A Formula for Simply Estimating Body Core Temperature Rise in Humans Due to Microwave Exposures

Akimasa Hirata #1, Hironori Sugiyama#, Osamu Fujiwara#2
#Nagoya Institute of Technology, Department of Computer Science and Engineering, Nagoya, Japan
1ahirata@nitech.ac.jp, 2fujiwara@odin.nitech.ac.jp

***Abstract*—Biological effects due to RF whole-body exposure can be caused by core temperature rise. According to safety guidelines, therefore, whole-body averaged specific absorption rate (WBA-SAR) is being used as a metric for human protection. The threshold level causing thermal effects was determined based on animal experimental results. In order to investigate the relationship between WBA-SAR and core temperature rise, we previously calculated SARs and the temperature rises in humans for microwave exposure with the finite-difference time-domain (FDTD) method. However, theoretical solution or a closed formula for predicting core temperature rise is essential for further understanding the relationship. In the present study, we derived a formula for simply predicting core temperature rise in human for whole-body microwave exposure. As a result, we found that core temperature rises are in reasonable agreement between the results from the formula and FDTD computation. We also clarified the main factors influencing the core temperature rise as the body surface area-to-weight ratio and sweating rate, together with an applicable range of the formula.**

***Key words*: whole-body averaged specific absorption rate (SAR), far field, core temperature, bio-heat equation**

I. INTRODUCTION

There has been increasing public concern about the adverse health effects of human exposure to electromagnetic waves. In the radio-frequency and microwave (MW) regions, elevated temperature (1-2°C) resulting from energy absorption is known to be a dominant factor inducing adverse health effects such as heat exhaustion and heat stroke [1]. Typical source or situation for whole-body exposures are patients for magnetic resonance imaging system and workers exposed from base antennas for wireless communications.

In safety guidelines/standards [2, 3], the whole-body average specific absorption rate (WBA-SAR) was used as a measure of human protection for MW whole-body exposure. The threshold WBA-SAR is noted as 4-8 W/kg. These thresholds are 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 [4]. In addition, decreased task performance by rats and monkeys has been observed at SAR values in the range of 1–3 W/kg [5]. According to [6], the physiological heat loss mechanisms are different for different species. Namely, small animals would be poor models for human beings.

We have developed an electromagnetic-thermal simulation method based on finite-difference time-domain scheme for humans [7] and rabbits [8]. The feature of the thermal computational code is that it can consider the time evolution of core or blood temperatures. However, theoretical solution or a closed formula for predicting core temperature elevation is essential for further understanding the relationship between WBA-SAR and core temperature elevation, since it takes a lot of time to analyze with the above method.

In the present study, we derive a formula for simply predicting core temperature rise in human for whole-body MW exposure. We focus the main factors influencing core temperature rise due to MW exposure, together with an applicable range of the formula proposed.

II. COMPUTATIONAL MODELS AND METHODS

A. Human Body Models

Whole-body voxel models for a Japanese adult male and a Japanese adult female were developed by Nagaoka et al. [9]. The resolution of these models was 2 mm segmented into 51 anatomical regions. Models for children of three, five and seven years of age were developed by applying a free form deformation algorithm to the male model. In this modeling, a total of 66 body dimensions was taken into account, and then reduced with different scaling factors. Manual editing was applied in order to maintain their anatomical validity. The resolution of these models was kept to 2 mm. More detailed explanation on these models can be found in [10].

B. Electromagnetic Dosimetry

The FDTD method is used for investigating MW power absorbed in the human phantoms. For a truncation of the computational region, we adopted perfectly matched layers as the absorbing boundary. To incorporate the human phantom into the FDTD scheme, the dielectric properties of tissues were required. They were determined with the 4-Cole-Cole extrapolation [11].

C. Thermal Dosimetry

Our formula for the temperature calculation was given in our previous study; for humans [7] and rabbits [8], together with their validation. For calculating temperature increases in the rabbit model, the bioheat equation was used [12]. A generalized form of the bioheat equation is given by the following equation:

$$C(\mathbf{r})\rho(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial t} = \nabla\cdot(K(\mathbf{r})\nabla T(\mathbf{r},t)) + \rho(\mathbf{r})SAR(\mathbf{r}) + A(\mathbf{r}) - B(\mathbf{r},t)(T(\mathbf{r},t) - T_B(t)) \tag{1}$$

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 boundary condition between air and tissue for Eq. (1) is given by the following equation:

$$-K(r)\frac{\partial T(\mathbf{r},t)}{\partial n} = h\cdot(T_s(\mathbf{r},t) - T_e(t)) \tag{2}$$

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 [13].

