://dx.doi.org/10.1109/TEMC.2006.870816>)

FDTD-Derived Correlation of Maximum Temperature Increase and Peak SAR in Child and Adult Head Models Due to Dipole Antenna

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Abstract—This paper investigates the correlation between the peak specific absorption rate (SAR) and the maximum temperature increase in head models of adults and children due to a dipole antenna. Much attention is paid to the effect of variation of electrical and thermal constants on the correlation for the child models, since these constants of child tissues are different from those of adult tissues. For investigating these correlations thoroughly, the total of 1400 situations is considered for the following six models: 3-year old child, 7-year old child, and adult models developed at Nagoya Institute of Technology and Osaka University. The numerical results are analyzed on the basis of statistics. We find that the maximum temperature increases in the head can be estimated linearly in terms of peak SAR averaged over 1 g or 10 g of tissue. In particular, no clear difference is observed between the adult and child models in terms of the slopes correlating the maximum temperature increase with the peak SAR. Also, the effect of electrical and thermal constants of tissue on these correlation is found to be marginal. Further, we discuss possible maximum temperature increases in the head and brain for SAR limits prescribed in safety guidelines. For the adult model developed at Osaka Univ., they are found to be 0.26 °C and 0.10 °C at the SAR value of 1.6 W/kg for 1-g cubic tissue, while they are 0.59 °C and 0.21 °C at the SAR value of 2.0 W/kg for 10-g cubic tissue. Similarly, for the 3-year old child model at Osaka Univ., they are 0.23 °C and 0.11 °C for the value of 1-g SAR, while they are 0.53 °C and 0.20 °C for the value of 10-g SAR.

Index Terms—dosimetry, bioheat equation, temperature increase, specific absorption rate (SAR), dipole antenna.

I. INTRODUCTION

IN recent years, there has been increasing public concern about health implication of electromagnetic (EM) wave exposures due to mobile telephones [1]. For this reason, various public organizations in the world have established safety guidelines for EM wave absorption [2]–[4]. For RF near field exposures, these guidelines are based on peak spatial-average SAR (specific absorption rate) for any 1 or 10 g of tissues of the body. However, the temperature increase may be one of the

dominant factors which induce adverse physiological effects. It is reported that a temperature increase in hypothalamus of 0.2 °C – 0.3 °C leads to altered thermoregulatory behavior [8]. It should be noted that diurnal variation of body core temperature is 0.2 °C – 0.3 °C [9]. Bioeffect might be caused by a whole-body temperature increase larger than the above level.

The temperature increase in the anatomically-based human head model due to a handset antenna has been calculated in several works [10]–[18]. Particularly, we attempted to correlate maximum temperature increases in the head and brain with peak SAR values [18]. For investigating these correlations thoroughly, the total of 660 situations was considered for the adult model. Then, the numerical results were analyzed on the basis of statistics. For the main result of the investigation, the maximum temperature increases in the head and brain were found approximately proportional to peak spatial-average SARs in the corresponding regions.

It is also concerned that the children might be more vulnerable to any adverse effects of RF radiation than adults [19]. In order to give some insight on this problem, the temperature increase in the child's head model has been conducted by two groups of the present authors [20], [21], but only insufficiently. The purpose of this paper is to investigate thoroughly the correlation between the peak SAR and maximum temperature increase in the child head models due to a dipole antenna. First, we discuss the effect of different head model's shapes due to age on the correlation. Then, our attention is paid to the effect of electrical and thermal constants on the correlation for a 3-year old child model, since the constants of child tissues are different from those of adult's [22].

II. METHOD AND MODEL FOR THE ANALYSIS

A. Human Head Model

Two head models for the adult are considered: one was developed at Nagoya Institute of Technology (NIT) [23] and the other at Osaka University [24]. Realistic head models for 3-year old and 7-year old children were developed from the adult models in the manner as shown in [25]. The resolution of these models are 2 mm. The feature of modeling is that a statistical database [26] for external shapes of heads is used in the scaling process. Then, the total of 6 head models is considered in this paper. These models are comprised of 17 and 18 tissues respectively: bone (skull), muscle, skin, fat,

Manuscript received January 20, 2002; revised November 18, 2002. This work was supported by the IEEE.

