Temperature Rise for the Human Head for Cellular Telephones and for Peak SARs Prescribed in Safety Guidelines

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Abstract — **The bioheat equations is solved for an anatomically-based model of the human head with resolution of 3 × 3 mm to study the thermal implications of exposure to EM fields typical of cellular telephones both at 835 and 1900 MHz. Up to 4.5°C temperature elevation may be caused for some locations of the pinna by a cellular telephone warmed by electronic circuitry to temperatures as high as 39°C, with temperature increases for the internal tissues such as the brain and the eye that are no more than 0.1-0.2°C higher than the basal values. Another objective was to study the thermal implications of the SAR limits for the occupational exposures of 8 W/kg for any 1-g, or 10 W/kg for any 10-g of tissue suggested in the commonly used safety guidelines. Such SARs would lead to temperature elevations for the electromagnetically-exposed parts of the brain up to 0.5°C, with 10 W/kg for any 10-g of tissue resulting in somewhat higher temperatures for larger volumes.**

I. INTRODUCTION

With the rapid introduction of wireless telephones into society, there is an increasing public concern about the health implications of the use of these devices. This concern is heightened because of the proximity of the electromagnetic radiating source to the brain and the sensation of warmth for the ear and the skin in close proximity to the telephone. There have been some recent subjective reports of headache and fatigue for users of cellular telephones in Sweden.

In this paper, we use a thermal model of the human head to study: (a) The effect of blocking of air convection to the ear by means of two warm 39°C insulating boxes of dimensions representative of cellular telephone handsets and (b) Heating of the various tissues e.g. the ear, brain, and the proximal eye (with and without the effect of the aforementioned conduction) due to EM radiation for two typical cellular telephones at 835 and 1900 MHz. The SAR distributions for each of the assumed cellular telephones placed against the left ear are obtained using the finite-difference time-domain (FDTD) method that has been reported earlier by us and by several other authors [1].

Similar to some unpublished experimental data, temperature increases up to 4.5°C are calculated for parts of the pinna due to blocking of air convection and heat conduction from the warm boxes representative of the wireless handsets [2]. This does not, however, result in much additional heating of the brain or the tissues of the eye for which temperature increases on the order of 0.125-0.2°C are calculated including SARs on the order of 1.6 W/kg for any 1-g of tissue or 2.0 W/kg for any 10-g of tissue, respectively. The latter results are similar to those reported recently by other authors [3-4] even though they had neglected the added heating due to the blocking of air convection and by heat conduction from the warm handsets.

Another thrust of the paper is to understand the thermal implications of the SAR limits suggested in the various safety guidelines. Whereas peak 1-g SARs of 1.6 W/kg and 8.0 W/kg are suggested for uncontrolled and controlled environments, respectively, in the IEEE Standard, somewhat higher peak 10-g SAR limits of 2.0 and 10.0 W/kg are prescribed in the ICNIRP guidelines. It is recognized that cellular telephones presently on the market or projected for the future will not use high enough radiated powers as to cause the aforementioned. Nevertheless, these SAR limits have been prescribed for controlled environments or for occupational exposures, and it would be instructive to examine the temperature elevations that the highest of the SARs may cause, most notably for the brain.

II. THERMAL MODEL OF THE HUMAN HEAD

The thermal model of the human head is derived from the previously described anatomically-based model of the human body [1]. This model was obtained from MRI scans of an adult male volunteer and has been segmented into 31 tissue types, 15 of which are also associated with the region representing the head and neck. The tissues, their mass densities, and the thermal properties assumed for the present calculations have been gleaned from several references. However, unlike some of the previous authors, we have taken a much higher value of the blood flow rate for the skin of the face and the head. The value of 56 mℓ / (min · 100g) is close to the average of 42.9 for the skin with hair and 70.3 mℓ/(min · 100g) for the skin of the face.

