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

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***Abstract*—The bioheat equation is solved for an anatomically based model of the human head with a resolution of $3 \times 3 \times 3$ mm to study the thermal implications of exposure to electromagnetic (EM) fields typical of cellular telephones both at 835 and 1900 MHz. It is shown that similar to the measured data, up to 4.5 °C temperature elevation may be caused for 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 eye that are no more than 0.1 °C–0.2 °C higher than the basal values. Similar to previous studies by other authors, additional temperature increases due to EM fields of cellular telephones are fairly small and typically less than 0.1 °C. 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 specific absorption rates (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 and for larger volumes. Similar temperature increases are also calculated by increasing the arterial blood temperature, except that the temperature increases due to the SAR are for the more limited volume rather than the entire brain.**

***Index Terms*—Anatomic model of the head, cellular telephones, safety standards, temperature increase.**

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 (EM) radiating source to the brain and the sensation of warmth for the ear and 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 [1].

In this paper, we use the bioheat equation for a thermal model of the human head to study: 1) 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 2) heating of the various tissues, e.g., the ear, brain, and 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. Each of the telephones is assumed to use a quarter-wavelength monopole-type antenna, which is typical of telephones in use today. The specific-absorption-rate (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 several other authors [2]–[6].

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 [7]. 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 0.1 °C–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 [8]–[10] 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 [11], [12]. Most of the recently developed RF safety guidelines in North America, Europe, Pacific Asia, and Australia/New Zealand are based on limiting rates of EM energy absorption [specific absorption rate (SAR)] for any 1 or 10 g of tissues of the body. Whereas peak 1-g SARs of 1.6 and 8.0 W/kg are suggested for uncontrolled and controlled environments, respectively, in the IEEE standard [11], somewhat higher peak 10-g SAR limits of 2.0 and 10.0 W/kg are prescribed in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [12]. It would be most interesting to examine the thermal implications of these various peak SARs if the limiting values were to occur for the brain tissue. It is recognized that cellular telephones currently on the market or projected for the future will not use such high radiated powers as to cause the upper SAR limits of 8.0 W/kg for any 1 g of tissue [11] or 10.0 W/kg for any 10 g of tissues [12] suggested in the two safety guidelines. Nevertheless, these SAR limits have been prescribed for controlled environments [11] or for occupational exposures [12] and it would be instructive to examine the temperature elevations that the highest of the SARs may cause, most notably for the brain tissue.

II. Thermal Model of the Human Head

We solve the transient bioheat conduction equation to obtain the thermal response of the various tissues in the head and neck regions of the body. The bioheat equation incorporates

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TABLE I
MASS DENSITIES AND THERMAL PROPERTIES ASSUMED FOR THE VARIOUS TISSUES [2], [9], [14]–[17]

Tissue	Mass Density ρ 10^3 kg/m^3	Specific Heat C W hr/(°C kg)	Heat Conductivity k W/(m°C)	Blood Flow Rate bf kg/m^3 hr	Basal Metabolic Rate h_m W/kg
Air	0.00116	0.28	0.0263	0	0
Muscle	1.05	1.014	0.5	1296	0.67
Fat	0.92	0.663	0.217	324	0.15
Bone	1.99	0.4	0.36	55.8	0.15
Cartilage	1.1	1.02	0.53	54	0.2
Skin	1.1	1.05	0.334	33,600	1.07
Nerve	1.04	1.022	0.565	32,760	9.7
Blood	1	1.06	0.51	0	0
Parotid gland	1.05	1	0.42	17,280	9.7
CSF	1.06	1.056	0.57	0	0
Eye humor	1.01	1.167	0.578	0	0.34
Sclera	1.07	1.167	0.5	0	0.34
Eye lens	1.1	0.833	0.4	0	0
Pineal gland	1.05	1.02	0.42	17,280	9.7
Pituitary gland	1.07	1.02	0.42	17,280	9.7
Brain	1.03	1.02	0.528	32,760	9.7

metabolic heat generation, EM energy deposition (SAR), heat exchange through blood flow into the various tissues and heat dissipation at the surface by radiative, convective, and evaporative losses (due to insensible perspiration) from the voxels at the surface of the model. The thermal model of the human head is derived from the previously described anatomically based model of the human body that has been used for SAR calculations for exposure to EM fields of cellular telephones both at 835 and 1900 MHz [2]. As described earlier, this model was obtained from magnetic resonance imaging (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 current calculations are presented in Table I. These thermal properties have been gleaned from several references, i.e., [8]–[10], [13]–[17]. However, unlike some of the previous authors [8]–[10], we have taken a much higher value of the blood-flow rate for the skin of the face and head. The value of 33 600 kg/m$^3 \cdot$ h is close to the average of 25 740 for the skin with hair and 42 180 kg/m$^3 \cdot$ h for the skin of the face [18].

