Comparison of Averaging Procedures for SAR Distributions at 900 and 1800 MHz

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***Abstract*—In this paper, we study the effect of the position of the averaging volume on the averaged specific-absorption-rate values at the typical European cellular telephone frequencies around 900 and 1800 MHz. The Council of the European Union recommends a 10-g contiguous volume, as the averaging volume. A simple cubic tissue can be used provided that the calculated dosimetric quantities have conservative values relative to the exposure guidelines of the Council of the European Union. Large differences can occur depending on the averaging procedure. The situation is definitely most critical at 1800 MHz.**

***Index Terms*—Biological effects of electromagnetic radiation, dosimetry, electromagnetic heating, FDTD methods, land mobile radio cellular systems.**

I. Introduction

DURING THE last decade, the use of mobile telephones has increased enormously. At the same time, the question whether the extensive use of the device is harmful becomes more and more important. The specific absorption rate (SAR) is defined by (in watts per kilogram)

$$\mathrm{SAR}(\vec{r}) = \frac{\sigma(\vec{r}) \cdot E_{\mathrm{rms}}^2(\vec{r})}{\rho(\vec{r})} \quad \mathrm{W/kg} \tag{1}$$

where $\sigma(\vec{r})$ is the conductivity (siemens per meter), $\rho(\vec{r})$is the mass density (kilogram per meters squared) and $E_{\mathrm{rms}}(\vec{r})$ is the root mean square value of the electrical field (volts per meter). For the general population, a limit value of 2 W/kg for the SAR averaged over any contiguous 10-g tissue for the head and trunk, is recommended by the Council of the European Union. This recommendation also states that a simple geometry, such as a cube, can be used if the calculated dosimetric quantities have conservative values relative to the exposure guidelines [1]. This last specification does not imply that the cubic volume must be completely within the tissue. This can make a large difference for strongly curved and irregular surfaces (e.g., the ear).

We will now investigate these criteria profoundly and apply them to a benchmark configuration for 900 and 1800 MHz. For this simple configuration, we are able to analytically define a 10-g cube with boundaries outside the sphere. This configuration also allows us to perform a comprehensive study of the averaging mechanisms.

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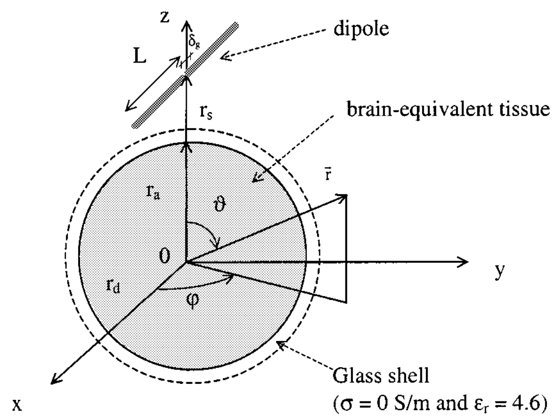

Fig. 1. Configuration under study.

II. Method and Results

A. Configuration

A simple benchmark configuration has been considered (Fig. 1) [2]. The sphere with radius $r_a = 10.65$ cm is filled with brain-equivalent tissue with parameters ε_r and σ. The sphere is irradiated by a dipole antenna of length $2L$ (L depends on the frequency) with a gap width δ_g of 1 mm and located at a distance $r_s - r_a = 1$ cm from the sphere ($r_s = 11.65$ cm). The conducting medium is surrounded by a nonconducting glass shell with at thickness of 5 mm and dielectric constant $\varepsilon_r = 4.6$, representing the recipient of the brain-equivalent liquid in testing situations. The radiated power of the dipole in presence of the sphere is 1 W (continuous-wave mode). We use a finite-difference time-domain (FDTD) simulation with a grid size of 1 mm for 900 and 1800 MHz [3]. We have also done measurements on that same configuration.