The thermoregulatory responses, such as sweating and temperature-dependent blood perfusion rate have been taken into account, although they are not shown due to the lack of space [7].

III. Derivation of Formula

In this section, we derive a formula for simply relating the core temperature elevation and WBA-SAR. Let us consider the heat balance given in [6], [14]:

$$M + P_{RF} - P_{conv} = S \tag{3}$$

where M is the rate at which thermal energy is produced through metabolic processes, P_{RF} the RF power absorbed in the the body, P_{conv} the rate of heat exchange with the convection, and S the rate of heat storage in the body. More specific expression for (3) is given in the following equation.

$$\begin{aligned}&\int_0^t\int_V\left(A(\vec{r},t) - A_0(\vec{r})\right)dVdt + \int_0^t\int_V SAR(\vec{r})\cdot\rho(\vec{r})dVdt \\ &-\left\{\int_0^t\int_S H(\vec{r})\left(T(\vec{r},t) - T_0(\vec{r})\right)dSdt + \int_0^t\int_S SW(\vec{r},t)dSdt\right\} \\ &= \int_V\left(T(\vec{r},t) - T(\vec{r})\right)\cdot\rho(\vec{r})\cdot C(\vec{r})dV\end{aligned} \tag{4}$$

where S is the surface of the model, T_o is the thermal steady temperature without MW exposures. The first term of (4) represent the energy due to the metabolism increment caused by the temperature elevation. In the present study, this term is considered to be neglected, since this is caused secondary by the temperature elevation due to MW energy absorption or the second term.

For (4), we apply the following two assumptions: 1) the temperature distribution is assumed to be uniform over the body, ii) the SAR distribution is assumed to be uniform. Then, we obtained the following equation:

$$\begin{aligned}\left(T(t) - T_0\right)\cdot\rho_{WBave}\cdot V\cdot C_{WBave} &= \int_0^t SAR_{WBave}\cdot\rho_{WBave}\cdot Vdt \\ &- \int_0^t\left(T(t) - T_0\right)dt\cdot\left\{\int_S H(\vec{r})dS + \int_S sw(t)dS\right\}\end{aligned} \tag{5}$$

Table 1: Estimated Parameters Used In the Formula.

		Female	Male	
		22years	22years	3years
$\int_S H(\vec{r})dS$	[W/℃]	13.2	16.2	7.3
W	[kg]	54	69	15
C_{WBave}	[J/kg・℃]	3440	3510	3460

where $sw(t)$ is a coefficient based on $SW(\vec{r},t)$, since we applied that the temperature is assumed to be uniform. For the sweating rate given in [7], we obtained the following equation:

$$sw(t) = \left\{\begin{aligned}&\left[B_{11}\tanh\left(b_{11}\left(T(t) - T_0\right) - b_{10}\right) + B_{10}\right] \\ &\quad + \left[B_{21}\tanh\left(b_{21}\left(T(t) - T_0\right) - b_{20}\right) + B_{20}\right]\end{aligned}\right\} \times\left\{\left(0.58\times 4.2\times 10^3\right)/S\cdot 60\right\} \tag{6}$$

By differentiating the equation (13), the temperature rise is obtained as

$$T(t) = T_0 + \frac{W\cdot SAR_{WBave}}{\int_S H(\vec{r})dS + \int_S sw(t)dS}\left(1 - \varepsilon^{-\frac{\int_S H(\vec{r})dS + \int_S sw(t)dS}{W\cdot C_{WBave}}t}\right) \tag{7}$$

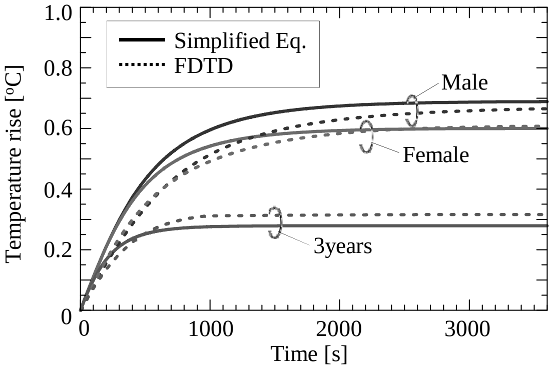
where W is the weight of the model [kg], SAR_{WBave} is the WBA-SAR[W/kg], H is the mean value of the heat transfer coefficient between the model and air [W/m^2 ^{o}C], C_{WBave} is the mean value of the specific heat [J/kg ^{o}C]. Table 1 lists the sets of parameters used in the present study.

