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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,
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

\[
\text{SAR} = \frac{\sigma}{2\rho} |\vec{E}|^2 = \frac{\sigma}{2\rho} \left( |\vec{E}_x|^2 + |\vec{E}_y|^2 + |\vec{E}_z|^2 \right)
\]

(1)

where \(\vec{E}_x, \vec{E}_y,\) and \(\vec{E}_z\) are the peak values of electric-field components, \(\sigma\) and \(\rho\) 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

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

(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 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

\[
H \cdot (T_s - T_c) = -K \frac{dT}{dn}
\]

(3)

where \(H, T_s,\) and \(T_c\) 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:

\[
\nabla \cdot (K \nabla \delta T) + \rho(SAR) - B\delta T = 0
\]

(4)

where \(\delta T = \delta T(r,t)\) 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:

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

where SAR\(_{ave}\), $\Delta T$, 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 °C · kg/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, 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

$$r^2 = \frac{\sum (T_i - \bar{T})^2}{\sum (T_i - \bar{T})^2} = 1 - \frac{\sum (T_i - \bar{T})^2}{\sum (T_i - \bar{T})^2}$$  (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).

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 $\Delta$ defined by the following equation is introduced:

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

$a_{max}$ and $a_{min}$ are the maximum and minimum slopes for the six models considered. $\Delta$ 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-
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.

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.

g SAR is better than the peak 1-g SAR in terms of the uncertainty in the slope $\Delta$. It should be noted that the modeling of pinna could affect this slope since heat potential ($\rho$ 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 $\alpha$

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 [42]:

$$\varepsilon_r = \varepsilon_{rw} \cdot \varepsilon_{rA} \cdot \left(1 - j \frac{1}{\omega \tau}\right)$$

(8)

where $\varepsilon_{rw}$ is the relative permittivity of water (74.3 at 37 °C [43]), $\varepsilon_{rA}$ is the relative permittivity of organic material, $\tau$ is relaxation time, $\alpha$ is the hydrated rate which is related to the mass density $\rho$ and the total body water (TBW) by $\alpha = \rho \cdot TBW$ and $\alpha_A$ is hydrated rate for adult tissue. Eq. (8) gives an empirical representation of the complex permittivity (relative permittivity $\varepsilon_r$) for a hydrated rate $\alpha$. 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]:

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

(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 [°C · kg/W] and the Coefficient of Determination for the Maximum Temperature Increase Versus the Peak (a) 1 g and (b) 10 g SARs.

<table>
<thead>
<tr>
<th></th>
<th>Osaka Univ.</th>
<th>NIT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α</td>
<td>r²</td>
</tr>
<tr>
<td>head (1-g SAR)</td>
<td>3-year</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>7-year</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>adult</td>
<td>0.119</td>
</tr>
</tbody>
</table>

(b) head (10-g SAR)

<table>
<thead>
<tr>
<th></th>
<th>Osaka Univ.</th>
<th>NIT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α</td>
<td>r²</td>
</tr>
<tr>
<td>3-year</td>
<td>0.211</td>
<td>0.891</td>
</tr>
<tr>
<td>7-year</td>
<td>0.242</td>
<td>0.823</td>
</tr>
<tr>
<td>adult</td>
<td>0.238</td>
<td>0.888</td>
</tr>
</tbody>
</table>

TABLE III
TBW of Humans.

<table>
<thead>
<tr>
<th></th>
<th>TBW [ml/Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>adult</td>
<td>543.5</td>
</tr>
<tr>
<td>7-year</td>
<td>563.3</td>
</tr>
<tr>
<td>3-year</td>
<td>581.6</td>
</tr>
</tbody>
</table>

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 ±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]:

\[ C = 1670 + 25.1 \cdot w \text{ [J/kg·°C]}, \quad K = 0.0502 + 0.00577 \cdot w \text{ [W/m·°C]} \]

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 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 guidelines.

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).

<table>
<thead>
<tr>
<th>Tissues</th>
<th>( K ) [W/m·°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(iv)</td>
</tr>
<tr>
<td>Skin</td>
<td>0.44</td>
</tr>
<tr>
<td>Skull</td>
<td>0.42</td>
</tr>
<tr>
<td>Fat</td>
<td>0.27</td>
</tr>
<tr>
<td>Grey Matter</td>
<td>0.59</td>
</tr>
<tr>
<td>White Matter</td>
<td>0.52</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.52</td>
</tr>
</tbody>
</table>
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.

### REFERENCES


Masaki Fujimoto was born in Osaka, Japan, on 25 September, 1980. He received the B.E. degree in communications engineering from Osaka University, Osaka, Japan, in 2003. He is engaged in the work on bioelectromagnetics.

Akimasa Hirata was born in Okayama, Japan, on November 27, 1973. He received the B.E., M.E., Ph.D degrees in communication engineering from Osaka University, Suita, Osaka, Japan, in 1996, 1998, and 2000, respectively. He was a research fellow of the Japan Society for the Promotion of Science (JSPS Research Fellow) for the 1999–2001 period and also a visiting research scientist in the University of Victoria, Canada from May to October in 2000. In 2001, he joined the Department of Communication Engineering, Osaka University as an Assistant Professor. In 2004, he joined the Department of Computer Science and Engineering, Nagoya Institute of Technology as an Associate Professor. His research interests are in electron beam devices for high-power millimeter or submillimeter generation, bioelectromagnetics, waveguide analysis, EMC and EMI in power line, and computational techniques in electromagnetics.

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Jianqing Wang received the B.E. degree in electronic engineering from Beijing Institute of Technology, Beijing, China, in 1984, and the M.E. and D.E. degrees in electrical and communication engineering from Tohoku University, Sendai, Japan, in 1988 and 1991, respectively.

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Toshiyuki Shiozawa was born in Tokyo, Japan, on January 16, 1941. He received the B. E., M. E. and Ph. D. degrees in communication engineering from Osaka University, Suita, Osaka, Japan in 1964, 1966 and 1969, respectively. In 1969 he joined the Department of Communication Engineering, Osaka University, where he is now a Professor.

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In 2001, he was elected to the grade of IEEE Fellow for contributions to engineering-oriented relativistic electromagnetic theory and theoretical study of free-electron lasers.