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As described earlier [1], the anatomically-based model is resolved into voxels of dimensions 1.974 × 1.974 mm for the cross sectional cuts and thickness 3.0 mm along the vertical z-axis. For the present calculations, the pixel size is assumed to be 2.0 × 2.0 mm and the cells are combined into voxels of dimensions 3.0 × 3.0 × 3.0 mm along the three axes, respectively. For each of the larger voxels, the tissue properties used are those of the predominant or majority tissue in these voxels. The new 3 × 3 × 3 mm resolution model used for the present calculations consists of 445, 740 cubical voxels representing the head and neck region.

For all of the calculations given in this paper, two different sizes of the plastic-covered handsets are assumed. For calculations at 835 MHz, the handset dimensions are 2.4 × 5.4 × 15.3 cm with the outermost cells for this metal box handset represented by an equivalent dielectric constant ε_r = 1.613 which is somewhat lower than the material dielectric constant 2.5 due to the fact that the plastic covering is thinner than 3.0 mm resolution used for the SAR calculations using the FDTD method [1]. The SAR calculations for a 30°-tilted model of the telephone are used as input to the transient bioheat equation used for temperature calculations. The handset dimensions used for calculations at the PCS frequency of 1900 MHz are somewhat smaller at 1.8 × 4.5 × 12.0 cm along the three axes, respectively.

The transient bioheat conduction equation which is solved for the thermal response of the model of the head and neck is given for voxel (i, j, k) as follows:

$$\rho_{i,j,k} C_{i,j,k} \frac{\partial T_{i,j,k}}{\partial t} = \nabla\left(k_{i,j,k} \nabla T_{i,j,k}\right) + h_{m_{i,j,k}} + h_{EM_{i,j,k}} - h_{E_{i,j,k}} - h_{RAD_{i,j,k}} - h_{CONV_{i,j,k}} + bf_{i,j,k} C_b \left(T_b - T_{i,j,k}\right)$$

Here for the voxel i,j,k (denoted by i for brevity), T_i = temperature of the tissue (°C), ρ_i = mass density of the tissue (kg/m^3), C_i = specific heat of the tissue (W · hr/°C · kg), k_i = thermal conductivity of the tissue [W/(°C · min)], h_{m_i} = metabolic heat generation per unit volume (W/m^3), h_{EM_i} = EM energy deposition per unit volume (W/m^3), h_{E_i} = evaporative heat dissipation per unit volume (W/m^3), h_{RAD_i}, h_{CONV_i} = radiative, convective heat losses from the peripheral cells per unit volume (W/m^3), bf_i = blood flow rate, [kg/m^3 ·hr], T_b = temperature of arterial blood entering the tissue (°C). The ambient temperature and the arterial blood temperature are assumed to be 25°C and 36.8°C, respectively.

The heat exchanged through the neck and the remaining parts of the body has been approximated by means of setting the neck boundary temperature as the temperature of the blood taken to be 36.8°C for the present calculations.

The problem is solved on a Pentium Pro P6 (CPU speed of 500 MHz). For the simulation time step taken to be 1 or 5 seconds, the results are very similar and steady-state temperatures for basal conditions are obtained for simulated times of 15-20 minutes.

III. EXPOSURE TO EM FIELDS OF CELLULAR TELEPHONES AT 835 AND 1900 MHZ

The various cases considered for the cellular telephones are as follows:

Cases I a, b. No RF but with warm insulating blocks at 39°C representing the handsets against the left ear.

Cases II a, b. With the same blocks as Cases I a, b but with the telephones radiating RF powers such as to obtain peak 1-g SAR of 1.6 W/kg suggested in the IEEE guidelines.

Cases III a, b. With the same blocks as Cases I a, b but with the peak 10-g SAR of 2.0 W/kg suggested in the ICNIRP guidelines.

