Uncertainty of the One-Gram Averaged Spatial Peak SAR in Human Head for Portable Telephones due to Average Procedures

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The U. S. Federal Communication Commission (FCC) has required the routine specific absorption rate (SAR) evaluation of portable telephones since 1997. The applicable SAR limit is 1.6 W/kg as averaged over any one gram of tissue, defined as a tissue volume in the shape of a cube. Because of the irregular surface of the human head and tissue heterogeneity, computing the one-gram averaged spatial peak SAR in the shape of a cube is not so easy. A lack of standardized procedure for computing the one-gram averaged spatial peak SAR is resulting in confusion in the SAR assessment. In this paper, the SAR in an anatomically based human head model is computed using the finite-difference time-domain (FDTD) method, and the uncertainties of different four kinds of one-gram average procedures are evaluated numerically. The results show that an uncertainty up to 2.4 times may exists at 900 MHz. A nearly 1 x 1 x 1 cm cube with a mass of just one gram, but not containing the air cells, seems to be reasonable for the one-gram average of SARs.

**Keyword**: SAR Compliance, Portable Telephone, One-Gram Average Procedure, FDTD.

1. Introduction

With the recent rapid increase in the use of portable telephones, safety guidelines have been issued in various countries to limit the radio frequency (RF) exposure. The exposure limits are commonly defined in terms of the specific absorption rate (SAR) averaged either over any one gram or ten grams of tissue. Since 1997, the U. S. Federal Communication Commission (FCC) requires the routine SAR evaluation of portable telephones prior to device authorization or use. The applicable SAR limit is 1.6 W/kg as averaged over any one gram of tissue, defined as a tissue volume in the shape of a cube. According to the FCC rule, any portable telephones in the U. S. have to be evaluated with respect to the SAR limit using either phantom measurement or computer simulation for a human head. Compared to the phantom measurement, one of the advantages of computer simulation is its ability to model the complex heterogeneous structure of a human head. The finite-difference time-domain (FDTD) method is currently the most widely accepted method for SAR computation. This method adapts very well to the human head models which are usually derived from MRI (Magnetic Resonance Imaging) or CT (Computed Tomography) scans and offers great flexibility in modeling the heterogeneous structures of anatomical tissues and organs. By using the FDTD method, a number of SAR computations have recently been reported for typical operating conditions of the portable telephones, but only little information has been given on how one-gram averaged spatial peak SAR was obtained. Due to the irregular surface of the human head and tissue heterogeneity, computing the one-gram averaged spatial peak SAR in the shape of a cube is neither so simple nor straightforward. One can not easily obtain an exact one-gram cube for an anatomic head model because a tissue volume of 1 x 1 x 1 cm will have a mass that may be in excess of, equal to, or less than one gram. Since there are no standardized procedures for computing the one-gram averaged spatial peak SAR, various methods have been used at present to test devices for FCC compliance. This is resulting in confusion in the SAR assessment and unreliable data may be submitted to support the compliance.

This paper concentrates on the approach to a reasonable one-gram average procedure for FCC compliance. Four one-gram average procedures are considered in...
FDTD modeling and computation. Their uncertainties on the one-gram averaged spatial peak SAR are evaluated and possibilities applicable to the SAR assessment are discussed.

2. Model and FDTD Analysis

The head model was constructed by our groups on the basis of an anatomical chart of a Japanese adult head\(^{11}\). It consists of about 270,000 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 mass density \(\rho\) and dielectric properties are given in Table 1 in which \(\varepsilon_r\) and \(\sigma\) are the relative permittivity and conductivity, respectively. These dielectric properties are supplied by Gabriel and recommended by the FCC\(^{12}\). Being aware of that the spatial peak SAR occurs around the ear in ordinary use of portable telephones and the one-gram averaged spatial peak SAR depends strongly upon the ear shape, we have modified the ear in our original head model in order to vividly model it to a realistic use case of portable telephone. Since the ear near the telephone is often pressed by the telephone, we also considered another two head models which were identical to the normal head model except that the ear was pressed or removed for modeling a more realistic case of RF exposure from the portable telephone. Fig. 1 shows the three head models and their positions relative to the portable telephone, and Fig. 2 shows detailed shapes of the ear for the three different models.