This work was partially supported by the Telecommunications Advancement Foundation, Japan and Grant-in-Aid for Young Scientist (B), The Ministry of Education, Culture, Sports, Science and Technology, Japan. M. Fujimoto is with Department of Communication Engineering, Osaka University, Suita-shi, Osaka 565-0871, Japan. A. Hirata, J. Wang, and O. Fujiwara are with Department of Computer Science and Engineering, Nagoya Institute of Technology, Aichi 466-8555, Japan. T. Shiozawa is with Department of Electronics and Information Engineering, Chubu University, Aichi 487-8501, Japan. e-mail: ahirata@nitech.ac.jp.

white matter, grey matter, cerebellum, blood, eye tissues, dura, and C.S.F.

B. Finite-Difference Time-Domain (FDTD) Method

The FDTD method [27] is used for investigating the interaction between the human head model and a dipole antenna. The resolution of cells is 2 mm, which matches those of the anatomically-based models. For this resolution, the wavelength in muscle (high water content tissue) is larger than 20 mm for the frequencies up to 2 GHz. In this paper, our attention is paid to the frequency up to 2.45 GHz. At this frequency, the wavelength in the muscle is 15 mm, and then the wavelength in this tissue does not include 10 cells, which is said to be a limit for computational accuracy. Due to high conductivity of tissue, however, peak spatial-average SAR can be calculated reasonably at this resolution (see, e.g., [28]). In order to incorporate the inhomogeneous head model into the FDTD scheme, the dielectric properties of the tissues are required. They are determined using the 4-Cole-Cole extrapolation [29]. For geometries in which wave-object interaction proceeds in the open region, the computational space has to be truncated by absorbing boundaries. In this paper, an 8-layered PML with a parabolic profile is adopted as the absorbing boundary.

C. SAR Calculation

For harmonically varying EM fields, the SAR is defined as

$$SAR = \frac{\sigma}{2\rho} |\hat{E}|^2 = \frac{\sigma}{2\rho} (|\hat{E}_x|^2 + |\hat{E}_y|^2 + |\hat{E}_z|^2) \quad (1)$$

where \hat{E}_x , \hat{E}_y , and \hat{E}_z are the peak values of electric-field components, σ and ρ denoting the conductivity and mass density of the tissue. The 12-component approach is used for obtaining a SAR in each cell [30]. For calculating peak spatial-average SAR, we chose a scheme presented in the IEEE guideline [31]. Note that the pinna is excluded when calculating the peak SARs.

D. Temperature Increase Calculation

Only the outline of algorithm for calculating the temperature increase is described, since our procedures are the same as those in [10]–[15], [17]. For calculating the temperature increase in the head model, the bioheat equation [32], [33], which takes into account the heat exchange mechanisms such as heat conduction, blood flow, metabolic processes and EM heating, is used. The bioheat equation is represented as

$$C\rho \frac{dT}{dt} = \nabla \cdot (K\nabla T) + \rho(SAR) + Q - B(T - T_B) \quad (2)$$

where T is the temperature of the tissue, T_B the blood temperature, K the thermal conductivity of the tissue, C the heat capacity of the tissue, B the term associated with blood flow, and Q the heat source due to metabolic processes. Note that the temperature increase due to a handset is sufficiently small, and thus the thermoregulatory mechanism was assumed negligible: the blood flow and metabolic generation is independent on the tissue temperature. It is also noteworthy that heat-sink term $B(T - T_B)$ is an approximation, resulting in a violation of

TABLE I
THERMAL PROPERTIES AND MASS DENSITIES OF TISSUES IN THE HUMAN HEAD.

Tissues	C [J/kg·°C]	K [W/m·°C]	B [W/m ³ ·°C]	ρ [kg/m ³]
Skin	3500	0.42	9100	1125
Muscle	3600	0.50	2700	1047
Bone	1300	0.40	1000	1700
Blood	3900	0.49	0	1058
Fat	2500	0.25	520	916
Grey Matter	3700	0.57	35000	1038
White Matter	3600	0.50	35000	1038
Cerebellum	4200	0.58	35000	1038
Humor	4000	0.60	0	1009
Lens	3000	0.40	0	1053
Sclera/Cornea	4200	0.58	0	1026
C.S.F.	4000	0.60	0	1007
Tongue	3300	0.42	13000	1047
Brain Dura	3600	0.50	2700	1125

the first law of thermodynamics. However, this effect is rather small, since the total amount of power is much smaller than metabolic heat generation of the whole body: 30 W for 3-year old child and 100 W for adults.

