35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Computation of Temperature Elevation in Fetus Due to Radio-Frequency Exposure with a New Thermal Modeling

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***Abstract*— The temperature elevation in the fetus is of concern for radio-frequency exposure. According to the IEC standard, the temperature elevation in the fetus should be lower than 0.5°C for exposure in magnetic resonance equipment. However, no previous study succeeded to simulate the temperature difference between the fetus and mother in the thermoneutral condition. The present study proposes a new thermal modeling for the pregnant woman model. The thermal modeling is then applied to the temperature variation for plane wave exposure at 80 MHz. From computational results, the core temperature in the fetus at the themoneutral condition was 37.5°C, which is 0.35 °C larger than that of the mother and coincident with measured data. When the pregnant woman model is irradiated by the plane wave with the whole-body averaged specific absorption rate of 2 W/kg for 1 hour, the temperature elevation in the fetus is 0.50 °C, which is larger than that in the mother by 0.11 °C.**

I. Introduction

There has been increasing public concern about adverse health effect due to electromagnetic exposure. As listed in the World Health Organization (WHO) high priority research [1], radio-frequency exposure of fetus is of interest. The dominant effect of radio-frequency field on the human is caused by the temperature elevation. It should be noted that the temperature elevation during magnetic resonance (MR) exposure should be smaller than 0.5°C according to the international standard [2]. Thus, the temperature elevation in the fetus due to radio frequency heating is of concern. In [3], the temperature elevation in the fetus for exposure in MR imaging was computed assuming that the blood temperature elevation in the mother and fetus is constant. However, the blood temperature elevation and thermoregulatory response cannot be neglected for the whole-body averaged specific absorption rate (SAR) larger than 0.4 W/kg [4]. Note that the threshold of whole-body averaged SAR in MR system is 2 W/kg [2, 5] with the static magnetic field of 1.5 T. In [6], the fetus temperature was calculated by considering the blood temperature variation based on [7]. The fetus temperature is concluded to be determined by the maternal blood temperature variation. The blood circulating in the fetus and its mother is, however, different. Then, the temperature in the fetus has been reported to be 0.3-0.5 °C higher than that in the mother in the thermoneutral condition [8, 9]. However, due to the above-mentioned assumption, the temperature difference between the fetus and its mother was not simulated in previous studies [3, 8]. In order to provide sufficient data for fetus protection from radio-frequency fields, the computational electromagnetic and thermal dosimetry are needed.

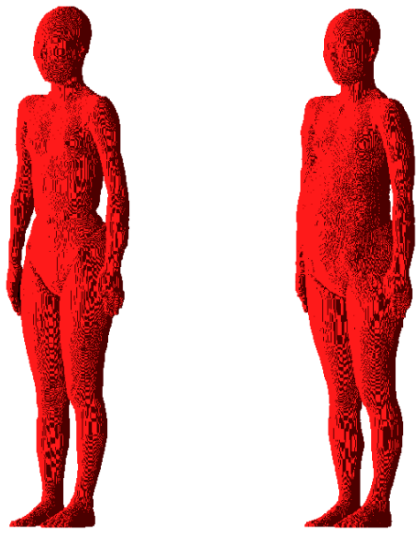

Fig. 1. Anatomically based adult female models with and without pregnancy.

The purpose of the present study is to propose a new thermal modeling in the pregnant woman model, in which the thermal exchange between the fetus and its mother in the placenta is taken into account. Then, the fetal and maternal temperature elevation for radio-frequency exposure is investigated. The computational results obtained herein are compared with those obtained in a previous modeling [6].

II. Models and Method

A. Numeric Human Models

Figure 1 illustrates the numeric Japanese women model with and without pregnancy [10]. The pregnant woman model is developed from the adult female model named HANAKO and segmented into 56 anatomic regions like skin, muscle, bone, brain, heart and so forth. The resolution of the model was 2 mm. The height and weight of the model are 1.60 m and 65 kg, respectively.