The generic portable telephone was modeled by a 1/4 wavelength monopole antenna mounted on a rectangular conducting box. It had a vertical alignment at the side of the head by the ear. The conducting box had a dimension of 12 (length) \(\times\) 4.25 (width) \(\times\) 2.25 (depth) cm. The monopole had a radius of 0.5 mm and was located at the top of the box, 0.25 cm far from the front edge of the 4.25 cm side and 2 cm far from the edge of the 2.25 cm side. It should be noticed that the distance between the monopole antenna and the closest head surface or the ear, if the model contains it, was 9 numerical cells. This is considered to define a physical separation of 2 cm because 1/2 cell extends beyond the feed point and 1/2 cell extends beyond the head, which cuts the separation distance by 1 numerical cell\(^{13}\). The hand was highly simplified and modeled by 2/3 muscle-equivalent material whose \(\varepsilon_r\) and \(\sigma\) are two-thirds of muscle’s ones, respectively. The hand was 8 cm wide and 2 cm thick and wrapped around three sides of the lower part of the portable telephone.

The parameters for the FDTD computations 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 \(d=2.5\) mm. The time step was set to \(\delta/\sqrt{3} c\), where \(c\) is the speed of light, to ensure the

<table>
<thead>
<tr>
<th>Tissue</th>
<th>(\rho) (kg/m(^3))</th>
<th>(\varepsilon_r)</th>
<th>(\sigma) (S/m)</th>
<th>(\varepsilon_r)</th>
<th>(\sigma) (S/m)</th>
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<tr>
<td>Bone</td>
<td>1,810.0</td>
<td>17.4</td>
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<td>16.1</td>
<td>0.32</td>
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<td>44.1</td>
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<td>47.8</td>
<td>1.08</td>
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<tr>
<td>Muscle</td>
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<td>51.8</td>
<td>1.11</td>
<td>50.2</td>
<td>1.39</td>
</tr>
<tr>
<td>Eyeball</td>
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<td>69.4</td>
<td>1.61</td>
<td>68.3</td>
<td>1.97</td>
</tr>
<tr>
<td>Fat</td>
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<td>0.11</td>
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<tr>
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</table>

Fig. 1. Human head models and their positions relative to the portable telephone: (a) normal head model, (b) pressed-ear model, (c) removed-ear model.

Fig. 2. Detailed shapes of the ear. (a) normal head model, (b) pressed-ear model, (c) removed-ear model.
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 a radius smaller than the FDTD cell dimensions\(^{(51)}\). An antenna excitation was introduced by specifying a sinusoidal voltage with an amplitude \(V\) across the one-cell gap between the monopole and the top surface of the conducting box. The current flowing through the voltage source gap was then obtained from Ampere's law on a small curve around the gap. The input power of the antenna was calculated from

\[
P_a = \frac{1}{2} R \Re(\mathbf{V}^\star) = \frac{1}{2} I^* R
\]

where \(I\) is the complex amplitude of the current, \(R\) is the real part of the antenna input impedance, and * denotes the complex conjugate. The SAR was computed by taking

\[
\text{SAR} = \frac{\sigma}{2\rho} |E|^2
\]

for each cell where \(E\) is the electric field in the cell.

3. One-gram Average Procedure

Because of the irregular shape of the ear, a volume in the shape of a cube may contain air cells in the ear region. Some researchers (the Dosimetry Working Group of Wireless Technology Research) have proposed that the tissue volume to consider should not extend beyond the most exterior boundaries of the ear but may include the air that is contained therein\(^{(50)}\). Gandhi et al. further proposed that the one-gram averaged spatial peak SAR should be obtained from such volumes where at least 80 percent of the cells are occupied by the tissues and no more than 20 percent of the cells are in the air\(^{(50)}\). On the other hand, in some computations and measurements the one-gram averaged spatial peak SAR is being obtained from such volumes which do not include the air cells based on the consideration that the SAR is not defined in the air because \(\sigma\) is zero\(^{(14,15)}\). Based on the same consideration, the authors also used the maximum averaged value of the SARs within \(1 \times 1 \times 1\) cm cube not including the air as the one-gram averaged spatial peak SAR\(^{(35)}\). The use of these different average procedures is resulting in confusion in the SAR assessment. To evaluate the uncertainties of the one-gram averaged spatial peak SAR, we considered the following four kinds of one-gram average procedures.

(A) Based on our previous procedure, the one-gram averaged spatial peak SAR is obtained from a nearly \(1 \times 1 \times 1\) cm cube with a mass of one gram by means of a linear interpolation algorithm. The cube does not contain air cells.

