Correlation of Maximum Temperature Increase and Peak SAR in the 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 the child and adult head models due to a dipole antenna. Much attention is paid to the effect of the variation of material constants on the correlation for the children model, since the material constants of children tissue are different from those of adults. For investigating these correlations thoroughly, the total of 200 situations is considered for each of following six models: 3- and 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 and brain can be estimated linearly in terms of peak SARs averaged over 1-g and 10-g of tissue in these regions. In particular, no clear difference is observed in the slopes correlating the maximum temperature increase and the peak SAR. Also, the effect of material constants of tissue on their correlation is found to be marginal.

Key words: Children, dosimetry, bioheat equation, temperature increase, specific absorption rate (SAR).

1. Introduction

In recent years, there has been an increasing public concern about health implications of electromagnetic (EM) wave exposures with the use of mobile telephones. For this reason, various public organizations in the world have established the safety guidelines for EM wave absorption [1]-[3]. For RF near field exposures, these standards are based on the spatial peak SAR (specific absorption rate) for any 1 or 10g of tissues of the body. However, possible physiological damage in humans for microwave exposures is induced by the temperature increase. The temperature increase of 4.5 °C in the brain has been remarked to be an allowable limit, which does not lead to any physiological damage (for exposures of more than 30 minutes) [4]. Additionally, the threshold temperature of the pricking pain in skin is 45 °C, corresponding to the temperature increase of 10-15 °C [5], [6]. In view of these circumstances, the temperature increase in the anatomically-based human head model for exposure to EM waves from handset antennas has been calculated in several works [7], [8], [9], [10], [11], [12], [13], [14], [15]. Particularly, we have attempted to correlate the maximum temperature increase in the head and brain to the peak SAR value due to handset antennas [15]. 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. As a main result, the maximum temperature increases in the head and brain have been found to be approximately proportional to peak SARs averaged over 1-g and 10-g of tissue in the corresponding regions.

It is also concerned that children might be more vulnerable to any adverse effects of RF radiation than adults [16]. However, the study on the temperature increase in child head models has been done by the two groups of the present authors [17], [18], but only insufficiently. The purpose of this paper is to investigate the correlations between the peak SAR and the maximum temperature increase in the child head models due to a dipole antenna. Then, we discuss the difference in the correlations for the head models of adults and children. In particular, our attention is paid to the effect of the variation of material constants on the correlation for the child models, since the material constants of children tissues are different from those of adults [19].

2. Method and Model for the Analysis

2.1 Human Head Model

Two head models for the adult are considered: one is developed at Nagoya Institute of Technology (NIT) [20] and the other at Osaka University [21]. Realistic head models of 3- and 7-year-old children are developed from the adult models in the manner as shown in [22]. The feature of the modeling is that a statistical database [23] 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: bone
(skull), muscle, skin, fat, white matter, grey matter, cerebellum, blood, and so forth.

2.2 Numerical Methods

The FDTD method [24] is used for investigating the interaction between the human head model and a dipole antenna. In order to incorporate the inhomogeneous head model into the FDTD scheme, the dielectric properties of the tissues are required. They are determined with the aid of the 4-Cole-Cole extrapolation [25]. Only the outline of the algorithm for calculating temperature increase is described, since our procedures are the same as those in [7], [8], [9], [10], [11], [12], [14].

For calculating the temperature increase in the human head, the bioheat equation [26], [27], which takes into account the heat exchange mechanisms such as heat conduction, blood flow, and EM heating, is used. The bioheat equation is represented as

\[ C \rho \frac{dT}{dt} = KV^2T + \rho(SAR) - BT \]  

(2)

where \( T \) is the temperature increase of the tissue, \( K \) the thermal conductivity of the tissue, \( C \) the heat capacity of the tissue, and \( B \) the term associated with blood flow.

3. Correlation Between Peak SARs and Temperature Increases

3.1 Correlation and Evaluation Scheme

We have demonstrated that maximum temperature increases in the head and brain were reasonably estimated linearly by using the peak 10-g and 1-g SAR in the corresponding regions [15]. Let us review the rational for this in short. At the thermally steady state (\( \frac{dT}{dt} = 0 \) at (2)), the temperature increase is linear in terms of SAR. The SAR is proportional to the output power of wave sources. Thus, it could be appropriate to express the maximum temperature increase in the head or brain approximately as the following equation:

\[ \hat{T} = a \cdot SAR \]  

(3)

where \( SAR_{\text{ave}}, \hat{T}, \) and \( a \) denote, respectively, the peak SAR averaged over 1 or 10 g of tissue in the head or brain, the maximum temperature increase estimated by the regression line, and the slope of the regression line with the unit of °C/Kg/W, which are determined by using the method of least squares.

