# Thermal Dosimetry in Human for Microwave Exposures

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## Abstract

This paper reviews computational techniques for calculating specific absorption rate (SAR) and temperature elevation in anatomically-based human models for microwave exposures. Computational examples are shown to explain the difference between temperature elevations in the human due to localized and whole-body exposures.

## 1. Introduction

In accordance with the rapid spread of wireless communications, there has been an increasing public concern about the adverse health effects due to microwave (MW) exposures. In the MW regions, elevated temperature (1-2$^{o}$C) resulting from energy absorption is known to be a dominant factor inducing adverse health effects such as heat exhaustion and heat stroke.

In the safety guidelines/standards [1, 2], the whole-body average specific absorption rate (SAR) was used as a measure of human protection for MW whole-body exposure. The threshold or basic restriction was 0.4 W/kg. One of the rationales for this value is based on the fact that MW exposure of laboratory animals in excess of approximately 4 W/kg has revealed a characteristic pattern of thermoregulatory response [3], and a safety factor of 10 was applied. Additionally, decreased task performance by rats and monkeys has been observed at SAR values in the range of 1–3 W kg (e.g., [4]). These phenomena would be caused by the body-core temperature elevation. However, some difference between these small animals and human would exist, especially because the physiological heat loss mechanisms of the small animals are limited [5]. For MW localized exposures, the guidelines/standards are based on peak spatial-average SAR (specific absorption rate) for any 1 or 10g of body tissue. However, physiological effects and damage to humans due to microwave absorption are induced by the temperature elevation, similar to whole-body exposures. A temperature elevation of 4.5 $^{o}$C in the brain has been noted to be an allowable limit which does not lead to any physiological damage (for exposures of more than 30 minutes) [6]. Additionally, the threshold temperature of the pricking pain in the skin is 45 $^{o}$C, corresponding to the temperature elevation of 10-15 $^{o}$C [7]. Although a temperature elevation in the human is a dominant factor due to microwave exposure, the relationship between incident electromagnetic fields, whole-body average SAR, and temperature elevation was not well quantified. The main reason for this is that until recently experimental and computational dosimetric techniques were not well established. This paper reviews briefly computational methods for calculating the temperature elevation in the anatomically-based human head model for microwave exposures. Computational examples are given to explain the difference of the temperature elevations between localized and whole-body exposures.

## 2. Computational Methods

### 2.1 SAR Calculation

The FDTD method [8] is used for investigating MW power absorbed in the rabbit phantom. For a truncation of the computational region, we adopted perfectly matched layers as the absorbing boundary. To incorporate the human model into the FDTD scheme, the dielectric properties of tissues were required. They were determined with the 4-Cole-Cole extrapolation [9].

For harmonically varying fields, the SAR is defined as

$$\mathrm{SAR} = \frac{\sigma}{2\rho} |\hat{E}|^2 = \frac{\sigma}{2\rho}(|\hat{E}_x|^2 + |\hat{E}_y|^2 + |\hat{E}_z|^2) \tag{1}$$

where $\hat{E}_x$, $\hat{E}_y$, and $\hat{E}_z$ are the peak values of the electric field components, $\sigma$ and $\rho$, denoting the conductivity and the mass density of the tissue, respectively.

### 2.2 Temperature Calculation

**Bioheat Equation:** For calculating temperature increases in the rabbit model, the bioheat equation was used [10] [11]. A generalized form of the bioheat equation is given by the following equation:

$$C(\mathbf{r})\rho(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial t} = \nabla\cdot(K(\mathbf{r})\nabla T(\mathbf{r},t)) + \rho(\mathbf{r})SAR(\mathbf{r}) + A(\mathbf{r}) - B(\mathbf{r},t)(T(\mathbf{r},t) - T_B(t)) \quad (2)$$