(B) Based on our previous procedure, the one-gram averaged spatial peak SAR is obtained from an exactly \(1 \times 1 \times 1\) cm cube with a mass close to one gram (within ±5%). The cube does not contain air cells.

(C) The one-gram averaged spatial peak SAR is obtained from a nearly \(1 \times 1 \times 1\) cm cube with a mass of one gram by means of a linear interpolation algorithm. According to the Gandhi's proposal, at least 80 percent of the cells are occupied by the tissues and no more than 20 percent of the cells are in the air.

(D) The one-gram averaged spatial peak SAR is obtained from an exactly \(1 \times 1 \times 1\) cm cube with a mass close to one gram (within ±5%). According to the Gandhi's proposal, at least 80 percent of the cells are occupied by the tissues and no more than 20 percent of the cells are in the air.

The linear interpolation for obtaining the one-gram averaged spatial peak SAR appears to be used by most researchers. It computes one-gram averaged spatial peak SAR based on the power absorbed in a cube (core) that has a mass close to but lower or higher than one gram. To obtain a spatial peak SAR averaged over just one gram, a layer is added or subtracted to the core and the power absorbed in the layer is determined by linear interpolation. However, since the peak SAR occurs in the skin tissue for portable telephones, i.e., the core is located at the head surface, adding a layer to the core will contain air cells in the side close to the portable telephone. In the above procedures, hence, we have used such an algorithm as illustrated in Fig. 3 (with a side view) in which only three sides of the added or subtract-

![Fig. 3. Linear interpolation for computing the one-gram averaged spatial peak SAR. Dark area: 1 cm\(^3\) cube, (a) the mass of the 1 cm\(^3\) cube < one gram, (b) the mass of the 1 cm\(^3\) cube > one gram.](https://example.com/fig3.png)
ed layer are used for the linear interpolation.

The details of the linear interpolation algorithm is as follows:

1. The maximum SAR averaged over a 1×1×1 cm cube is first determined by shifting the cube across the head volume and computing the SAR averaged over the cube at every position;
2. If the mass of the 1 cm³ cube with the maximum averaged SAR is smaller than one gram, three sides of a layer are added to the 1 cm³ cube to obtain a new cube. Then the one-gram averaged SAR is calculated by
   \[ \text{SAR}_{1g} = \frac{P_1 + P_2 (m_{1g} - m_1)}{m_{1g}} \] (3)
   where \( P_1 \) is the power absorbed in the 1 cm³ cube, \( m_1 \) is its mass, \( P_2 \) is the power absorbed in the added layer and \( m_{1g} \) is its mass;
3. If the mass of the 1 cm³ cube with the maximum averaged SAR is larger than one gram, three sides of the outer layer are subtracted from the 1 cm³ cube to obtain a new cube. Then the one-gram averaged SAR is calculated by
   \[ \text{SAR}_{1g} = \frac{P_1 - P_2 (m_1 - m_{1g})}{m_{1g}} \] (4)

Of course, the selection of three sides of a layer is not unique and all the options need to be examined in order to obtain the one-gram averaged spatial peak SAR.

4. Results and Discussion

Fig. 4 shows the SAR distributions on the head surface at 900 MHz. It should be emphasized that the SAR distributions are plotted with the one-cell SAR values. It is not difficult to find from Fig. 4 that the electromagnetic absorption in the head surface for the pressed-ear model was larger than that for the normal model and smaller than that for the removed-ear model. The reason is that the electromagnetic absorption in the head is strongly dependent on the distance between the head and the antenna. In fact, different ear shapes lead to different distances between the head surface and the antenna and then result in the variation of antenna load.

Table 2 gives the relationship between the three head models and the antenna input impedance (\( Z_{in} = V/I \)) as well as antenna feedpoint current (\( |I| \)). The antenna input power \( P_{in} \) was fixed at 0.6 W at 900 MHz and 0.27 W at 1.5 GHz. It can be found that the real part of antenna input impedance for the pressed-ear model was larger than that for the removed-ear model and smaller than that for the normal model. As a result the antenna current has such a relationship as the normal model < the pressed-ear model < the removed-ear model. This relationship is identical to the observation in Fig. 4. According to equation (7) in which the spatial peak SAR was elucidated to be related to the antenna current for dipole-like sources, it is natural to consider that the above relationship, i.e., the normal model < the pressed-ear model < the removed-ear model, still holds for the spatial peak SAR.