The boundary condition for (2) is given by

$$H \cdot (T_s - T_e) = -K \frac{\partial T}{\partial n} \quad (3)$$

where H , T_s , and T_e denote, respectively, the convection coefficient, the surface temperature of the tissue, and the temperature of the air. The finite-difference expressions for (2) and (3) are given in [11], [15].

At the thermally steady state, Eq. (2) is reduced to the following equation:

$$\nabla \cdot (K\nabla \delta T) + \rho(SAR) - B\delta T = 0 \quad (4)$$

where $\delta T = \delta T(\mathbf{r}, t)$ is the temperature increase of the tissue. It is noteworthy that the metabolic heat generation does not affect the steady-state temperature increase. This equation means that the temperature increase and SAR distributions are not identical. However, the temperature increase is linear in terms of the output power of the antenna, or the SAR amplitude. Note that it takes 30 minutes or more for getting thermally steady state.

The thermal parameters of tissues are listed in Table I [5], [34]–[38], together with mass densities. The values of metabolic heat generation Q are not listed in this figure, since they do not affect the temperature *increase*. The metabolic heat generation of each tissue is roughly proportional to the blood flow [37]. It should be noticed that the results based on animal experiments are used for most thermal parameters, because we have no reliable actual data available for the parameters required in the human head model. The uncertainties in the maximum temperature increases caused by those in thermal parameters can be found in [13].

III. CORRELATION BETWEEN PEAK SARs AND TEMPERATURE INCREASE

A. Correlation and Evaluation Scheme

We have demonstrated that maximum temperature increases in the head and brain were reasonably estimated linearly with

peak spatial-average SARs in the corresponding regions [18]. Let us review the rationale for this briefly. At the thermally steady state, the temperature increase is linear in terms of SAR (see Eq.(4)). The SAR is proportional to the output power of wave sources. Thus, it could be appropriate to express maximum temperature increase approximately as:

$$\hat{T} = a \cdot \text{SAR}_{ave} \quad (5)$$

where SAR_{ave} , \hat{T} , and a denote, respectively, a peak spatial-average SAR averaged over a specific mass of tissue, the maximum temperature increase estimated by a regression line, which is determined by the method of least squares, and the slope of the regression line with the unit of $^{\circ}\text{C} \cdot \text{kg}/\text{W}$. Note that the intercept of the regression line is set to zero since no temperature increase is induced without EM power absorption. There exist two main reasons why they are not fully proportional to each other. One is the difference between the SAR and temperature increase distributions, which are caused by the heat diffusion [10]–[13], [15], [16]. Then, we pay attention to a one-voxel peak value for the temperature increase, while we note a peak value averaged over a specific mass for the SAR. The other reason is the uncertainty involved in the peak SAR value due to averaging schemes, the SAR distribution, and the curvature of the actual head models, which amounts to 20 - 30% (e.g., [30], [39]).

For assessing the effectiveness of the estimation scheme for the maximum temperature increase, the coefficient of determination r^2 is introduced as

$$\begin{aligned} r^2 &= \frac{\sum_i (\hat{T}_i - \bar{T})^2}{\sum_i (T_i - \bar{T})^2} \\ &= 1 - \frac{\sum_i (T_i - \hat{T}_i)^2}{\sum_i (T_i - \bar{T})^2} \end{aligned} \quad (6)$$

where T_i is the maximum temperature increase for the i th case, and \bar{T} is the mean value of T_i . It should be noted that r^2 can be considered a measure of how well the regression line agrees with the observed values [40], [41]. Namely, the less the observed values depart from the fitted line, the closer to unity r^2 is.

B. Effectiveness of Estimation Scheme for Models with Different Shapes

The effectiveness of the correlation scheme between maximum temperature increase and peak spatial-average SAR in the head are discussed for a dipole antenna. This subsection investigates the effectiveness of the estimation scheme for the models with different shapes due to age. The following total of 1200 situations is considered for a dipole antenna:

- six head models: 3-year old child, 7-year old child, and adult models of NIT and Osaka Univ.;
- the head models with pressed or unpressed ear;
- five frequencies: 900 MHz, 1.5 GHz, 1.9 GHz, 2.1 GHz, and 2.45 GHz;
- two polarizations: the horizontal polarization (HP) and vertical polarization (VP);
- ten feeding points (see Fig.1).