The data on the calculated steady-state elevations in the maximum 1-voxel temperatures (ΔT) for the pinna, the brain, and the eye are given in Tables 1 and 2. Also given in these tables in parentheses are the temperature increases ΔT only due to SAR without additional heating due to a warm (39°C) handset. In Table 1 as well as in Table 2, two different sets of basal temperatures are given because of different locations of the voxels at which the maximum temperature rise is calculated. For example, for SAR only, the maximum temperature increase is calculated at connection of pinna to the head for which the basal temperature is approximately 2.2°C higher, and for the eye, the maximum temperature increase is calculated for a voxel at the surface for which the basal temperature was 1.22°C to begin with. Temperature increases are generally less than 0.1°C for SAR alone and typically another 0.1°C higher due to the heat conduction from a warm (39°C) handset. Also, similar to the experimental data of [2], we note that a substantial temperature elevation on the order of about 4.5°C results for the pinna because of the suppressed air convection and heat conduction from the warm handset, but the additional temperature rise for the highest temperature voxels of the brain and the eye as compared to the respective basal temperatures is still fairly small and generally on the order of 0.1-0.2°C. The additional temperature increases due to SAR are very similar to those obtained by other authors [3-4]. Even with additional heating due to warm handsets at 39°C (Cases I a, b), the additional temperature increases for the well-perfused internal organ such as the brain are typically on the order of 0.1°C, somewhat higher and about 0.2°C for the non-perfused organ such as the eye and considerably higher on the order of 4.5°C for the pinna because of suppressed air convection and more importantly because of heat conduction from the warm handset.

IV. THERMAL IMPLICATIONS OF THE SAR LIMITS IN THE SAFETY GUIDELINES

An important objective of this paper was to understand the thermal implications of the SAR limits in the various safety guidelines. Whereas peak 1-g SARs of 1.6 or 8.0 W/kg are suggested for uncontrolled and controlled environments in the IEEE Standard, somewhat higher peak 10-g SAR limits of 2.0 and 10.0 W/kg are prescribed for general public and occupational exposures in the ICNIRP guidelines, respectively. Rather than assume artificial SAR distributions which may or may not be physically realizable, we have scaled the power output of the two assumed wireless devices appropriately to obtain peak 1- or 10-g SARs of 8.0 or 10 W/kg prescribed in the IEEE and ICNIRP guidelines, respectively. For such irradiation conditions, the calculated steady-state temperature rises for the maximum 1 voxel temperatures for the pinna, the brain, and the eye are given in Table 2. Also given in the same table are the corresponding temperature rises ΔT that would result if the SAR limits of 1.6 and 8.0 W/kg in the present IEEE Standard were to apply only to the body tissues with the tissue of the pinna excepted and treated as an extremity where considerably higher limits of 4.0 and 20 W/kg for any 10-g of tissue of the pinna would then apply. This proposed revision of the IEEE Standard is presently before the Standards Committee SCC28 and is being considered seriously.

We have calculated and give in Table 3 the masses of the brain tissue for the various temperature elevations up to and somewhat greater than 0.5°C for the SAR limits of 8 W/kg for any 1-g of tissue or 10 W/kg for any 10-g of tissue given in the IEEE or ICNIRP guidelines, respectively. Also given in the same table are the masses of the brain tissue if a presently proposed change of 8 W/kg for any 1-g of body tissue (excluding pinna) were to be adopted by the IEEE. By looking at the numbers given in Table 3, the following conclusions may be drawn.

1) The temperature elevations for the electromagnetically-exposed parts of the brain are up to 0.5°C or considerably smaller.

2) The masses of the brain tissue for selected temperature increases are considerably larger at the lower frequency of 835 MHz than at the PCS frequency of 1900 MHz. This is on account of the more diffused and hence a larger volume of EM energy deposition at 835 MHz both because of depth of penetration and longer extent parallel to the antenna. Hence, considerably larger irradiated power is needed at this lower frequency as compared to 1900 MHz (see footnote of Table 1) for any of the prescribed SAR limits.

To put these numbers in perspective, we have also examined the effect on the brain temperature if a higher arterial blood temperature of 37°C is taken instead of 36.8°C. The calculated basal temperatures for the various regions of the brain are commensurably higher and are on the order of 36.3-37.3°C (against 36.1-37.1°C). Hence, the end effect of the SAR-caused temperature elevation (see Table 3) is very similar to that resulting from commensurably higher arterial blood temperatures from 36.8°C to 37.3°C, but for the rapidly reducing masses of the brain given in Table 3 for higher temperatures.

V. CONCLUSIONS

The paper gives the temperature increases for the various tissues of the head in response to SAR and blocking of air convection and heat conduction from cellular telephones that may be warmed to temperatures as high as 39°C by internal electronic circuitry. Results are also given for the temperature increases if peak SARs corresponding to the IEEE and ICNIRP safety limits are used.

