Localized Specific Absorption Rate in the Human Head in Metal-Framed Spectacles for 1.5 GHz Hand-Held Mobile Telephones

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Enhancements of the localized specific absorption rate (SAR) caused by metal-framed spectacles are analyzed numerically for 1.5 GHz hand-held mobile telephones. The finite-difference time-domain (FDTD) method and an anatomically based human head model are employed in the analysis. Enhancements up to 1.2 times for the ten-gram-averaged spatial peak SAR in the head and up to 2.75 times for the one-gram-averaged SAR in the eye are found, whereas there is no significant variation on the absorbed power or averaged SAR in the whole head. The mechanism of localized SAR enhancement is clarified to be due to an induced current on the metal frame.

Key words: specific absorption rate, hand-held mobile telephone, anatomically based head model, metal-framed spectacles, FDTD analysis.

1. Introduction

With the recent rapid increase in the use of hand-held mobile telephones, public concern regarding potential health hazards due to the absorption of electromagnetic energy emitted by these telephones has been growing. Safety guidelines for protecting the human body from radio wave exposure have been issued in various countries. The specific absorption rate (SAR) in W/kg is commonly used to express the rate of electromagnetic energy deposition in these safety guidelines. A spatial peak SAR value not exceeding 1.6 W/kg averaged over any one-gram of tissue [1] or 2 W/kg averaged over any ten-grams of tissue [2][3], for a specified uncontrolled environment, should be acceptable. A number of experimental and numerical SAR assessments have recently been reported for typical operating conditions of the mobile telephones using realistic shaped phantoms or anatomically based numerical models [4]-[10]. Increased spatial peak SARs were shown for 900 MHz due to metallic accessories such as metal-framed spectacles or jewellery [5][11]. Enhancements of several dBs were reported to be possible for heterogeneous human head models, while the effects were shown to be negligible for homogeneous human head models.

The Japanese mobile telephone system, or the personal digital cellular (PDC) system, has employed two frequency bands of 800 MHz and 1.5 GHz. The frequency band of 1.5 GHz is not used in other countries for mobile telephone systems. As a result the enhancement effects of metallic accessories on spatial peak SAR values are unclear for 1.5 GHz because the sizes of metallic accessories relative to the wavelength are different from the reported ones. Especially, due to half a wavelength at 1.5 GHz having approximately the same length as metallic frames of spectacles, it is concerned whether or not a resonant effect could exist.

In this paper, possible SAR enhancements caused by metal-framed spectacles at 1.5 GHz are investigated numerically using an anatomically based human head model and a generic hand-held mobile telephone model. Since the ear affects strongly the maximum spatial peak SAR values and most of measurement systems for SAR assessments use a homogeneous phantom, the enhancement effects of metal-framed spectacles for a head model without ears and a head model with homogeneous material are also investigated, respectively. In these investigations the finite-difference time-domain (FDTD) method is used because of its flexibility and efficiency in solving complex heterogeneous geometries. The mechanism of spatial peak SAR enhancement caused by metal-framed spectacles is also examined in relation to an induced current on the metal frame.
2. Model and Analysis Method

Figure 1 shows the models of a human head in metal-framed spectacles and a hand-held mobile telephone for the present study. The head model was constructed by our group on the basis of an anatomical chart of a Japanese adult head [12]. It consists of 273 108 cubical cells with a resolution of 2.5 \( \times \) 2.5 \( \times \) 2.5 mm. Seven types of tissues, i.e., bone, brain, muscle, eyeball, fat, skin and lens, are involved in this model. Their dielectric properties at 1.5 GHz are given in Table 1 in which \( \varepsilon_r \) and \( \sigma \) are the relative permittivity and conductivity, respectively [13]. The mass density \( \rho \) of each of tissues was assumed to be 1050 kg/m\(^3\). Being aware of the fact that in ordinary use of mobile telephones the ear near the telephone is often pressed by the pressure of the telephone, we also therefore used a removed-ear model which was identical to the normal head model except that it had no ears.

The spectacles were modeled by a metallic frame and two pieces of optical glass as shown in Fig. 2. Two types of spectacles, denoted by S1 and S2, respectively, were considered. S1 had both metallic rims and legs, whereas S2 was rimless (only the legs were metallic). The material of metallic frames were titanium with \( \varepsilon_r = 1 \) and \( \sigma = 1.8 \times 10^6 \) S/m, and the optical glass had \( \varepsilon_r = 2 \) and \( \sigma = 0 \).