For evaluating the effectiveness of the estimation scheme for the maximum temperature increase, the coefficient of determination \( r^2 \) is introduced as

\[ r^2 = \frac{\sum_i (\hat{T}_i - \bar{T})^2}{\sum_i (T_i - \bar{T})^2} = 1 - \frac{\sum_i (T_i - \bar{T})^2}{\sum_i (T_i - \bar{T})^2} \]  

(4)

where \( \bar{T}_i \) is the maximum temperature increase for the \( i \)th case, and \( \bar{T} \) is the mean value of \( \bar{T}_i \).

3.2 Effectiveness of the Estimation Scheme for Child Models

The effectiveness of the estimation scheme for the correlation between the maximum temperature increase and peak SAR values are discussed for a dipole antenna. The following total of 1200 situations is considered for the dipole antenna:

- Six head models; 3-year-old and 7-year-old child and adult models of NIT and Osaka Univ.,
- The head models with pressed or unpressed ear;
- Five frequencies; 900MHz, 1.5GHz, 1.9GHz, 2.1GHz, and 2.45GHz,
- Two polarizations; the horizontal polarization (HP) and vertical polarization (VP),
- Ten feeding points. (see Fig. 1 in [15])

The diameter of the dipole antenna is fixed to 1.0 mm, but the length takes several values; 160, 92, 72, 64, and 54mm for 900MHz, 1.5GHz, 1.9GHz, 2.1GHz and 2.45GHz, respectively. The output power is assumed to be 1.0 W.

Tables I (a) and (b) show the comparison for the slope of regression line and the adjusted coefficient of determination between the models of Osaka Univ. and NIT. Since it has been shown that maximum temperature increases in the head and brain were well estimated by using the peak SARs in the corresponding regions [15], attention is paid only to these correlations. From these tables, it is found that the maximum temperature increases in the head and brain can be reasonably estimated in terms of peak 1-g or 10-g SARs. The point to be stressed is that the slope and the adjusted coefficient are marginally affected by age. This is true both for the models of Osaka Univ. and NIT. Figure 1 illustrates the correlation between the temperature increase in the head and peak 10-g SAR in head for the adult head model of Osaka Univ. with pressed ear. In this figure, note that the dotted, broken, and solid lines mean the regression lines for the 3- and 7-year-old, 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.

3.3 Effect of the Material constants on the Slope \( a \)

The material constants of tissue for children are larger than those for adults by 20-50%[19]. The variation in the material constants with age is mainly due to the changes in the water content of tissues. This subsection investigates the effect of the material constants on the correlation between the peak SARs and maximum temperature increase. The 3-year-old child head model of Osaka Univ. with the pressed ear is used in this discussion.
TABLE I

Estimated slope [°C Kg/W] and the adjusted Coefficient of Determination for the Maximum Temperature Increase in (a) the Head and (b) the Brain Versus the Peak 10 g SAR.

<table>
<thead>
<tr>
<th></th>
<th>Osaka Univ.</th>
<th>NIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>head (10 g SAR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-year</td>
<td>0.207</td>
<td>0.191</td>
</tr>
<tr>
<td>7-year</td>
<td>0.218</td>
<td>0.197</td>
</tr>
<tr>
<td>adult</td>
<td>0.247</td>
<td>0.200</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th></th>
<th>Osaka Univ.</th>
<th>NIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>brain (10 g SAR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-year</td>
<td>0.147</td>
<td>0.149</td>
</tr>
<tr>
<td>7-year</td>
<td>0.159</td>
<td>0.158</td>
</tr>
<tr>
<td>adult</td>
<td>0.169</td>
<td>0.145</td>
</tr>
</tbody>
</table>

The complex permittivity of the tissue is reasonably proportional to that of water for \( f \geq 1 \) GHz [28]. Then, the water content of tissue \( w \) is approximately given by the following equation:

\[
w = 0.653 \cdot \varepsilon_r + 47.1 [\%] \tag{5}\]

where \( \varepsilon_r \) is the relative permittivity of tissue at very low frequency. This equation has been derived by the fitting for the data presented in [29] (summarized in Table II).