IV. Computational Results

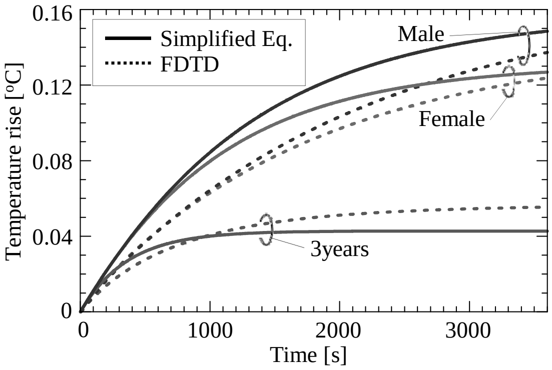
In this section, we discuss the effectiveness of the formula (7) derived in the above section. For this purpose, we chose three values of WBA-SAR; 4.0 W/kg which is said to induced core temperature rise of 1 ^{o}C [7], 0.4 and 0.08 W/kg which are the basic restriction for occupational exposure and public exposures [2, 3]. In this discussion, the frequency of MW is 1.5 GHz.

Fig. 1 shows the time evolution of core temperature rise for different WBA-SAR in adult male and female models, 3-year-old child model. From Fig.1, the time evolutions of the temperature rise less than a few minutes are in good agreement between FDTD-derived and estimated results for different models and WBA-SAR. On the other hands, some difference can be observed in the time course from a few minutes till getting the thermally-steady state. The main reason for this reason is attributed to our assumption that the temperature rise in the body is constant over the whole body. Note that the sweating rate is determined by the temperature rises in the skin and hypothalamus, although they are assumed to be the same as in (6).

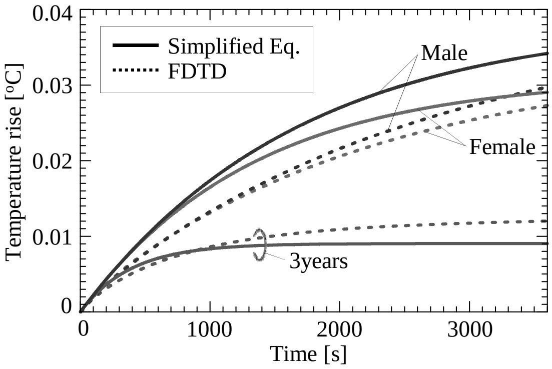
The temperature rise in the 3-year-old child estimated by (7) is obviously smaller than that computed by the FDTD method. This is because of its smaller thermal time constants than



(a)



(b)

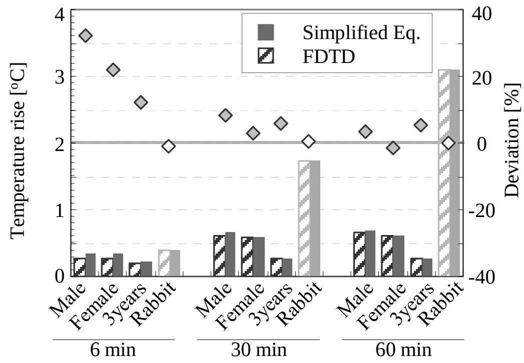


(c)

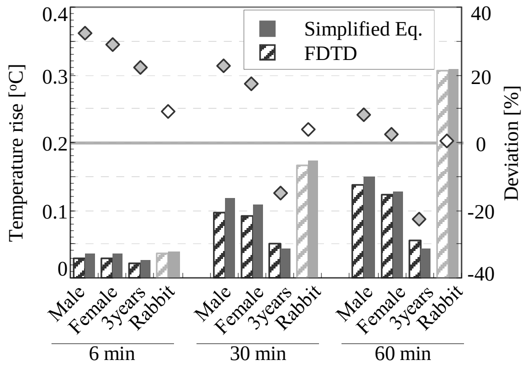
Fig. 1 Time course of core temperature rise at WBA-SAR of (a) 4 W/kg, (b) 0.4 W/kg, and (c) 0.08 W/kg.

other models. However, the time course of temperature rises between these two schemes roughly coincides with each other. The differences between two schemes at arbitrary time were within 30%. In particular, the formula (7) is effective for higher WBA-SAR inducing the temperature rise of 1°C or so, which is useful for the threshold of the guidelines/standards.

