Energy Absorption in Layered Biological Tissues in the Near- and Far-Fields of the Antennas of Body-Mounted Devices

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INTRODUCTION

Since the introduction of cellular phones, the scientific community has gained substantial knowledge and understanding of the interaction between wireless transmitters operated at the head and the electromagnetic (EM) energy absorption in the user. However, novel body-worn devices (laptop computers with wireless network, wireless health support systems) and new usage patterns of cellular phones (Bluetooth, modem or video functionalities) require the consideration of a large variation of parameters with respect to the frequency range, distance to the body, exposed location and tissue composition of the body. The parameter range covered in this study encompasses:

- distances between the transmitter and body from 10 mm to 200 mm,
- frequency range between 30 MHz and 5800 MHz and
- different tissue compositions considering the whole body.

OBJECTIVE

The goal of this study is to analyze the impact of the layering of different body tissues on the absorption of electromagnetic energy considering near-field and far-field effects and to discuss possible consequences on the compliance testing of body-worn devices with respect to SAR safety limits when using body phantoms filled with tissue simulating liquid.

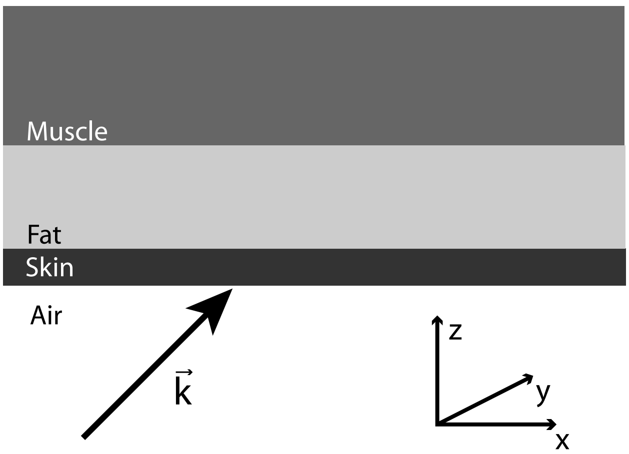

Figure 1: Generic body model as planar layered structure with incident plane wave $\vec{k}$.

METHODS

Generic Body Model

In order to characterize the absorption in layered body tissue, a generic body model was defined consisting of planar layers of skin, fat and muscle tissue (Figure 1). Fat tissue has a very low water content and therefore a significantly lower permittivity and conductivity ($\epsilon_r = 5.5$, $\sigma = 0.05$ S/m at 900 MHz) [2], whereas muscle tissue has a permittivity of $\epsilon_r = 55.0$ and conductivity of $\sigma = 0.94$ S/m at the same frequency. Most other body tissues with high water content have similar dielectric properties.

In order to determine the tissue compositions with the highest absorption, the thicknesses of the skin and fat layers were modified. Skin tissue was varied from 0.4 mm to 2.6 mm. These values include the epidermis and the dermis and cover an age range from newborn to 60 years [4]. Fat layer thicknesses between 0 and $\lambda/2$ were used in order to take into account all possible effects due to impedance matching in the layers. At lower frequencies, the maximum fat thickness was limited to anatomically realistic cases. A layer of muscle tissue terminates the body model.

SAR Calculation in Layered Tissue

The absorption of electromagnetic energy in the layered body tissue was analyzed for 1) far-field conditions assuming a perpendicularly incident plane wave in a frequency range from 236 MHz to 5800 MHz and 2) for the near-field of a $\lambda/2$- and a $\lambda/16$-dipole antenna at distances between 10 mm and 200 mm. The worst-case tissue compositions were evaluated with respect to the 1 g peak spatial SAR in the layered structure in comparison to the SAR in a homogeneous lossy half space with the dielectric properties of head tissue simulating liquid (HTSL) and body tissue simulating liquid (BTSL) [1].

Under far-field conditions, a layered transmission line model is used to calculate the electric field in the tissues. For the near-field evaluation, the fields of the two dipole antennas were simulated using the FDTD method (SEMCAD X, Schmid & Partner Engineering AG, Zürich) and the method of moments with layered Green's functions. The peak spatial average SAR was calculated over a 1 g cube according to the procedure described in [3].