B. Considerations on the Cube Averaging

We now investigate the dimensions of a 10-g cube. This dimension depends on whether the cube is completely in the sphere or not. The volume averaged SAR value SAR is defined as

$$\overline{\mathrm{SAR}} = \frac{\displaystyle\int_V \mathrm{SAR}(\vec{r})\, dV}{\displaystyle\int_V \xi(\vec{r})\, dV}, \quad \text{with} \quad \begin{cases} \xi(\vec{r}) = 0, & \text{if } |\vec{r}| > r_a \\ \xi(\vec{r}) = 1, & \text{if } |\vec{r}| < r_a. \end{cases} \tag{2}$$

Following the European Committee for Electrotechnical Standardization (CENELEC), V has the shape of a cube and must exactly contain 10 g of tissue. As we will see later, the maximum SAR values are obtained on the z-axis. Thus, we move

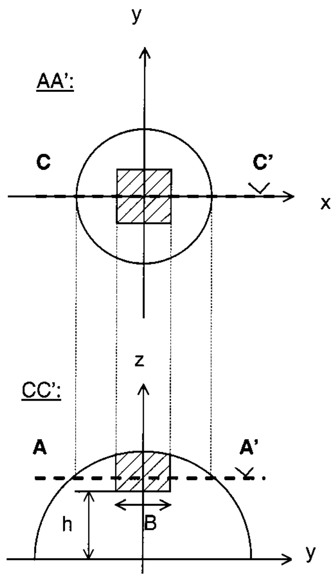

Fig. 2. Zone of integration.

the cube along this axis. The difficulty is that the size of the cube is changing as a function of its position. When the cube is completely in the sphere, its size B is

$$B = \sqrt[3]{\frac{M}{\rho}}, \qquad \text{with} \quad M = \text{the mass of the cube.} \tag{3}$$

Considering $M = 10$ g and $\rho = 1000$ kg/m^3, $B \approx 2.15$ cm is obtained. If a part of the cube is outside the sphere, we have to recalculate the size of the cube using the following integral:

$$V = \int_{-B/2}^{B/2} \int_{-B/2}^{B/2} \left[\sqrt{r_a^2 - x^2 - y^2} - h\right] \cdot dx \cdot dy. \tag{4}$$

The zone of integration is represented in Fig. 2. If the integration zone would be circular in the xy-plane, the solution of the integral would be trivial. However, we have a squared zone of integration in the xy-plane. By using polar coordinates, we can reduce this double integral to an expression with two single integrals.

$$\begin{aligned} V &= \int_{-B/2}^{B/2} \int_{-B/2}^{B/2} \left[\sqrt{r_a^2 - x^2 - y^2} - h\right] \cdot dx \cdot dy \\ &= 4 \int_{B/2}^{(\sqrt{2}/2)B} \sqrt{r^2_{-} r^2} \left\{ \arcsin\left(\frac{B}{2 \cdot r}\right) \right. \\ &\qquad \left. - \arcsin\left(\frac{B}{2 \cdot r}\right) \right\} r\, dr \\ &\quad + 2\pi \int_0^{B/2} \sqrt{r_a^2 - r} r\, dr - B^2 h \\ &= 4 \int_{B/2}^{(\sqrt{2}/2)B} \sqrt{r_a^2 - r^2} \left\{ \arcsin\left(\frac{B}{2 \cdot r}\right) \right. \\ &\qquad \left. - \arcsin\left(\frac{B}{2 \cdot r}\right) \right\} r\, dr \\ &\quad + \frac{2\pi}{3} \left\{ r_a^3 - \left(r_a^2 - \left(\frac{B}{2}\right)^2\right)^{3/2} \right\} - B^2 h. \end{aligned} \tag{5}$$

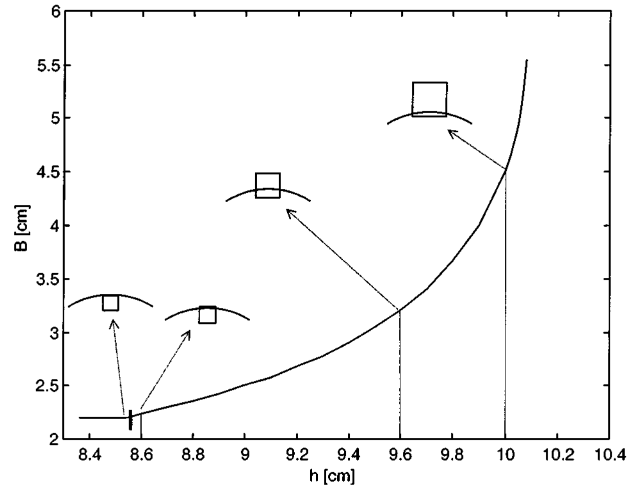

Fig. 3. Size of the averaging cube as a function of h.