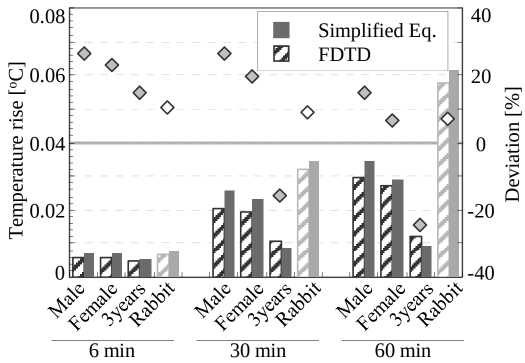
Fig.2 show the difference in the core temperature rises between FDTD results and results with (7). In Fig.2, the results computed for rabbits are also shown for comparison. Next, we discuss the effect of the frequency of MW on the temperature rise estimated with (7).In this discussion, we chose frequencies at respective resonance frequency and 1.5 GHz.



(a)



(b)



(c)

Fig. 2 Comparison of core temperature rise in different models for WBA-SAR of (a) 4.0 W/kg, (b) 0.4 W/kg, and (c) 0.08 W/kg.

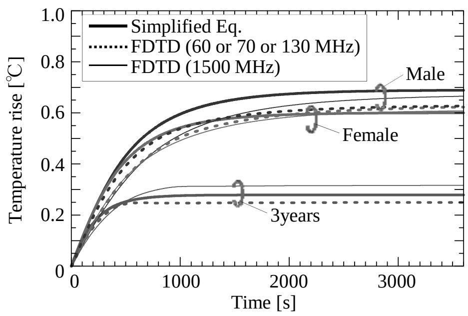


Fig. 3. Time course of core temperature elevation for different microwave frequencies.

The reason for this choice is that the WBA-SAR has two peaks for plane-wave exposure at the ICNIRP reference level; more precisely, it becomes maximal at 60 MHz and 1.5 GHz in the adult male phantom, 70 MHz and 1.5 GHz in the adult female phantom and 130 MHz and 1.5 GHz in the 3-year-old child phantom. The point to be stressed here is that the SAR distributions at these frequencies have been reported to quite different. When comparing with the results of rabbits, the difference between the FDTD results and estimated values is somewhat large, since the sweating in the rabbit is virtually nonfunctional. Then, the core temperature rise in the rabbit is larger than those in humans.

Figure 3 shows the time evolution of the core temperature rise at the WBA-SAR of 4.0 W/kg. From Fig. 3, the time course of the core temperature estimated with the formula and computed with the FDTD method are in better agreement with each other at respective resonance frequencies compared to those at 1.5 GHz. The reason for this is that the differences between core and skin temperature rises at resonance frequencies are smaller than those at 1.5 GHz, which is mainly caused by the SAR distribution. Therefore, the approximation of (6) is well applicable at resonance frequencies. For WBA-SARs of 0.4 and 0.08 W/kg, the maximum difference was less than 30% against the FDTD computed values, suggesting that the formula proposed in the present study is useful for different frequencies.

Finally, let us discuss the dominant factors influencing the core temperature elevation based on (7). In that formula, there exist the term associated with sweating in the coefficient and decaying factor of that equation. These facts suggested that the heat loss due to the sweating influences the steady-state core temperature rise and the thermal time constants. This is confirmed from the comparison of the core temperature rise between humans and rabbits whose sweating gland is virtually nonfunctional (see Figs. 2). This tendency can be confirmed from the results computed with the FDTD method.

The point to be stressed here is that the same formula (7) can be applied to humans with different ages and genders. The steady-state core temperature rise is governed by the body surface area-to-weight ratio. The similar conclusion can be said to the thermal time constant, since the specific heat does not depend on the human model with different genders and ages [7]. This can be confirmed from Figs.1 that the steady-state temperature rise and thermal time constant in the three-year-old child model are smaller than those of the adult models. Note that the body surface area-to weight ratio was 0.041 m^2/kg for adult male, 0.043 m^2/kg for adult female, and 0.060 m^2/kg for three-year-old child. The FDTD-computed results given in these figures support the discussion based on the simplified equation.

V. Summary

In the present study, we proposed a formula estimating the core temperature rise in the human models with the WBA-SAR. As a result, we found that core temperature rises are in reasonable agreement between the results from the formula and FDTD computation. In particular, we clarified the main factors influencing the core temperature rise as the body surface area-to-weight ratio and sweating rate, together with an applicable range of the formula.

Acknowledgments

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