The generic mobile telephone was modeled by a 1/4-wavelength monopole antenna mounted on a rectangular metal box. The metal box had a dimension of 12(length) \( \times \) 4(width) \( \times \) 2.5(depth) cm. The monopole had a radius of 0.5 mm and was located at the top of the box, 0.5 cm far from the edge of the 4 cm side and 2 cm far from the edge of the 2.5 cm side. The hand model was highly simplified and modeled by 2/3 muscle-equivalent material (its \( \varepsilon_r \) and \( \sigma \) are two-thirds of muscle's ones, respectively). It was 8 cm wide and 2 cm thick and wrapped around three sides of the lower part of the mobile telephone. It should be noticed that the distance \( d \) between the monopole antenna and the closest head surface or the ear, if the model contains it, was 2.25 cm.

The FDTD method used in this analysis was first described by Yee and further details about the method can be found in [14] and [15]. The parameters for the FDTD calculations were as follows. A space domain enclosing the human head and the portable telephone had 200 \( \times \) 200 \( \times \) 200 Yee-cells. Each cell had a size \( \Delta = 2.5 \) mm. The time step \( \Delta t \) was set to \( \Delta / \sqrt{3} c \), where \( c \) is the speed of light, to ensure the numerical stability. The time-stepping was performed for about seven sinusoidal cycles in order to reach a steady state. To absorb the outgoing scattered waves, the second order Mur absorbing boundaries acting on electric fields were used. The boundary was placed at least 50 cells from the nearest surface of the telephone or the head. The monopole antenna was approached by thin-wire approximation which can include the effects of a wire with radius smaller than the FDTD cell dimensions [16]. According to this approach, the basic FDTD algorithm was modified to calculate the circumferential H-fields in the cells immediately adjacent to the monopole antenna, i.e., \( H_x(i, j - \frac{1}{2}, k + \frac{1}{2}), H_x(i, j + \frac{1}{2}, k + \frac{1}{2}), H_y(i - \frac{1}{2}, j, k + \frac{1}{2}) \) and \( H_y(i + \frac{1}{2}, j, k + \frac{1}{2}) \) if assuming the monopole positioned along z-axis. As described in

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Table 1. Dielectric properties of tissues at 1.5 GHz

<table>
<thead>
<tr>
<th>Tissue</th>
<th>( \varepsilon_r )</th>
<th>( \sigma ) [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>16.1</td>
<td>0.32</td>
</tr>
<tr>
<td>Brain</td>
<td>42.8</td>
<td>1.08</td>
</tr>
<tr>
<td>Muscle</td>
<td>50.2</td>
<td>1.39</td>
</tr>
<tr>
<td>Eyeball</td>
<td>73.9</td>
<td>2.21</td>
</tr>
<tr>
<td>Fat</td>
<td>9.7</td>
<td>0.20</td>
</tr>
<tr>
<td>Skin</td>
<td>39.1</td>
<td>0.86</td>
</tr>
<tr>
<td>Lens</td>
<td>45.0</td>
<td>1.10</td>
</tr>
</tbody>
</table>
detail in [16], the modified form for $H_y(i + \frac{1}{2}, j, k + \frac{1}{2})$
is given by
\[
H_y^{n+\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}) = H_y^{n-\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}) \\
- \frac{\delta t}{\mu_0 \varepsilon_0} [E_z^n(i + \frac{1}{2}, j, k + 1) - E_z^n(i + \frac{1}{2}, j, k)] \\
+ \frac{2\delta t}{\mu_0 \varepsilon_0} \ln(\delta/a) E_z^n(i + 1, j, k + \frac{1}{2}) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1)
\]
where the radius $a$ of the monopole has to satisfy the condition $a \leq \delta/2$. An antenna excitation was introduced by specifying a voltage with complex amplitude $V$ across the one-cell gap between the monopole and the top surface of the metal box. The current flowing through the voltage source gap was then obtained from Ampere's law on a small curve around the gap. The power radiated from the antenna was calculated from $Re(VI^*)/2$ where $I$ is the complex amplitude of the current and $*\nu$ denotes the complex conjugate. The SAR was calculated by taking $\sigma|E^2|/2\rho$ for each cell where $E$ is the electric field in the cell. Since Japanese safety guidelines recommend that the localized SAR should be averaged over a ten-gram region to assess the human hazard [3], we have used averaged ones of the SAR values within $8 \times 8 \times 9$ or $8 \times 9 \times 8$ cells ($=576$ cells $= 9.45$ g) as the ten-gram-averaged SAR. It should be noted that these cells used for the average did not contain air because $\sigma$ is zero for air.