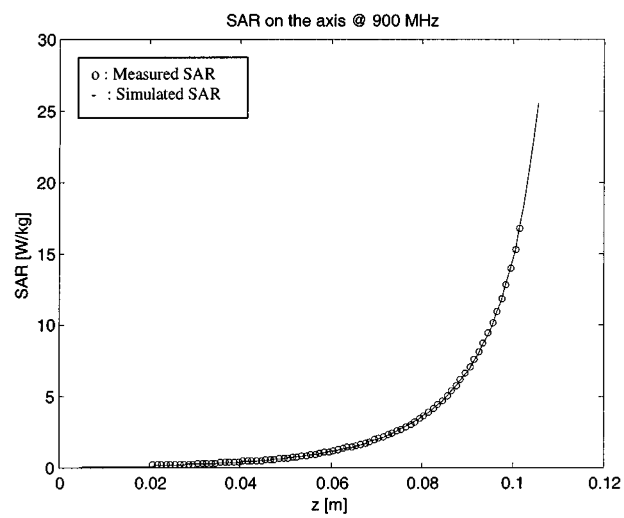

Fig. 4. SAR distribution along the z-axis at 900 MHz.

As far as we know, no analytical solution is available for the first single integral in the previous relation. A numerical solution of this integral was obtained by using MATLAB. Now, the B has to be chosen so that $\int_V \rho(\vec{r})\, dV = 10$ g. It is obvious that B will depend on h in order to contain 10 g of tissue. Fig. 3 gives the dependence of B as a function of h. Once this relationship is established, the $\overline{\text{SAR}}$ as a function of h can now be obtained for the different frequencies.

C. Considerations on the Irregular Volume Averaging

Finding the maximizing irregular coherent volume was done by the following procedure. First of all, we searched for a maximum SAR value in an FDTD cell, which was, in our case, on the z-axis, but for the more general case, it can be anywhere. We then searched for the next maximum, and so on. This loop was repeated until the required mass of 10 g was obtained. The fact that the volume had to be coherent slightly complicated the procedure. The use of this procedure is not limited to symmetrical SAR distributions, but can be applied to any situation.

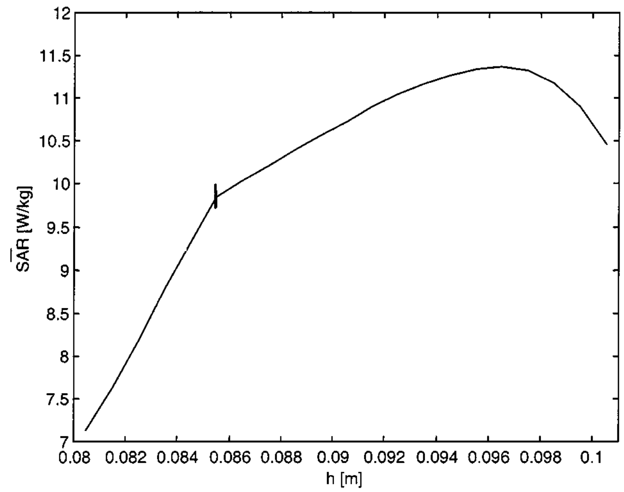

Fig. 5. S̄AR as a function of h at 900 MHz.