where $T(\mathbf{r},t)$ and $T_B(t)$ denote the respective temperatures of tissue and blood, $C$ the specific heat of tissue, $K$ the thermal conductivity of tissue, $A$ the basal metabolism per unit volume, and $B$ the term associated with blood perfusion. The blood temperature is assumed to be spatially constant over the whole body, since the blood circulates throughout the human body in one minute or less. For localized exposures, $T_B(t)$ is simplified as a constant, since the EM power absorption is much smaller than the basal metabolism. The boundary condition between air and tissue for Eq. (2) is given by the following equation:

$$-K(r)\frac{\partial T(\mathbf{r},t)}{\partial n} = h\cdot(T_s(\mathbf{r},t) - T_e(t)) \quad (3)$$

where $H$, $T_s$, and $T_e$ denote, respectively, the heat transfer coefficient, surface temperature, and air temperature. The heat transfer coefficient $h$ is given by the summation of radiative heat loss $h_{rad}$, convective heat loss $h_{conv}$, and evaporative heat loss $h_{e}$,. A review of heat transfer coefficient for human is summarized in [12].

The temperature of blood is changed according to the following equation in order to satisfy the thermodynamic laws [13]:

$$T_B(t) = T_{B0} + \int_t \frac{Q_{BTOT}(t)}{C_B\rho_B V_B}dt \quad (4)$$

$$Q_{BTOT}(t) = \int_V B(t)(T_B(t) - T(\mathbf{r},t))dV \quad (5)$$

where $Q_{BTOT}$ is the rate of heat acquisition of blood from body tissues. $C_B$ (=4000 J/kg·$^{o}$C), $\rho_B$ (=1050 kg/m$^3$), and $V_B$ denote the specific heat, mass density, and total volume of blood, respectively. The blood volume is put at 5.0 l. A detailed explanation for varying temperature elevation can be found in [11]. This formulation is shown to be reasonable by comparing computed and measured temperature elevation at the rectum [14].

**Thermoregulatory response:** For a temperature elevation above a certain level, the blood perfusion was activated in order to carry away the excess heat evolved. As to blood perfusion for all tissues except the skin, the regulation mechanism was governed by the local tissue temperature. When that temperature remained below a certain level, blood perfusion was equal to its basal value $B_0$. Once the local temperature exceeded a given threshold, the blood perfusion increased almost linearly with the temperature in order to carry away the heat evolved. For humans, some formulas have been proposed by different research groups (e.g., [15] [16]). These formula work marginally for exposure to RF at the level comparable to or below ICNIRP reference level. This is because the threshold for activating the blood perfusion in the inner tissues is 1 $^{o}$C or larger [15], which is well below the level activating the above equations. The variations of blood perfusion in the skin through vasodilatation are expressed in terms of the temperature increase in the hypothalamus and the average temperature increase in the skin [17], [18].

For sweating modelings, there are well-known two formulas. One is the formula proposed in [17] and improved in [13], which is given by the following equation:

$$SW(\mathbf{r},t) = [SW_o + F_{HS}(T_H(t) - T_{HO}) + F_{SS}\Delta T_S]\times 2^{(T(\mathbf{r})-T_0(\mathbf{r}))/10} \quad (6)$$

where $SW_o$ is insensible perspiration, or the basal evaporative heat loss from the skin. The coefficients of $F_{HS}$ and $F_{SS}$ in Eq. (11) were 140 W/m$^2$/$^{o}$C$^2$ and 13 W/m$^2$/$^{o}$C$^2$ [13]. The other formula is presented in [18]. Similar to the above formula, the sweating coefficients are assumed to depend on the temperature elevation in the skin and/or hypothalamus. Due to the lack of the space, we did not present the detailed explanation of that formula.