3. Results and Discussion

3.1 SAR and Absorbed Power

Fig. 3 shows the effects of the metal-framed spectacles on the ten-gram-averaged spatial peak SAR for the normal model and the removed-ear model. It is impossible to take a ten-gram region which does not include the air cells within the ear area. As a result the ten-gram-averaged spatial peak SAR has to be obtained from the regions beyond the ear even if the model includes it. This fact resulted in that the SAR values obtained with the removed-ear model are much larger than those for the normal model because the distance $d$ between the monopole antenna and the closest head surface or the ear, if the model contains it, was always kept at the same distance (see Fig.1). This means that pressing the telephone to the ear would yield the higher ten-gram-averaged spatial peak SAR. With the head models in metal-framed spectacles, enhanced spatial peak SARs were found to occur in the vicinity of the ear. Types S1 and S2 enhanced the ten-gram-averaged spatial peak SAR levels by a factor up to 1.20 and 1.17, respectively. There were not obvious differences either between Type S1 and Type S2 or between the normal and the removed-ear models for the spatial peak SAR enhancement.

Within the head, the eyes have been considered to.
be particularly vulnerable because they have not blood supply and therefore have a limited ability to dissipate the heat induced by electromagnetic absorption. Since it is impossible to obtain a localized SAR value averaged over ten grams in the eye, we have used a one-gram average to assess the hazard in the eyes because the one-gram-averaged spatial peak SAR best fits the peak temperature-rise in the eyes [17]. Fig. 4 shows the effects of the metal-framed spectacles on the one-gram-averaged spatial peak SAR in the eye near the mobile telephone. It is found that Type S1, which had metallic rims in front of the eye, enhanced the one-gram-averaged spatial peak SAR levels in the eye by a factor of 2.12 for the normal model and 2.75 for the removed-ear model. On the other hand, Type S2, which was rimless, did not enhance the SAR levels in the eye both for the normal model and the removed-ear model. The SAR enhancement in the eye by Type S1 is considered to be due to the metallic rims of spectacles which were just in front of the eye. It should be emphasized, however, that the spatial peak SAR values in the eye were much lower than the safety limits even if the SAR enhancement effect by the metal-framed spectacles occurred. With an antenna radiating power of 1 W, the one-gram-averaged spatial peak SAR values in the eye were only 0.15 W/kg for the normal model in Type S1 and 0.18 W/kg for the removed-ear model in Type S1, which are much below the ANSI/IEEE safety level of 1.6 W/kg specified in an uncontrolled environment.

Since most of measurement systems for SAR assessments use a homogeneous phantom model, also shown for comparison in Fig. 5 is the enhancement effect of metal-framed spectacles on the ten-gram-averaged spatial peak SAR obtained for the homogeneous model with dielectric properties identical to those of the brain. It is noticed that the enhancement effect is smaller than that for the heterogeneous models. This result is identical to that at 900 MHz reported in [11].

Table 2 gives the power absorbed by the head. It is interesting to note that the metal-framed spectacles reduced slightly the power absorbed by the whole head, in other word, the averaged SAR in the whole head, although they enhanced the spatial peak SAR. This phenomenon was observed for all of the considered cases, but the reduced quantity was insignificant.

### 3.2 Enhancement Mechanism

The enhancement effect of metal-framed spectacles on the spatial peak SAR is considered to be due to an induced current on the metallic frame. The current results in stronger electric fields in its vicinity. This can be easily observed from Fig. 6 in which the electric field distributions in a horizontal cross section just above the metallic frame of spectacles for the normal head model are shown. It should be noted that the electric fields were approximately zero inside the metallic frame but strong in the vicinity of (for instance, just above) the metallic frame. Since a human head is of dielectric property, the outline of the head is observed clearly from the electric field distributions. It is easy to see from Fig. 6 that the electric fields were increased in the vicinity of the metallic segments of the spectacles, especially, in the vicinity of the eyes for S1 because the metallic rims were just in front of the eyes. This resulted in the SAR enhancement in the eyes. Conversely, for the head in S2 without the metallic rims, no strong electric fields were induced in the vicinity of eyes. As a result there was not the SAR enhancement in the eyes for S2.