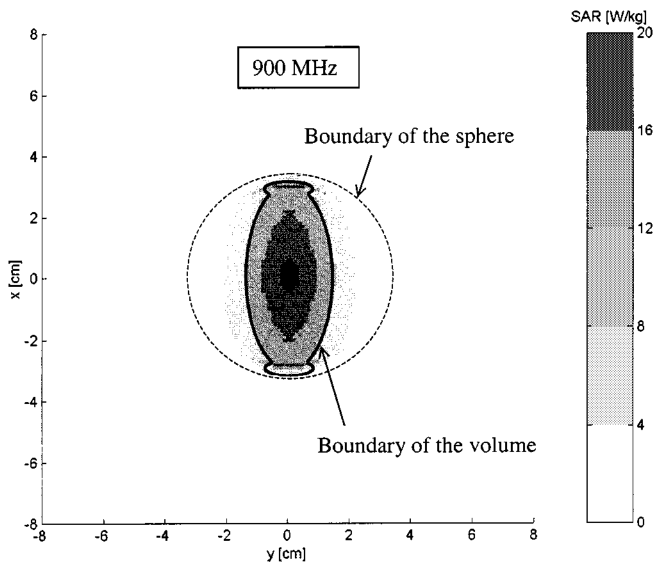

Fig. 6. SAR distribution for the irregular 10-g volume at 5 mm under the top of the sphere at 900 MHz.

D. Results for 900 MHz

At 900 MHz, the conducting medium has an ε_r of 41.5 and a σ of 0.86 S/m. The length L of one arm of the antenna is 74 mm. From the FDTD simulation, it is clear that the field is maximal along the z-axis and at the top of the sphere. Fig. 4 shows the SAR distribution along the z-axis (FDTD) and measured values, which are in very good agreement with the simulations. The values shown may not be interpreted in terms of the limits because the configuration of Fig. 1 is far from the realistic mobile-handset-user configuration. The maximal SAR is 26.7 W/kg. We move the geometrical center of the 10-g cube along the z-axis and then calculate the averaged S̄AR. This is shown in Fig. 5. A maximum is found for $h\approx$ 9.65 cm, namely, about 11.36 W/kg. The value is 9.32 W/kg when the cube is just completely in the sphere and 9.85 W/kg when it has its upper plane equal to the tangential plane of the sphere. In Figs. 3 and 5, one can see a short vertical bold line. At the left-hand side of this line, the cube is completely in the sphere and at the right-hand side, it has its upper plane outside the sphere. There are two

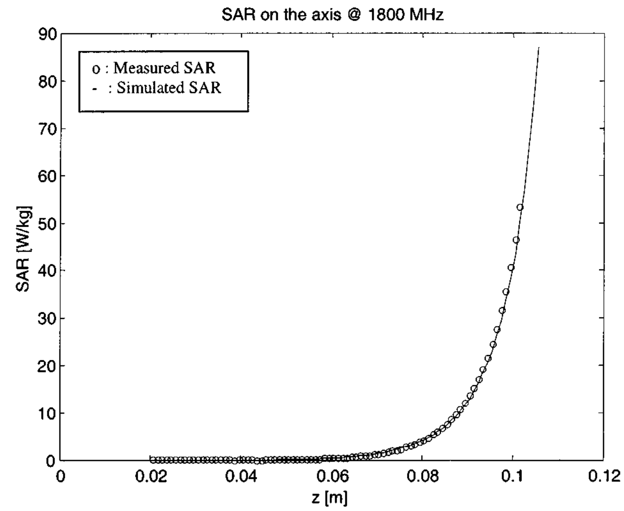

Fig. 7. SAR distribution along the z-axis at 1800 MHz.

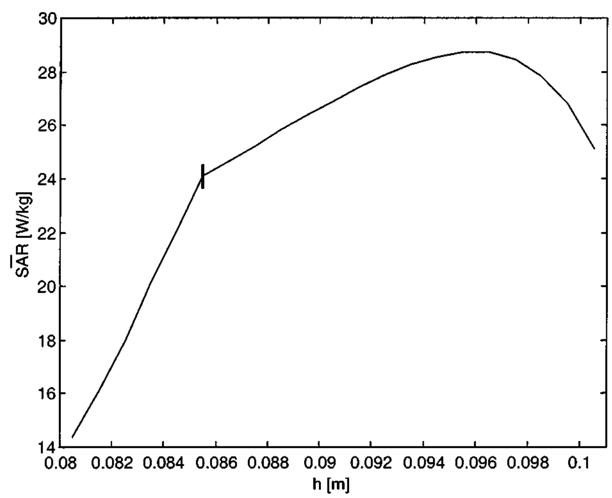

Fig. 8. S̄AR as a function of h at 1800 MHz.

remarkable events in Fig. 5. First of all, one can see that the derivative is discontinuous at the bold line. This is, of course, due to the fact that the volume of the cube is changing (but the mass inside the cube is constant). Second, and more important, is that the maximum value is obtained when an important part of the cube is outside the sphere. This is due to the specific distribution of the SAR.