As described earlier [2], the anatomically based model is resolved into voxels of dimensions 1.974 $\times$ 1.974 mm for the cross-sectional cuts and 3.0-mm thickness along the vertical z-axis. For the current calculations, the pixel size is assumed to be 2.0 $\times$ 2.0 mm and the cells are combined into voxels of dimensions 3.0 $\times$ 3.0 $\times$ 3.0 mm along the three axes, respectively. This is accomplished by first subdividing each of the voxels into smaller voxels each of dimensions 1.0 $\times$ 1.0 $\times$ 1.0 mm along the three axes and then combining 3 $\times$ 3 $\times$ 3 (or 27) of these smaller voxels into voxels of dimensions 3.0 $\times$ 3.0 $\times$ 3.0 mm. For each of the larger voxels, the tissue properties used are those of the predominant or majority tissue in these voxels. The new 3 $\times$ 3 $\times$ 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 presented in this paper, two different sizes of the plastic-covered handsets are assumed. For calculations at 835 MHz, the handset dimensions are 2.4 $\times$ 5.4 $\times$ 15.3 cm with the outermost cells for this metal box handset represented by an equivalent dielectric constant $\varepsilon_r = 1.613$, 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 [2]. 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 personal communications system (PCS) frequency of 1900 MHz are somewhat smaller at 1.8 $\times$ 4.5 $\times$ 12.0 cm along the three axes, respectively. Here too, the outermost cells are represented by an equivalent dielectric constant $\varepsilon_r = 1.613$.

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 [13], [14]:

$$m_{i,j,k}C_{i,j,k}\frac{\partial T_{i,j,k}}{\partial t} = \Big[\nabla(k_{i,j,k}\nabla T_{i,j,k}) + h_{m_{i,j,k}} + h_{\mathrm{EM}_{i,j,k}} + b_{f_{i,j,k}}C_b(T_b - T_{i,j,k})\Big]V_{i,j,k} - h_{\mathrm{RAD}_{i,j,k}} - h_{\mathrm{CONV}_{i,j,k}} - h_{\mathrm{E}_{i,j,k}} \quad (1)$$

Here, for the voxel i, j, k (denoted by i for brevity)

- T_i instantaneous temperature of the tissue (°C);
- m_i mass of the tissue for the voxel (kg);
- C_i specific heat of the tissue (W $\cdot$ hr/°C $\cdot$ kg);
- k_i thermal conductivity of the tissue [W/(°C $\cdot$ m)];
- h_{m_i} metabolic heat generation per unit volume (W/m^3);
- h_{EM_i} EM energy deposition per unit volume (W/m^3);
- bf_i blood-flow rate [kg/m$^3 \cdot$ hr];
- T_b temperature of arterial blood entering the tissue (°C);
- V_i volume of the voxel (m^3);
- h_{RAD_i}, h_{CONV_i} radiative and convective heat losses from the peripheral cells per unit volume (W);
- h_{E_i} evaporative heat dissipation per unit volume (W).

In (1), the heat losses of the voxels at the surface of the model include radiative, convective, and evaporative losses. The radiative heat loss is represented by the Stefan–Boltzmann formula [19], [20]

$$h_{\mathrm{RAD}} = \varepsilon'\delta \cdot A_{\mathrm{eff}}\Big[(T_{\mathrm{skin}} + 273)^4 - (T_{\mathrm{air}} + 723)^4\Big] \quad (2)$$

where

- δ $= 5.67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4) is the Stefan–Boltzmann constant;
- ε' $\approx$ 0.98 emissivity of the head (skin);
- A_{eff} area of the head that is effective in radiating heat (m^2);
- T_{skin} temperature of the skin (°C);

$T_{\rm air}$ ambient air temperature (assumed to be 25 °C for the current calculations).