## 3. Computational Results

As an example for localized exposures, a dipole antenna was considered as a source. Anatomically-based human head model developed at Osaka University was used in this computational example [19]. This model was comprised of 18 tissues with the resolution of 2mm. The distance between the pinna and the antenna was 24 mm. For this scenario, SAR and temperature elevation was calculated and illustrated in Fig.1. As seen from this figure, the SAR and temperature elevation distributions were not proportional to each other, due to heat diffusion in biological tissue. However, in [20], good correlation is observed between peak spatial-average SAR and temperature elevation. 10 g was found to be better average

mass of SAR correlating maximum temperature elevation than 1 g. This fact can be explained using the heat diffusion length in biological tissues, which can be derived from Green's function for the bioheat equation [21].

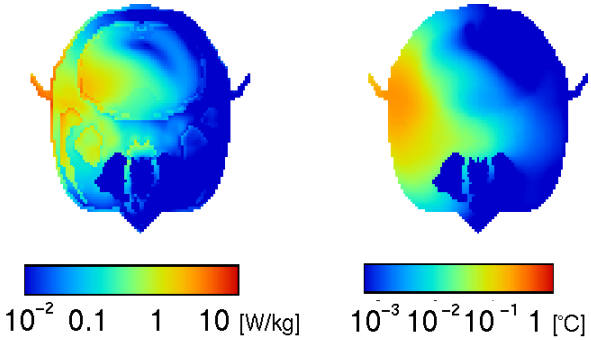
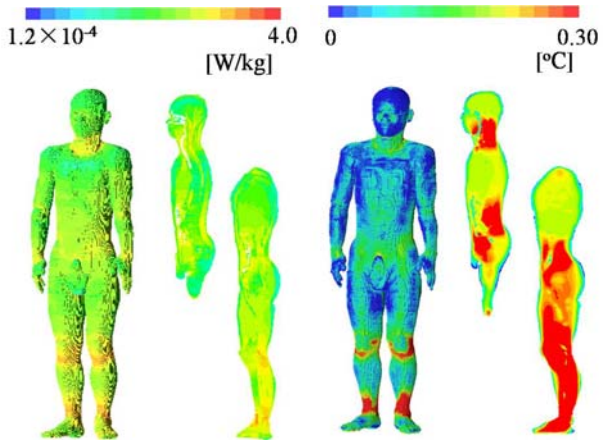



Figure 1: SAR and temperature distribution in the head across the pinna.




(a) (b)

Figure 3: SAR (a) and temperature elevation (b) distribution on the human body for plane wave exposure at 65 MHz.

For an example for whole-body exposures, a vertically-polarized plane wave is incident on TARO, an anatomically-based Japanese male model. The frequency dependency of whole-body average SAR can be found in [22]. As a computational example, SAR and temperature elevation distributions at 65 MHz are illustrated in Fig. 2. As seen from this figure, these distributions are not identical to each other, which is attributed to heat diffusion. In addition to this, thermoregulatory response, or sweating, is activated to remove the heat away. Then, the temperature elevation at the skin or the surface is relatively low even though SAR distribution is high. The effect of sweating on the body-core temperature elevation can be investigated by substituting different physiological parameters into the formulas in [18]. A detailed discussion for thermal dosimetry due to RF energy can be found in [11]. As a main result, the body-core temperature elevation at the basic restriction in the ICNIRP guidelines of 0.4 W/kg is 0.25 $^{o}$C even for a man with low sweating rate. This value is marginally influenced by the frequency of incident wave. The thermal time constant of blood temperature elevation was 23 min and 52 min for a man with lower and higher sweating rate, respectively, which is longer than the average time of SAR in the ICNIRP guidelines [11].

## 4. Summary

This paper reviewed computational techniques for calculating specific absorption rate (SAR) and temperature elevation in anatomically-based human models for microwave exposures. Computational examples were shown to explain

the temperature elevation for localized and whole-body exposures. Development of thermal model for child and pregnant will be required since they are listed as a high priority work in WHO research agenda.

## Acknowledgments

This work was partially supported by International Communications Foundation and Research grant from TELEC, Japan.

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