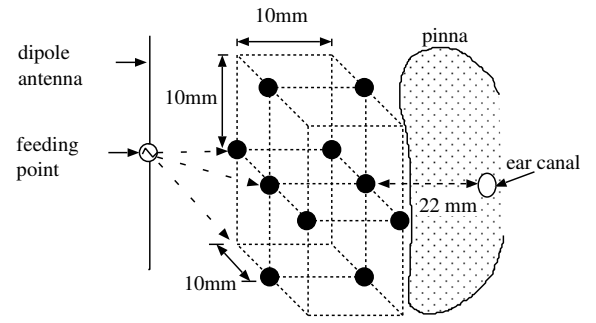


Fig. 1. The positions for the feeding point of the dipole antenna relative to the auricle.

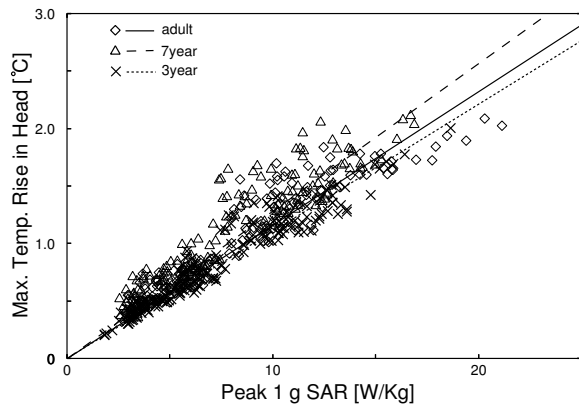
The thicknesses of unpressed and pressed ears are 18 mm and 6 mm for the adult model of Osaka Univ., and 22 mm and 8 mm for the NIT adult model. The diameter of the dipole antenna is fixed to 1.0 mm, but the length takes values of 160, 92, 72, 64, and 54 mm for 900 MHz, 1.5 GHz, 1.9 GHz, 2.1 GHz and 2.45 GHz, respectively. The output power of the antenna is 1.0 W.

Figures 2 and 3 illustrate the correlation between the temperature increase and peak 1-g and 10-g SAR for the adult head model of Osaka Univ and NIT. Note that maximum temperature increase in the head excluding the pinna is considered, as is the same as the peak spatial-average SAR. This is because an accurate correlation cannot be obtained for cases where the position of the maximum temperature increase is not included in the averaging volume of peak SAR for the majority of samples [13], [18]. In these figure, note that the dotted, broken, and solid lines correspond the regression lines for the 3-year old child, 7-year old child, and adult models, which are determined by using the method of least squares. The effectiveness of the estimation scheme can be confirmed from this figure. It is noteworthy that the difference in peak SARs between the two head models would be caused by different antenna input impedance, resulting in different current at the head surface [25].

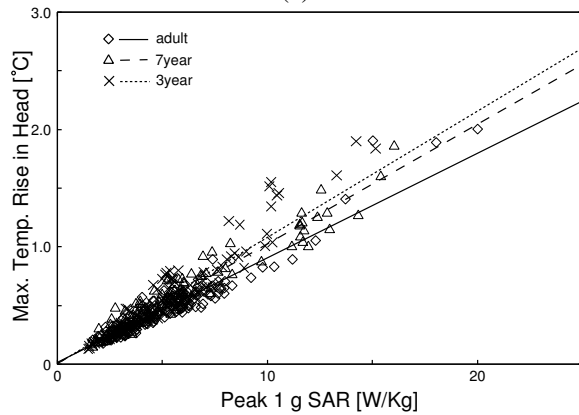
For more quantitative discussion, the comparisons of the slope of regression line and the coefficient of determination between the models of Osaka Univ. and NIT are listed in Table II. From these tables, it is found that the maximum temperature increases can be reasonably estimated in terms of peak 1-g or 10-g SARs. The point to be stressed is that no clear difference is observed between the models of adult and children. These values are also comparable for those of the NIT models. For proper evaluation of uncertainty in the slope correlating between the peak SAR and the maximum temperature increase, a measure of Δ defined by the following equation is introduced:

$$\Delta = \frac{a_{max} - a_{min}}{a_{max} + a_{min}} \quad (7)$$

a_{max} and a_{min} are the maximum and minimum slopes for the six models considered. Δ is 0.19 and 0.12 for peak 1-g and 10-g SAR, respectively. In terms of the coefficient of determination r^2 , the peak 1-g SAR is slightly better measure than the peak 10-g SAR. On the other hand, the peak 10-



(a)



(b)

Fig. 2. The maximum temperature increase versus the peak SAR averaged over 1-g tissues in the head:(a) Osaka Univ. model and (b) NIT model.