The convective heat loss from the body is given from [15]

$$h_{\rm CONV} = h_{\rm c} A_{\rm eff} (T_{\rm skin} - T_{\rm air}) \text{ W} \tag{3}$$

where $h_{\rm c} = 2.7\,{\rm W}/({\rm m}^2\,^\circ{\rm C})$ is the convective heat transfer coefficient. The evaporative heat loss due to insensible perspiration from the surface voxels is given by Inouye *et al.* [19] as follows:

$$h_{\rm E} = k_{\rm evap} A_{\rm N} \left(P_{\rm w,skin} - P_{\rm w,air} \right) \tag{4}$$

where

$k_{\rm evap}$ $= 0.35$ W/(m^2 · mmHg) is the evaporative coefficient;

$P_{\rm w,skin}, P_{\rm w,air}$ vapor pressures of water at skin and in air, respectively (mm · Hg);

$A_{\rm N}$ area of the voxel exposed to air $({\rm m}^2)$.

The vapor pressure of water over the range of roughly 27 °C–37 °C can be represented well by [20]

$$P_{\rm w,skin} = 1.92 T_{\rm skin} - 2.53 \text{ mmHg}. \tag{5}$$

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 current calculations.

The EM energy deposition per unit volume $h_{\rm EM_1}$ to use for each of the voxels in (1) is obtained using the FDTD method detailed in some of our earlier papers [2], [21]. The ambient temperature and the arterial blood temperature are assumed to be 25 °C and 36.8 °C, respectively.

This three-dimensional transient heat conduction equation [see (1)] is solved by an implicit finite-difference method [22] that achieves a higher order accuracy of the Crank–Nicholson formulation. The successive over-relaxation method is used for rapid convergence.

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 s, the results are very similar and steady-state temperatures for basal conditions are obtained for simulated times of 15–20 min.

Two test runs for a canonical problem of a homogeneous sphere were performed to check the accuracy of the above numerical method. One is for radiative heat dissipation to air and the other is for conductive heat dissipation where a higher temperature (37 °C) sphere is immersed in a lower constant temperature (30 °C) bath. For both of these cases, the numerical solutions were very close and within 1%–2% of the temperatures obtained from the analytical solutions.

III. Exposure to EM Fields of Cellular Telephones at 835 and 1900 MHz

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

- *Cases I a, b*: No RF, but with warm insulating blocks at 39 °C representing the handsets against the left ear at 835 MHz (2.4 × 5.4 × 15.3 cm) and 1900 MHz (1.8 × 4.5 × 12.0 cm), respectively. This has the effect of blocking air convection and heating of the pinna because of heat conduction from the warm handset.
- *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 and FCC guidelines [11], [23].
- *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 [12].

TABLE II
Salient Features of the Calculated SAR Distributions for Cellular Phones Selected for 835 and 1900 MHz

	835 MHz	1900 MHz
Handset dimensions (cm)	2.4 x 5.4 x 15.3	1.8 x 4.5 x 12.0
Peak 1-g SAR (W/kg)	1.6	1.6
Radiated power (mW)	310	121
Peak 10-g SAR (W/kg)	0.87	0.78
% power absorbed by the head	46	50.3
% power absorbed by the brain	19.8	13.4
% power absorbed by the left pinna	6.2	14.1
% power absorbed by the left eye	0.1	0.1

As mentioned above, the handset dimensions used for the cellular telephones at 835 and 1900 MHz are somewhat different (both handset dimensions are, however, representative of the present-day telephones), but each of the telephones uses a quarter-wave monopole antenna at the respective frequencies. Each of the telephones is held at an angle of 30° relative to the upright position—a forward-tilted model of the head [21] is, therefore, used to avoid stair-step approximation in modeling the linear monopole antenna. Some salient features of the calculated SARs for the two telephones are given in Table II. For Cases III a, b, appropriately scaled higher-radiated powers of 709 and 311 mW are assumed to obtain peak 10-g SAR of 2.0 W/kg at 835 and 1900 MHz, respectively.