If we consider an irregular shape of a volume with 10 g of mass, we obtained a maximum value of 12.25 W/kg. Fig. 6 gives an impression of the shape of this volume.

E. Results for 1800 MHz

At 1800 MHz, the conducting medium has an ε_r of 40.5 and a σ of 1.69 S/m. The length L of one arm of the antenna is 35.5 mm. Fig. 7 gives the simulated and measured SAR distribution along the z-axis. The maximal SAR is 98.37 W/kg. As for 900 MHz, we move the cube along the z-axis and calculate the corresponding S̄AR. This is shown in Fig. 8. A maximum is found for $h\approx$ 9.55 cm, namely about 28.73 W/kg. The value is 22.12 W/kg when the cube is just completely in the sphere and

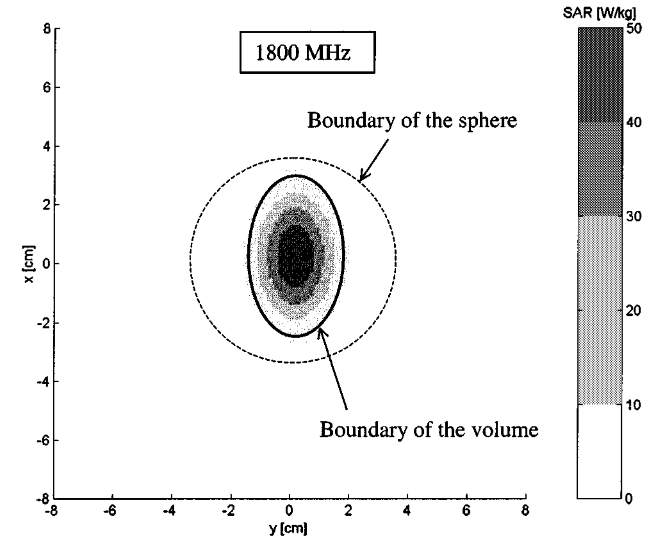

Fig. 9. SAR distribution for the irregular 10-g volume at 5 mm under the top of the sphere at 1800 MHz.

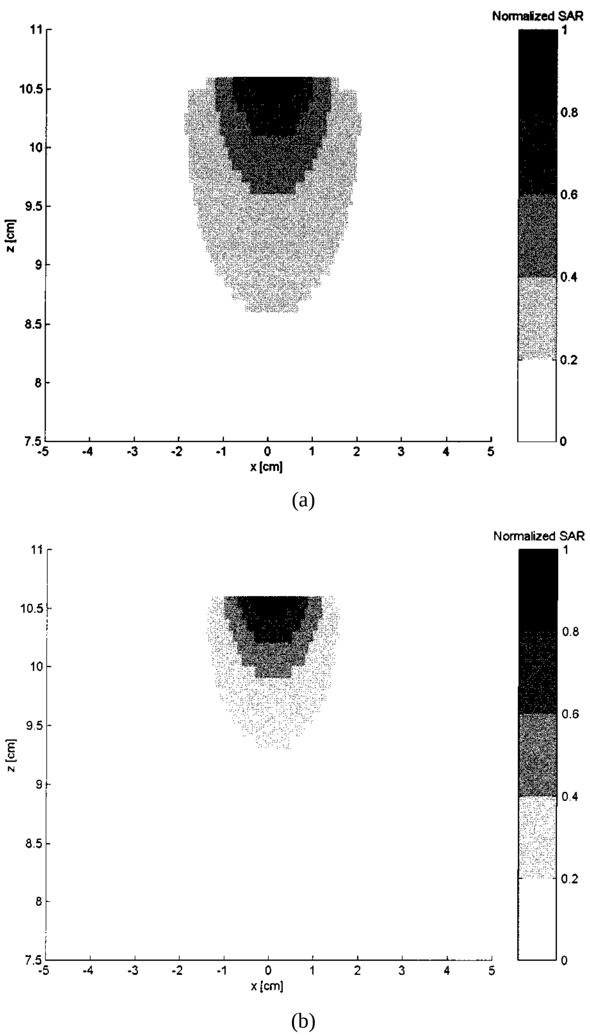

Fig. 10. Normalized SAR at both frequencies under consideration. (a) 900 MHz. (b) 1800 MHz.