Let us change the material constants so that the water content of tissue does not exceed 100%. The water content of high-water content tissues, such as muscle and brain, is 70-80%. When increasing the relative permittivity of muscle by 30%, for example, the water content of the muscle increases from 74 to 92%, then, the increase of the conductivity is about 20%.

In the following discussion, the permittivity and conductivity of all tissues are varied uniformly as follows: the relative permittivity and conductivity of tissue are changed by (i) (+30%,+20%), (ii) (+15%,+10%), (iii) (± 0%, ± 0%), respectively.

The following total of 100 situations are considered for each set of material constants:

- Five frequencies; 900MHz, 1.5GHz, 1.9GHz, 2.1GHz, and 2.45GHz,
- Two polarizations; the horizontal polarization (HP) and vertical polarization (VP),
- Ten feeding points.

Table III lists the effect of material constants on the estimation parameters. As is evident from this table, the effect of material constants on the estimation parameters is negligible for both the head and brain. This result can be expected from the above discussion; the correlation between the maximum temperature increase and the peak SAR is not dependent on the frequency of an EM wave, although the material constants of tissue is largely dependent on the frequency. Note that the effect of the variation of \( C \) and \( K \) on the correlation is not shown, since it is sufficiently small.

TABLE II

Debye’s Parameters of Major High-Water Content Tissues in the Head

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Water [%]</th>
<th>( f_r ) [GHz]</th>
<th>( \varepsilon_r )</th>
<th>( \sigma_r ) [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humor</td>
<td>90</td>
<td>24.3</td>
<td>65.7</td>
<td>1.57</td>
</tr>
<tr>
<td>Skin</td>
<td>68</td>
<td>20.2</td>
<td>32.0</td>
<td>1.04</td>
</tr>
<tr>
<td>Grey Matter</td>
<td>82</td>
<td>22.8</td>
<td>53.5</td>
<td>1.38</td>
</tr>
<tr>
<td>White Matter</td>
<td>73</td>
<td>21.2</td>
<td>39.7</td>
<td>1.16</td>
</tr>
<tr>
<td>Muscle</td>
<td>74</td>
<td>21.3</td>
<td>41.2</td>
<td>1.19</td>
</tr>
<tr>
<td>Blood</td>
<td>74</td>
<td>21.3</td>
<td>41.2</td>
<td>1.19</td>
</tr>
</tbody>
</table>

TABLE III

The Effect of Material Constants of Tissues on the Correlations between the Maximum Temperature Increase and the Peak SARs in the Head and Brain.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>head (10 g SAR)</th>
<th>brain (10 g SAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>( r^2 )</td>
<td>a</td>
</tr>
<tr>
<td>(i)</td>
<td>0.1943</td>
<td>0.967</td>
</tr>
<tr>
<td>(ii)</td>
<td>0.1946</td>
<td>0.966</td>
</tr>
<tr>
<td>(iii)</td>
<td>0.1947</td>
<td>0.967</td>
</tr>
</tbody>
</table>
4. Summary
In this paper, we investigated the correlation between the peak SAR and the maximum temperature increase in the models of children and adults due to a dipole antenna. The rationale for this study was that physiological effects and damage to humans due to EM wave exposure are induced through temperature increases, although the safety standards are regulated in terms of the peak SARs. For investigating these correlations thoroughly, we considered the total of 1400 different situations. The numerical results for these cases were analyzed on the basis of statistics. For the result of our investigations, we have first found that maximum temperature increases in the head and brain can be estimated in terms of peak SARs averaged over 10g of tissue and 1- or 10-g tissue in these regions. Next, the slopes to correlate the maximum temperature increases in the head and brain to the peak SARs in the head and brain were almost identical for different head models (within 10%). Furthermore, no clear difference in the correlation between the peak SAR and the maximum temperature increase was observed for child and adult models. Additionally, the effect of the material constant on the slope was negligible. On the other hand, the correlation between the peak SAR in the head and the maximum temperature increase in the head was marginally affected by the variation in their thermal properties.

References