Frequency in MHz	d_{skin} in mm	d_{fat} in mm
236	2.6	100
450	2.6	50
900	2.6	24
1500	1.5	15
1800	1.3	13
2450	1.2	7
5800	0.4	3.8

Table 1: Skin and fat layer thicknesses for maximum 1 g peak spatial average SAR (worst case) in the generic body model for far-field conditions.

RESULTS

Far-Field Conditions

Table 1 shows the combinations of skin and fat layer thicknesses for which the maximum 1 g peak spatial average SAR was found. Only frequencies above 236 MHz are considered because at lower frequencies, far-field conditions can no longer be assumed considering the maximum distance of 200 mm. The comparison of the 1 g SAR in the layered tissue to the 1 g SAR in HTSL and BTSL for an incident power density of 1 W/m^2 is shown in Figure 2. For all frequencies, the SAR in the layered tissue exceeds the SAR in the tissue simulating liquid by 3 dB and more. This can be explained by standing wave effects in the tissues due to reflections at the fat-muscle interface. If the thickness of the fat layer corresponds to approximately a quarter of the wavelength in the tissue, the standing wave maximum will be in the skin layer giving rise to a very high local SAR.

SAR in the Near-Field of Dipole Antennas

The 1 g peak spatial average SAR is evaluated numerically in two different layered tissue structures and in HTSL at 236 MHz with different dipole antennas. Figure 3 shows a comparison of the SAR in the different tissue structures for the two dipole antennas as described above and a distance range from 10 mm to 200 mm. The skin thickness is 2.6 mm, and two different fat layer thicknesses are used. The results for the $\lambda/2$-dipole (black lines in Figure 3) show that the 1 g SAR in HTSL is generally higher than in the layered tissue for distances below approximately 150 mm. If the distance increases further, the SAR in the layered structure with a fat layer thickness of 105 mm increases due to the standing wave effects discussed above. For the $\lambda/16$-dipole (grey lines in Figure 3), the SAR in the layered tissue at short distances (< 30 mm) is higher than in HTSL. This effect is due to enhanced coupling of reactive electrical fields into the low permittivity fat tissue, giving rise to a high local SAR in the skin. It does not depend on the actual thickness of the fat layer but only occurs for the electrically small dipole antenna.

In Figure 4, the 1 g SAR ratio in layered tissue to HTSL for $\lambda/16$-dipole antennas is shown for frequencies between 30 MHz and 900 MHz. The maximum enhancement in the near-field occurs at antenna distances of approximately λ/40. At 30 MHz, an enhancement of approximately 5 dB can be observed. The effect decreases with the frequency;

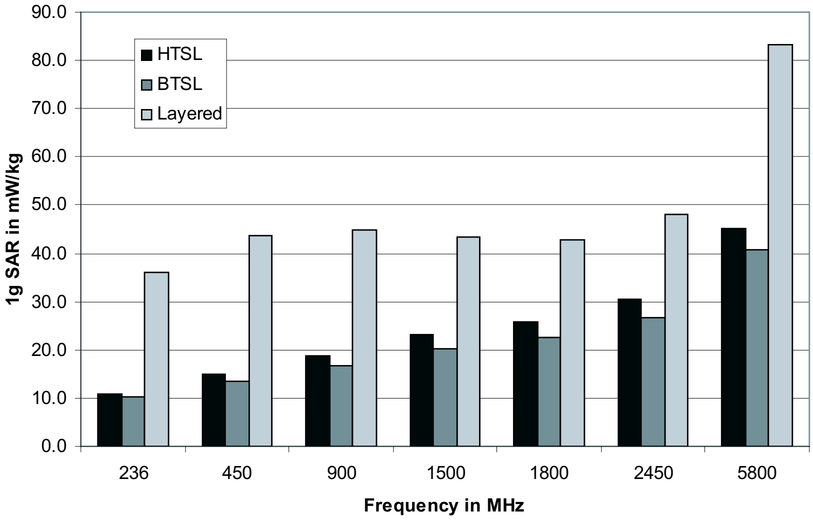

Figure 2: 1 g peak spatial averaged SAR for far-field conditions ($p_{inc} = 1$ W/m^2) in HTSL, BTSL and the worst-case combinations of layered tissue given in Table 1.

at 900 MHz, the SAR in the near-field of the antenna is always lower in the layered tissue than in HTSL. Here, however, an increase due to standing wave effects in the layered tissue can be observed at approximately 50 mm.