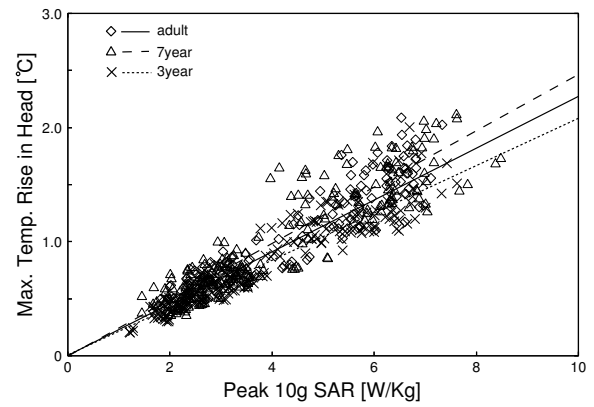
g SAR is better than the peak 1-g SAR in terms of the uncertainty in the slope Δ . It should be noted that the modeling of pinna could affect this slope since heat potential (ρ SAR) in the pinna is not included when calculating the peak-spatial average SAR in our discussion. From this result, the correlation between peak 1-g SAR and maximum temperature increase could be more sensitive to the modeling of pinna than that of peak 10-g SAR.

It should be noted that peak 10-g SAR was better than peak 1-g SAR as a measure for estimating maximum temperature increase in our previous work [18]. The difference between the conclusion in this section and that in our previous paper is due to the averaging scheme for calculating the peak spatial-average SARs.

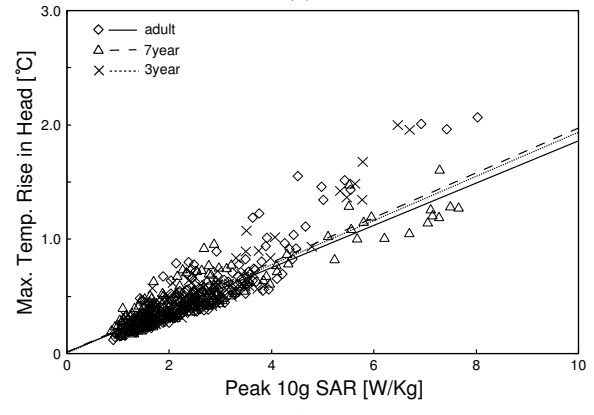
C. Effect of Electrical and Thermal Constants on Slope a

The electrical and thermal constants of tissues for children are larger than those for adults [22]. The variation in these constants with age is mainly due to the changes in the water content of tissues. This subsection investigates the effect of these constants on the correlation between the peak SARs and the maximum temperature increase.

The electrical constants of adult, 7-year old and 3-year old children can be interpolated by using the following equations



(a)



(b)

Fig. 3. The maximum temperature increase versus the peak SAR averaged over 10-g tissues in the head: (a) Osaka Univ. model and (b) NIT model.

[42]:

$$\epsilon_r = \epsilon_{rw} \frac{\alpha - \alpha_A}{1 - \alpha_A} \cdot \epsilon_{rA} \frac{1 - \alpha}{1 - \alpha_A} \left(1 - j \frac{1}{\omega\tau} \right) \quad (8)$$

where ϵ_{rw} is the relative permittivity of water (74.3 at 37 °C [43]), ϵ_{rA} is the relative permittivity of organic material, τ is relaxation time, α is the hydrated rate which is related to the mass density ρ and the total body water (TBW) by $\alpha = \rho \cdot \text{TBW}$ and α_A is hydrated rate for adult tissue. Eq. (8) gives an empirical representation of the complex permittivity (relative permittivity ϵ_r) for a hydrated rate α . It is therefore available to derive the dielectric properties at different ages from Eq. (8) as long as the TBW is known as a function of age and the dielectric properties are known at adult.

Table III lists the TBW for the adult, 7-year old, and 3-year old, which is based on the data in [44]. The TBW can be fitted with the following equation [42]:

$$\text{TBW} = 784 - 241 \exp \left[- \left(\frac{\ln(\text{Age}/55)}{6.9589} \right)^2 \right] \quad (9)$$

The resultant electrical constants of main tissues are given for adult, 7-year old and 3-year old children in Table IV. In order to clarify proper effect of electrical constants on the correlation between the peak SAR and maximum temperature increase, the permittivities and conductivities for all tissues are varied as is the same as in Table IV, while the 3-year old model developed at Osaka University with pressed ear is used.