24.08 W/kg when it has its upper plane equal to the tangential plane of the sphere. Again, the maximal value is obtained when the major part of the cube is outside the sphere. Considering an irregular volume, a maximal value of 30.54 W/kg was obtained. Fig. 9 gives an impression of the shape of the irregular volume.

TABLE I
DIFFERENCE IN INCREASE OF SAR AVERAGED VALUES FOR 900 AND 1800 MHz

	900 MHz			1800 MHz		
	Dimension of the averaging cube B (cm)	Max. $\bar{\text{SAR}}$ (W/kg)	Rel. (%)	Dimension of the averaging cube B (cm)	Max. $\bar{\text{SAR}}$ (W/kg)	Rel. (%)
Cube completely in the tissue	2.15	9.32	0	2.15	22.12	0
Upper plane cube identical to the tangential plane sphere	2.25	9.85	5.7	2.25	24.08	8.86
Part of the cube outside the tissue	3.30	11.36	21.89	3.13	28.73	29.88
Irregular coherent volume	n.d.	12.25	31.44	n.d.	30.54	38.07

F. Comparison Between the Results for 900 and 1800 MHz

From previous sections, it is obvious that there are quite some differences in the results for the two frequencies taken under consideration. First of all, the maximum SAR at 1800 MHz is much higher, as can be seen by comparing Figs. 4 and 7. Secondly, at 1800 MHz, the penetration depth of the SAR distribution is smaller due to the higher frequency and higher conductivity. This can be seen in Fig. 10, where a SAR scan in the xz-plane is shown, but normalized to the maximum SAR at each frequency. The area where high SAR values occur is much more extended at 900 MHz than at 1800 MHz. One can see in this same figure that the high SAR zone is close to the surface at 1800 MHz and rather small compared with the situation at 900 MHz. This has important consequences for the averaged SAR. If we first consider averaged values obtained with a 10-g cube as an averaging volume, one can see that the maximum values are more or less at the same position ($h_{\bar{\text{SAR}}_{\max}} = 9.65$ cm for 900 MHz and $h_{\bar{\text{SAR}}_{\max}} = 9.55$ cm for 1800 MHz). Table I gives the absolute values of the averaged $\bar{\text{SAR}}$ and relative values with respect to the maximum when the cube is completely inside the sphere. We remark a much higher variation at 1800 MHz than at 900 MHz. Variations are in the order of 30%–40%.

III. CONCLUSIONS

From the results shown in this paper, we can conclude that a decision on the averaging procedure for SAR distributions is very important when we want to compare the averaged values with the limits. Basically, there are three possibilities. First of all, we consider the criterion with the cube. Here, we have two possibilities: the cube completely in the tissue or the cube with a part of its volume outside the tissue. The latter choice seems more practically adapted for small irregular human body parts such as the ear. A third possibility is taking a mass of 10-g coherent tissue of any irregular shape. It is clear that the last criterion will deliver the highest value. We considered these three possibilities at 900 and 1800 MHz for a benchmark configuration. The choice of the criterion is most critical at 1800 MHz, and this due to its specific SAR distribution. We found variations of 20%–30% in the maximal averaged SAR depending on the applied criterion.

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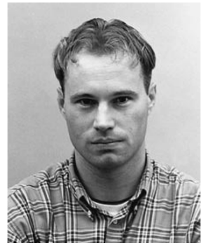

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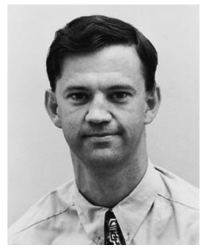

Luc Martens (M'92) was born in Ghent, Belgium on May 14, 1963. He received the M.Sc. degree in electrical engineering and Ph.D. degree from Ghent University, Ghent, Belgium, in 1986 and 1990, respectively.

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