DISCUSSION AND CONCLUSIONS

The analysis of the coupling of electromagnetic fields into layered biological tissue has shown that two different effects can lead to a significant increase of the average SAR in comparison to the SAR assessed with tissue simulating liquid. In the far-field, standing wave effects lead to a rise of the local SAR in the skin. At higher frequencies, these conditions can already be reached at a few centimeters distance between the antenna and the body. In the near-field, the enhanced coupling of reactive fields into low permittivity fat tissue can also lead to a SAR increase for certain antenna types. For both effects, the observed SAR enhancement was in the order of magnitude of 3 dB and higher in comparison to the SAR obtained with the standardized liquid parameters. As a consequence, an additional safety factor may be needed to warrant a conservative exposure assessment for the compliance testing of body-worn devices with a liquid filled phantom. The current methods used for the compliance testing of devices operating at the ear, such as cellular phones, are not affected by the presented results and can be regarded as conservative.

ACKNOWLEDGMENTS

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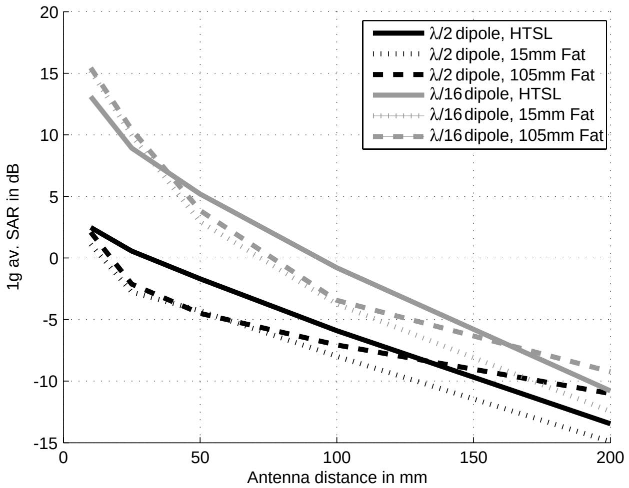

Figure 3: 1 g peak spatial averaged SAR for 1 W antenna output power in dB (0 dB = 1 W/kg) at 236 MHz for a $\lambda/2$- and a $\lambda/16$-dipole antenna in layered tissue (2.6 mm skin thickness, 15 mm and 105 mm fat thickness) and HTSL.

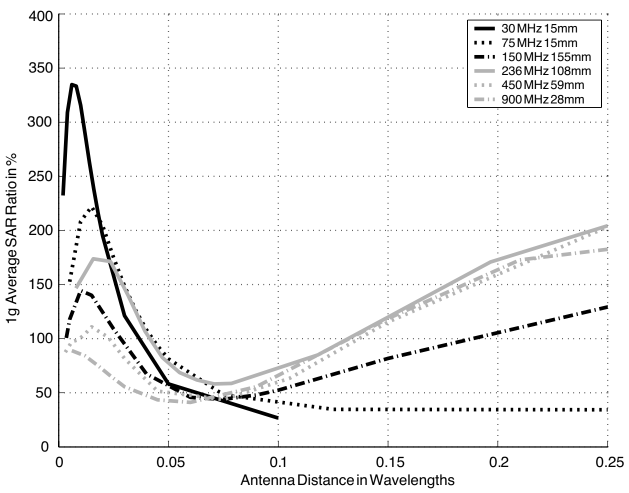

Figure 4: Worst-case ratio of the 1 g peak spatial averaged SAR (layered vs. homogeneous, normalized to the antenna output power) for a $\lambda/16$-dipole for frequencies from 30 MHz and 900 MHz. The skin thickness is 2.6 mm, and the fat thicknesses are given in the legend.