The calculated temperature variations as a function of time for the voxels corresponding to the maximum temperatures for the ear, brain, and eye are given for Cases I–III a, b in Figs. 1–4, respectively. It is interesting to note that the steady-state temperatures are reached for exposure times on the order of 20–30 min, except for the pinna where 99.5% of the final temperature is reached in a matter of 5–6 min (see Fig. 1). Since it is difficult to see the incremental temperature differences in Fig. 1, Figs. 2–4 are drawn with considerably expanded temperature scales to clearly show steady-state values of ΔT. The data on the calculated steady-state elevations in the maximum one-voxel temperatures (ΔT) for the pinna, brain, and eye are given in Table III. Also given in this table (in parentheses), are the temperature increases ΔT only due to the SAR without additional heating due to a warm (39 °C) handset. In Table III, as well as in Table IV, two different sets of basal temperatures are given

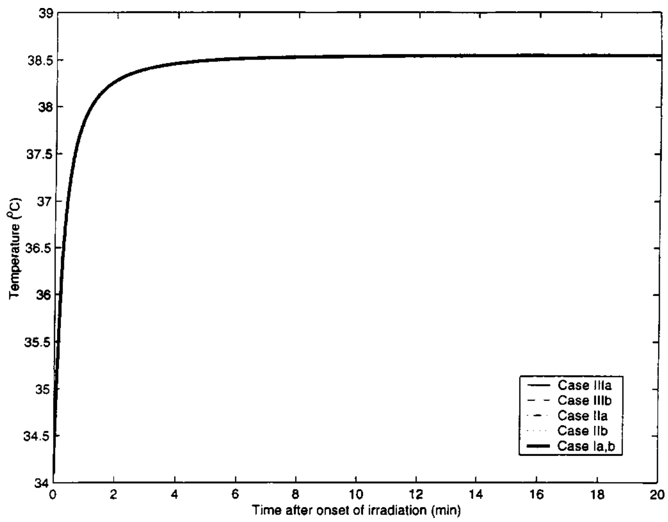

Fig. 1. Maximum one-voxel temperature for the pinna for Cases I a, b (with warm handsets at 39 °C), Cases II a, b (1.6 W/kg for any 1 g of tissue [11]) and Cases III a, b (2.0 W/kg for any 10 g of tissue [12]). Irradiated powers for Cases II a, b are given in Table II and may be scaled to 709 and 311 mW to obtain a peak 10-g SAR of 2.0 W/kg at 835 and 1900 MHz (Cases III a, b), respectively.

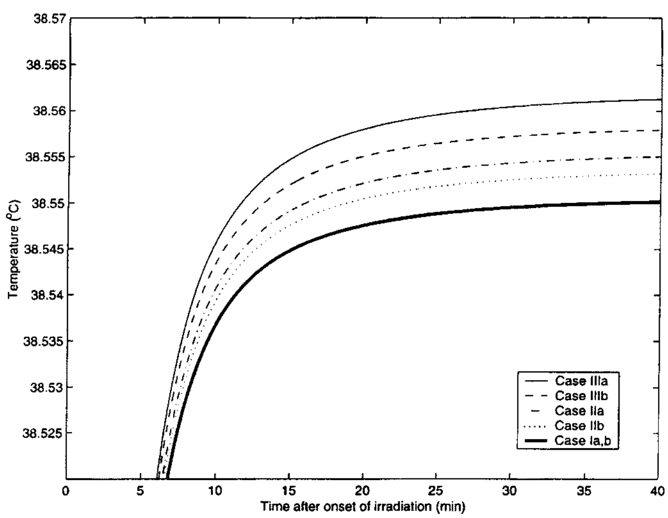

Fig. 2. Shown on a considerably expanded temperature scale is the maximum one-voxel temperature for the pinna for Cases I–III a, b, respectively. Due to the larger irradiated power at 835 versus 1900 MHz, the temperature increases for Cases II a and III a are somewhat larger than those for Cases II b and III b, respectively.