TABLE II
ESTIMATED SLOPE [$^{\circ}\text{C} \cdot \text{kg}/\text{W}$] AND THE COEFFICIENT OF
DETERMINATION FOR THE MAXIMUM TEMPERATURE INCREASE VERSUS
THE PEAK (a) 1 g AND (b) 10 g SARs.

	head (1-g SAR)			
	Osaka Univ.		NIT	
	a	r^2	a	r^2
3-year	0.111	0.930	0.107	0.870
7-year	0.134	0.878	0.103	0.945
adult	0.119	0.877	0.0912	0.843

(a)

	head (10-g SAR)			
	Osaka Univ.		NIT	
	a	r^2	a	r^2
3-year	0.211	0.891	0.193	0.705
7-year	0.242	0.823	0.196	0.847
adult	0.238	0.888	0.187	0.751

(b)

TABLE III
TBW OF HUMANS.

	TBW [ml/Kg]
adult	543.5
7-year	563.3
3-year	581.6

The following total of 100 situations is considered for each set of the electrical constants:

- five frequencies: 900 MHz, 1.5 GHz, 1.9 GHz, 2.1 GHz, and 2.45 GHz;
- two polarizations: the HP and VP;
- ten antenna feeding points (see Fig. 1).

Table V lists the effect of electrical constants on the slope and determination coefficient of the regression line. As is evident from this table, the effect of electrical constants on the slope and determination coefficient of the regression line is negligible. In our previous paper [45], the effect of electrical constants on the correlation is investigated with the 3-year old model whose material constants were changed by $\pm 50\%$. Even for such empirical and overestimated change, the difference in the slope was less than 10%. This result can be expected from the foregoing discussion; the correlations between the maximum temperature increase and the peak SARs are not dependent on the EM wave frequency, although the electrical constants of tissues are largely dependent on the frequency.

The thermal properties of tissue are also varied with the changes in the water content (w). The thermal properties of tissue can be obtained by the following equation [34], [46]: $C = 1670 + 25.1 \cdot w$ [J/kg $\cdot^{\circ}\text{C}$], and $K = 0.0502 + 0.00577 \cdot w$ [W/m $\cdot^{\circ}\text{C}$]. Table VI lists the variation of thermal conductivity K according to the change of TBW. Note that the variation of heat capacity C is not listed, since it does not affect the temperature increase at the thermally steady state (See Eq.(4)). The values of blood flow B are assumed to be fixed, since no reliable parameters for it can be found. It is noteworthy that the effect of blood flow of tissues on the temperature increase in humans is larger than that due to the thermal conductivity and heat capacity of tissues [13], [47]. A quantitative discussion on the effect of blood flow on the correlation can be found

TABLE IV
ELECTRIC CONSTANTS OF ADULT AND CHILDREN AT (A) 900 MHZ AND
(B) 2.45 GHZ. THEY ARE DERIVED BASED ON THE SCHEME PRESENTED
IN [43].

tissue	(a)					
	adult		7year		3year	
	ϵ_r	σ	ϵ_r	σ	ϵ_r	σ
skin	46.08	0.84	47.04	0.86	47.96	0.88
grey matter	52.72	0.94	53.51	0.96	54.26	0.97
white matter	38.89	0.59	39.99	0.61	41.05	0.62
muscle	55.96	0.97	56.65	0.98	57.30	0.99
blood	61.36	1.54	61.87	1.55	62.35	1.56

tissue	(b)					
	adult		7year		3year	
	ϵ_r	σ	ϵ_r	σ	ϵ_r	σ
skin	38.01	1.46	39.12	1.51	40.02	1.55
grey matter	48.91	1.81	49.80	1.84	50.65	1.87
white matter	36.17	1.22	37.31	1.25	38.41	1.29
muscle	53.57	1.81	54.34	1.84	55.06	1.86
blood	58.26	2.54	58.88	2.57	59.46	2.60

TABLE V

THE EFFECT OF ELECTRICAL CONSTANTS OF TISSUES ON THE
CORRELATIONS BETWEEN THE MAXIMUM TEMPERATURE INCREASE AND
THE PEAK SARs IN THE HEAD: THE ELECTRICAL CONSTANTS OF (i)
3-YEAR OLD CHILD, (ii) 7-YEAR OLD CHILD, AND (iii) ADULT ARE USED.

	head (1-g SAR)		head (10-g SAR)	
	a	r^2	a	r^2
(i)	0.0996	0.886	0.1943	0.967
(ii)	0.0989	0.885	0.1946	0.966
(iii)	0.0998	0.883	0.1947	0.967

in [48]. According to the paper [48], the slope correlating between the maximum temperature increases and the peak SAR is decreased by 87% and 75% for the change of blood flow by 120% and 150%, respectively.