Due to the heterogeneity of human head, possible health effects related to the use of portable telephones may be organ-dependent. The brain is considered to be the most interest target because of its critical control function. Most of research programs recommended by an European Commission expert group are related to the brain, such as DNA damage in brain cells and brain cancer risk. Fig. 5 shows the one-gram averaged spatial peak SAR in the brain for the three head

\( \text{SAR}_{1g} = \frac{P_1 + P_2 (m_{1g} - m_1)}{m_{1g}} \)
Fig. 5. The one-gram averaged spatial peak SAR in the brain. The antenna input power is 0.6 W at 900 MHz and 0.27 W at 1.5 GHz.

models. Fig. 6 shows the averaged SARs for the brain and whole head, respectively. All of the results support the relationship found above, i. e., the normal model < the pressed-ear model < the removed-ear model, both for the spatial peak SAR and the averaged SAR.

With these prior knowledges, we now examine the one-gram averaged spatial peak SAR in the whole head computed by the four different average procedures. Fig. 7 shows computed one-gram averaged spatial peak SARs at 900 MHz. For the removed-ear model, the one-gram averaged spatial peak SARs were almost the same for the four average procedures. This is because almost no air cells were used for the one-gram average in all of the average procedures. The obtained one-gram averaged spatial peak SAR is thus considered to be reliable for the removed-ear model. Except for the removed-ear model, the one-gram averaged spatial peak SARs were highly scattered, depending on whether or not the air cells were included and whether or not an exact one-gram cube was used. An uncertainty up to 2.4 times (see Fig. 7, between the procedures B and C) has been observed for the normal head model. This results from the fact that the procedures A and B used most of the SAR values for one-gram average of the head tissue except for the ear, while the procedures C and D used them in the head tissues containing the ear. The procedures C and D, in which the air cells were allowable, have given larger one-gram averaged spatial peak SAR than the procedures A and B.

A finding from Fig. 7 is that the procedures A and B have given an identical trend to the local SAR on the head surface as shown in Fig. 4. That is to say, the SAR for the pressed-ear model was larger than that for the normal model but smaller than that for the removed-ear model. This trend was also found for the spatial peak SAR and the averaged SAR in the brain as shown in Figs. 5 and 6. On the contrary, the above trend did not hold for the procedures C and D in which the largest one-gram averaged spatial peak SARs were found in the pressed-ear model. This contradicts the finding in Figs. 4−6. The reason may be due to a strong electric field was induced in the ear tissues because of the highly irregular shape of the ear pressed by the telephone. This suggests that the procedures C and D is easily affected by the ear tissues containing the air.

Since a physiological ground of the SAR limits for near field exposure is unclear, it is difficult to say which average procedure is more adequate. But from the point of view that the one-gram averaged spatial peak SAR should reflect the amount of electromagnetic absorption in the important organ, i. e., the brain, the procedures A and B seem to be adequate candidates for the one-gram average. This observation is also supported by the antenna feedpoint current, as shown in Table 2, which is
related to the peak SAR. Moreover, since a maximum SAR value averaged over a 1 cm³ cube in excess of one gram would not give the maximum one-gram averaged SAR (the larger the mass of a cube, the averaged SAR over it would be smaller in general), the procedure A using a linear interpolation seems to be more reasonable to obtain an exact one-gram averaged value. As a matter of fact, by comparing the four average procedures with the FCC definition for the one-gram averaged spatial peak SAR, it can also be found that the procedure A is the most reasonable explanation to it.

Fig. 8 shows the one-gram averaged spatial peak SARs obtained from the different average procedures at 1.5 GHz. This frequency band is not used in the U. S. and only in Japan at present. The results given in Fig. 8 support the finding at 900 MHz. An uncertainty has been observed up to 2.8 times for the normal head model (between the procedures B and C).

5. Conclusion

Four kinds of average procedures for one-gram averaged spatial peak SAR have been discussed and their uncertainties have been evaluated using an anatomically base human head model. The results have shown that an uncertainty up to 2.4 times may exists at 900 MHz, depending on whether or not the air cells were contained and whether or not an exact one-gram cube was used. Not containing the air in the average procedure has lead to an identical trend to the local SAR on the head surface and the spatial peak SAR as well as the averaged SAR in the brain. A nearly 1×1×1 cm³ cube with a mass of just one gram, but not containing the air cells, seems to be reasonable for the one-gram average of SARs. These findings will be very valuable to the standardization of one-gram average procedure of the spatial peak SAR.

A further subject is to investigate the gram average procedures from a physiological point of view.

References

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