### Table 2. Power absorbed by the head [%] for the antenna radiating power of 1 W

<table>
<thead>
<tr>
<th></th>
<th>WoS*</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heterogeneous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal model</td>
<td>26.6</td>
<td>26.5</td>
<td>26.3</td>
</tr>
<tr>
<td>Removed-ear model</td>
<td>43.3</td>
<td>41.3</td>
<td>40.9</td>
</tr>
<tr>
<td>Homogeneous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal model</td>
<td>23.8</td>
<td>23.7</td>
<td>23.6</td>
</tr>
<tr>
<td>Removed-ear model</td>
<td>38.1</td>
<td>36.5</td>
<td>36.5</td>
</tr>
</tbody>
</table>

* without spectacles
Fig. 7 shows the induced current on the metallic rims of S1. Also shown are enhanced surface-SAR distributions for both S1 and S2 in front view. The currents were obtained by integration of the circumferential magnetic fields surrounding the corresponding segments of the metallic rims. The enhanced surface-SAR values were obtained by taking the ratio of the surface-SAR in the head with spectacles to that without spectacles. Light gray areas in Fig. 7 mean unchanged or reduced SARs. It should be noted that these SAR values were one-voxel\(^1\) ones and not the spatial averaged ones. An enhancement exceeding 10 dB was found for the one-voxel SAR values. For the head in S1, large current values were induced on the part of metallic rims which was near the mobile telephone. Therefore the larger SAR enhancement was observed in the right side of the face. For S2, however, the SAR enhancement was only observed in the ear area because it was rimless and no current was induced in front of the face.

The metallic leg of spectacles, especially the bent segment, was a main contributor to the spatial peak SAR enhancement in the ear area. Fig. 8 shows the currents on the metallic leg near the mobile telephone and enhanced surface-SAR distributions in side view. For both S1 and S2, the induced currents were similar because they had the same metallic legs. The current induced on the segment E-F of the metallic leg of spectacles, which was parallel to the antenna, was larger than that on the segment D-E which was vertical to the antenna. As a result the maximum current value was not found on the segment D-E. The second peak current value on the metallic leg was found in the vicinity of the feed point but much lower than the maximum current value on the segment E-F. These facts imply that the metallic segment parallel to the antenna, or the bent segment of the metallic leg, is easier to cause a resonant effect. It is natural to consider that the enhanced surface-SARs shown in Fig. 8 stem from the current distributions on the metallic leg. For both S1 and S2, the large SAR enhancement areas, i.e., the ear areas, are just in the vicinity of the segment of the metallic leg on which the maximum current level was induced.

4. Conclusions

The localized SAR in the human head in metal-framed spectacles was analyzed numerically at 1.5 GHz using an anatomically based head model and a generic hand-held mobile telephone model. The FDTD method

\(^1\)One-voxel means one FDTD cell.
was employed in the analysis. The major findings are summarized as follows:

(1) The metallic leg of spectacles enhances the spatial peak SAR in the vicinity of the ear. An enhancement up to 1.2 times for the ten-gram-averaged spatial peak SAR is possible to occur.

(2) The metallic rims of spectacles enhance the SAR in the eyes. An enhancement up to 2.75 times for the one-gram-averaged spatial peak SAR in the eye near the mobile telephone is possible to occur.

(3) No obvious difference between the normal model and the removed-ear model is observed for the enhancement effect on the spatial peak SAR.

(4) The enhancement effect on the spatial peak SAR is lower than 1.1 times for homogeneous head models. This suggests that the homogeneity of tissue may mask the enhancement effect of metal-framed spectacles on the spatial peak SAR.

(5) The metal-framed spectacles have not significant effect on the absorbed power or averaged SAR in the whole head.

The enhancement effect of metal-framed spectacles on the localized SAR levels is due to an induced current on the metallic frame. Although an enhancement on the spatial peak SAR occurs in the vicinity of the ear and in the eyes, the resultant localized SAR levels are still lower, especially for the eyes, compared to the Japanese safety limits. In view of the low enhancements shown above for the metal-framed spectacles, it is unlikely that other metallic accessories like earrings would significantly increase the localized SAR in the ear area.

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References


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