Table VII shows the effect of variation in the thermal properties of tissues on the regression line. The notations of (iv) and (v) correspond to the results for the thermal constants of 3-year old and 7-year old children as shown in Table VI.

As is evident from this table, the effect of variation in the thermal properties on the regression line is at most 1%.

D. Maximum Temperature Increase at the SAR Limits in Safety Guidelines

This subsection discusses maximum temperature increases in the head and brain at the SAR limits prescribed in the safety

TABLE VI
MODIFIED THERMAL CONDUCTIVITY OF MAJOR TISSUES IN THE HEAD:
(IV) 3-YEAR OLD CHILD, (V) 7-YEAR OLD CHILD, AND ADULT (ORIGINAL
VALUES).

Tissues	K [W/m $\cdot^{\circ}\text{C}$]		
	(iv)	(v)	adult
Skin	0.44	0.43	0.42
Skull	0.42	0.41	0.40
Fat	0.27	0.26	0.25
Grey Matter	0.59	0.58	0.57
White Matter	0.52	0.51	0.50
Muscle	0.52	0.51	0.50

TABLE VII

THE EFFECT OF VARIATION IN THE THERMAL PROPERTIES OF TISSUES ON THE ESTIMATION PARAMETERS: THE THERMAL PROPERTIES OF (iv) 3-YEAR OLD CHILD, (v) 7-YEAR OLD CHILD ARE USED.

	head (1-g SAR)		head (10-g SAR)	
	a	r^2	a	r^2
(iv)	0.0993	0.874	0.1939	0.969
(v)	0.0995	0.877	0.1941	0.968
(iii)	0.0998	0.883	0.1947	0.967

guidelines. The upper limit for near-field exposures in public environments is 1.6 W/kg for any tissue averaged over 1 g in the IEEE standard [4], while 2.0 W/kg for 10 g of tissue in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline [3]. Note that the averaging volume for peak spatial-average SAR calculation in this paper is a cube as mentioned in Sec. II, while they are arbitrary and adopted for contiguous tissue in the ICNIRP guideline.

Figure 4 depicts the histogram and cumulative function of the ratio of maximum temperature increase to peak (a) 1-g and (b) 10-g SARs for the adult head model of Osaka Univ. As seen from this figure, these ratios do not follow normal distributions. This tendency was observed for the other head models. The reason for this would be the contrast of blood flow in the tissues, together with complicated anatomy around the pinna. It should be noted that the blood flow is one of the most dominant factors which affects these ratios [48]. The amount of blood flow in the muscle and fat are relatively small, while that of skin is large (See Table I). Thus, the ratios of maximum temperature increase to peak SARs are affected by the anatomical structure where maximum temperature increase appears. Additionally, the resolution of the head models is 2 mm at most, and thus this would be one of the factors which affects the ratios. In order to suppress uncertainties caused by the above-mentioned factors, the 95th percentile is used as a basis of possible maximum temperature increase in the following discussion. Note that maximum values of possible temperature increases are defined as the product of the SAR limit in the guidelines and a 95th percentile value of the slope.

Table VIII shows maximum limits of possible temperature increases in the head and brain at the SAR values prescribed in the guidelines. For the adult model of Osaka Univ., they are 0.28 °C and 0.10 °C for 1-g cubic tissue with 1.6 W/kg, while they are 0.59 °C and 0.21 °C for 10-g cubic tissue with 2.0 W/Kg. As summarized in [18], these values reasonably agree with those in the previous papers. Similarly, for the 3-year old child model of Osaka Univ., they are 0.23 °C and 0.11 °C for the SAR value of 1-g tissue, while they are 0.53 °C and 0.20 °C for the SAR value of 10-g tissue. Namely, no clear difference is observed between adult and children. These values are also comparable for those of the NIT models.