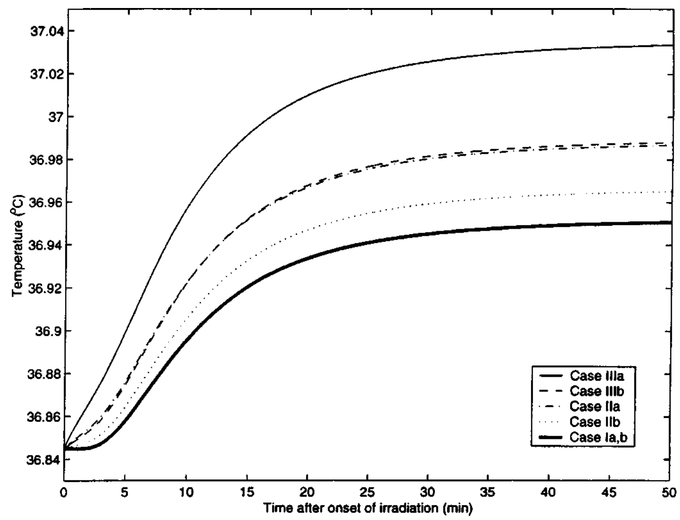

Fig. 3. Shown on a considerably expanded temperature scale is the maximum one-voxel temperature for the brain for Cases I–III a, b, respectively. Due to the larger irradiated power at 835 versus 1900 MHz, the temperature increases for Cases II a and III a are somewhat larger than those for Cases II b and III b, respectively.

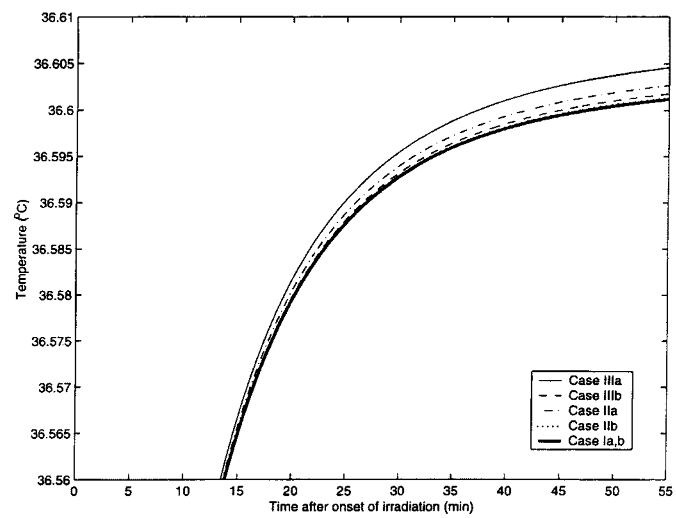

Fig. 4. Shown on a considerably expanded temperature scale is the maximum one-voxel temperature for the proximal left eye for Cases I–III a, b, respectively. Due to larger irradiated power at 835 versus 1900 MHz, the temperature increases for Cases II a and III a are somewhat larger than those for Cases II b and III b, respectively.

because of different locations of the voxels at which the maximum temperature increases for the corresponding tissues are 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 rise is calculated for a voxel at the surface for which the basal temperature was 1.22 °C lower 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 [7], 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 eye as compared to the respective basal temperatures is still fairly small and generally on the order of 0.1 °C–0.2 °C. The additional temperature increases due to SAR are very similar to those obtained by other authors [8]–[10]. 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 nonperfused organ such as the eye, and considerably higher on the order of 4.5 °C for the ear because

TABLE III
CALCULATED BASAL TEMPERATURES AND THE MAXIMUM ONE-VOXEL STEADY-STATE VALUES OF TEMPERATURE INCREASE ΔT FOR THE PINNA, BRAIN, AND PROXIMAL LEFT EYE FOR CASES I-III, RESPECTIVELY. ALSO SHOWN IN PARENTHESES ARE THE VALUES WITH HEATING ONLY DUE TO THE 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)

* See Table 2 for radiated powers at 835 and 1900 MHz.

TABLE IV
CALCULATED BASAL TEMPERATURES AND THE MAXIMUM ONE-VOXEL STEADY-STATE VALUES OF TEMPERATURE INCREASE ΔT FOR THE PINNA, BRAIN, AND EYE FOR THE PEAK 1- AND 10-G SARs OF 8.0 AND 10.0 W/kg SUGGESTED IN THE SAFETY GUIDELINES [11], [12] 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 [11]	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 [12]	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.