REFERENCES

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TABLE 1

The calculated basal temperatures and the maximum 1-voxel steady-state values of temperature increase ΔT for the pinna, the brain, and the eye for Cases I, II, and III, respectively. Also shown in parentheses are the values with heating only due to SAR without additional heating due to a warm (39°C) handset.

	Pinna	**Brain**	**Eye**	**Pinna**	**Brain**	**Eye**
Basal temperature (°C)	34.089 (36.285)	36.769 (36.848)	36.391 (35.174)	34.089 (36.087)	36.844 (36.849)	36.391 (36.086)
	Steady-State ΔT(°C) for Irradiation at **835 MHz**			Steady-State ΔT(°C) for Irradiation at **1900 MHz**		
Case I: No SAR, warm handset	4.461	0.127	0.211	4.461	0.127	0.211
Case II: Peak 1-g SAR = 1.6 W/kg*	4.466 (0.089)	0.143 (0.045)	0.213 (0.011)	4.464 (0.076)	0.128 (0.026)	0.211 (0.003)
Case III: Peak 10-g SAR = 2.0 W/kg*	4.472 (0.203)	0.189 (0.103)	0.215 (0.025)	4.469 (0.196)	0.144 (0.068)	0.212 (0.008)

* Irradiated powers of 310 and 121 mW for 1.6 W/kg; 713 and 310 mW for 2.0 W/kg at 835 and 1900 MHz, respectively.

TABLE 2

The calculated basal temperatures and the maximum 1-voxel steady-state values of temperature increase ΔT for the pinna, the brain, and the eye for the peak 1-g and 10-g SARs of 8.0 and 10.0 W/kg suggested in the safety guidelines for controlled or occupational exposure, respectively*. Also given for comparison are the values of ΔT (°C) if the SAR limits were to be applied to the body tissues excepting the pinna.

	Pinna	**Brain**	**Eye**	**Pinna**	**Brain**	**Eye**
Basal temperature (°C)	34.089 (36.285)	36.769 (36.848)	36.391 (35.173)	34.089 (36.087)	36.844 (36.849)	36.391 (36.086)
SAR	Irradiation at **835 MHz**			Irradiation at **1900 MHz**		
8.0 W/kg for any 1-g of tissue	4.486 (0.443)	0.288 (0.225)	0.219 (0.054)	4.476 (0.380)	0.179 (0.131)	0.212 (0.016)
10.0 W/kg for any 10-g of tissue	4.517 (1.013)	0.567 (0.513)	0.228 (0.123)	4.500 (0.979)	0.374 (0.338)	0.214 (0.040)
1.6 W/kg for any 1-g of **body** tissue [IEEE proposed]	4.466 (0.089)	0.143 (0.045)	0.213 (0.011)	4.464 (0.076)	0.128 (0.026)	0.211 (0.003)
8.0 W/kg for any 1-g of **body** tissue [IEEE proposed]	4.514 (0.960)	0.540 (0.486)	0.227 (0.116)	4.505 (1.091)	0.412 (0.377)	0.214 (0.044)

* Given in parentheses are the values with heating only due to SAR without additional heating due to a warm (39°C) handset.

TABLE 3

Masses of the brain tissue in g for various temperature increases ΔT.

Irradiation Frequency (MHz)	Peak 1- or 10 SAR	Mass of the Brain Tissue (g)			
		0.2 ≤ΔT<0.3 (°C)	0.3≤ ΔT<0.4 (°C)	0.4 ≤ΔT<0.5 (°C)	ΔT≥ 0.5 (°C)
835	8 W/kg for any 1-g of tissue	30	0	0	0
	8 W/kg for any 1-g of **body** tissue	283	88	25	2
	10 W/kg for any 10-g of tissue	317	105	23	6
1900	8 W/kg for any 1-g of tissue	0	0	0	0
	8 W/kg for any 1-g of **body** tissue	124	13	1	0
	10 W/kg for any 10-g of tissue	92	10	0	0