IV. SUMMARY

In this paper, we investigated the correlation between the peak SAR and the maximum temperature increase in the head models of child and adults due to a dipole antenna. The rationale for this study was that damage and physiological

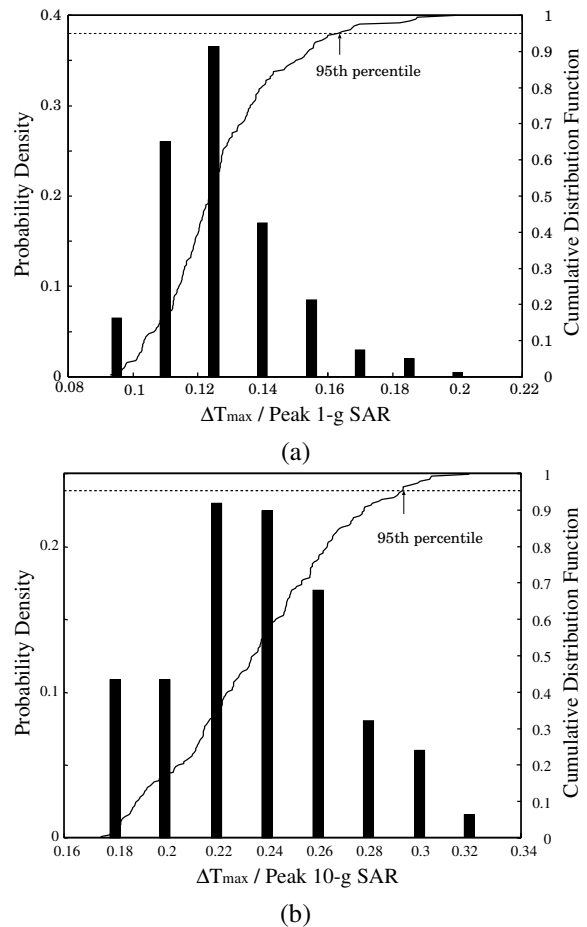


Fig. 4. Histogram and cumulative function of the ratio of maximum temperature increase to peak (a) 1-g and (b) 10-g SARs for the adult head model of Osaka Univ.

effect to humans due to EM wave exposure were induced through the temperature increase, although the safety guidelines are regulated in terms of the peak SARs. For investigating these correlations thoroughly, we considered the total of 1400 different situations, and the numerical results for these cases were analyzed on the basis of statistics. For the result of our investigations, first, we found that maximum temperature increase in the head can be estimated in terms of peak SARs averaged over 1-g or 10-g tissue. Next, the slopes correlating between the maximum temperature increases and the peak SARs were almost identical for different head models (within 20%). Furthermore, no clear difference in the correlation between the peak SAR and the maximum temperature increase was observed for different shape models.

Additionally, we investigated the effect of variation of electrical and thermal constants on the correlations. Note that these constants are derived in terms of the TBW, which is dependent on age. It was found that the effect of electrical and thermal constants on the correlation was marginal.

It is worth presenting maximum values of possible temperature increases in the head and brain of adults for the SAR values prescribed in the safety guidelines. They are 0.28 °C and 0.10 °C for the 1-g cube with 1.6 W/Kg, while they are 0.59 °C and 0.21 °C for 10-g cubic tissue with 2.0W/Kg.

TABLE VIII

POSSIBLE MAXIMUM TEMPERATURE INCREASES [$^{\circ}\text{C}$] DUE TO THE DIPOLE ANTENNA: (a) OSAKA UNIVERSITY AND (b) NIT MODELS.

			head	brain
3-year	(a)	1-g cube	0.23	0.11
		10-g cube	0.53	0.20
	(b)	1-g cube	0.23	0.10
		10-g cube	0.65	0.23
7-year	(a)	1-g cube	0.30	0.12
		10-g cube	0.67	0.23
	(b)	1-g cube	0.24	0.11
		10-g cube	0.62	0.23
adult	(a)	1-g cube	0.26	0.10
		10-g cube	0.59	0.21
	(b)	1-g cube	0.19	0.10
		10-g cube	0.52	0.21

Similarly, they are 0.23°C and 0.11°C for the SAR value of 1-g cubic tissue, while they are 0.53°C and 0.20°C for the SAR value of 10-g cubic tissue. Additionally, these values are comparable for the NIT models. Namely, no clear difference in the correlations is observed for all models considered in this paper.

It should be noted that physiological differences between adult and child were not taken into account, unlike physical differences. Uncertainties of the correlation caused by physical parameters, i.e., electrical and thermal constants of tissues and the head shape, were investigated thoroughly. The results obtained in this paper would be useful for further discussion in this field.

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