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

As mentioned above, an important objective of this paper is to understand the thermal implications of the SAR limits in the various safety guidelines [11], [12]. Most of the recently developed RF safety guidelines in North America, Europe, Pacific Asia, and Australia/New Zealand are based on limiting rates of EM energy absorption or the SAR for any 1 or 10 g of tissues of the body. Whereas peak 1-g SARs of 1.6 or 8.0 W/kg are suggested for uncontrolled and controlled environments in the IEEE standard [11], 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 [12]. Rather than assume artificial SAR distributions that may or may not be physically realizable, we have scaled the power output of the two assumed wireless devices in Table II appropriately to obtain peak 1- or 10-g SARs of 8.0 or 10 W/kg prescribed in the IEEE and ICNIRP guidelines, respectively [11], [12]. For such irradiation conditions, the calculated steady-state temperature rises for the maximum one-voxel temperatures for the pinna, brain, and eye are given in Table IV. Also given in this table are the corresponding temperature rises ΔT that would result if the SAR limits of 1.6 and 8.0 W/kg in the current 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 Coordinating Committee SCC28 and is seriously being considered.

We have calculated and present in Table V 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 [11] or ICNIRP [12] guidelines, respectively. Also given in this table are the masses of the brain tissue if a currently 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 V, 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 due to 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 also Table II) for any of the prescribed SAR limits.
3) The proposed change in the IEEE SAR limit of 8 W/kg being applied to nonextremity body tissue rather than any 1 g of tissue would lead to an over two times increase in the irradiated power and considerably larger masses of the brain for which the temperature elevation above the basal temperatures of 36.1 °C–37.1 °C would be exceeded by 0.2 °C.

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 commensurately higher and are on the order of 36.3 °C–37.3 °C (against 36.1 °C–37.1 °C). Hence, the end effect of the SAR-caused temperature elevation (see Table V) is very similar to that resulting from commensurately higher arterial blood temperatures from 36.8 °C to 37.3 °C, but for the rapidly reducing masses of the brain given in Table V for higher temperatures.

TABLE V
MASSES OF THE BRAIN TISSUE IN GRAMS FOR VARIOUS TEMPERATURE INCREASES ΔT

Irradiation Frequency (MHz)	Peak 1- or 10-g SAR	Mass of the Brain Tissue (g)			
		$0.2 \leq \Delta T < 0.3$ (°C)	$0.3 \leq \Delta T < 0.4$ (°C)	$0.4 \leq \Delta T < 0.5$ (°C)	$\Delta T \geq 0.5$ (°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

V. CONCLUSIONS

We have solved the bioheat conduction equation for an anatomically based model of the human head to study the thermal implications of exposure to EM fields that are typical of cellular telephones both at 835 and 1900 MHz. Unlike previous authors [8]–[10], we have studied the effect of blocking of air convection and heat conduction to the pinna from cellular telephones that may be warmed by internal electronic circuits to temperatures as high as 39 °C. Similar to the measured data [7], this itself results in a temperature elevation for parts of the pinna by about 4.5 °C with temperature increases for the internal tissues such as the brain and eye that are no more than 0.1 °C–0.2 °C higher than the basal values. Similar to the previous authors [8]–[10], the additional temperature elevations because of SARs caused by the EM fields of cellular telephones are fairly small and typically less than 0.1 °C.

Another thrust of the paper has been to study the thermal implications of the SAR limits, particularly for the occupational exposures in the various safety guidelines [11], [12]. Typically, these are at least five times higher than the SARs permitted by the regulatory agencies for the cellular telephones. Exposures to SARs of 8.0 W/kg for any 1 g of tissue (IEEE and Federal Communications Commission (FCC) standards [11], [23]) or 10.0 W/kg for any 10 g of tissue (ICNIRP standard [12]) are shown to result in temperature increases greater than or equal to 0.2 °C of 30 and 451 g of the brain tissue at 835 MHz and 0 and 102 g of the brain tissue at 1900 MHz, respectively. This is understandable because of the deeper penetration of EM fields at 835 MHz and over two times higher irradiated powers that are needed to cause the prescribed SAR limits at 835 MHz, as compared to 1900 MHz. However, this 0.2 °C temperature elevation is similar to that caused for the brain by increasing the arterial blood temperature from 36.8 °C to 37.0 °C, except that the temperature increases due to SAR are for the more limited volume of the brain rather than the entire brain.

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