B. SAR Computations

The finite-difference time-domain (FDTD) method is used to calculate the electromagnetic power absorption in the human models [11]. The FDTD method is commonly used in the electromagnetic dosimetry for its capability to handle lossy dielectric medium like human body. The FDTD domain is discretized at 2 mm so as to coincide with the resolution of the human models. For geometries in which the wave-object

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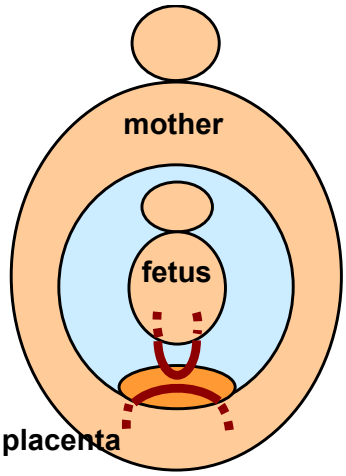


Fig. 2. Schematic explanation of heat exchange between the fetus and mother in the placenta. The heat exchange in the placenta is considered with (2) unlike previous modelings.

interaction has to be considered in open regions, the computational space has to be truncated by absorbing boundaries. The dielectric properties of tissues have been determined using the four Cole–Cole extrapolation [12]. The dielectric properties of fetus tissue are determined as in [3].

C. Temperature Computations

The temperature variation in the numeric human model was calculated by solving the bioheat equation [13], which is an equation modelling the thermodynamics in the human body. A generalized bioheat equation is given as:

$$C(\vec{r})\cdot\rho(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t} = \nabla\left(K(\vec{r})\cdot\nabla T\right) + A(\vec{r},t) - Q_b(\vec{r},t) \qquad (1)$$

where $T(\vec{r},t)$ is the temperatures of tissue and blood, C is the specific heat of tissue, ρ is the mass density of tissue, K is the thermal conductivity of tissue, A is the basal metabolism per unit volume.

Both the maternal and fetal blood exists in the placenta; the volume ratio of the maternal and fetal blood is 2:1 [14]. The schematic explanation is given in Fig. 2. To simulate this thermophysiology, we propose to introduce the following equations to represent the term Q_b:

$$Q_b(\vec{r},t) = \begin{cases} B(\vec{r},t)\cdot\left(T(\vec{r},t) - T_{bm}(t)\right) & ,\text{mother } (Q_{bm}(\vec{r},t)) \\ B(\vec{r},t)\cdot\left(T(\vec{r},t) - T_{bm}(t)\right) & ,\text{placenta} \\ \quad + B(\vec{r},t)\cdot\left(T(\vec{r},t) - T_{bf}(t)\right) & \\ B(\vec{r},t)\cdot\left(T(\vec{r},t) - T_{bf}(t)\right) & ,\text{fetus } (Q_{bf}(\vec{r},t)) \end{cases} \qquad (2)$$

where T_{bm} and T_{bf} are the blood temperature of the mother and fetus, respectively, B is a term associated with blood perfusion.

The boundary condition between air and tissue for (1) is expressed as:

$$-K(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t} = H(\vec{r})\cdot\left(T_s(\vec{r},t) - T_e(t)\right) + 40.6\cdot\left(SW(\vec{r},T_s(\vec{r},t)) + PI\right)/S \qquad (3)$$

where H, T_s and T_e denote the heat transfer coefficient, the body surface temperature and the air temperature, respectively. The heat transfer coefficient includes the convective and radiative heat losses. S is the surface area of the human body, SW [g min^{-1}] is the sweating rate, and PI, the insensible water loss, is 0.63 g min^{-1} for adults. The value of 40.6 is a coefficient for converting the unit [J min g^{-1} s^{-1}]. One of the main features in our computational modelling is that the temperature variation in the deep region can be tracked in addition to that in the shallow regions, unlike in conventional computational schemes. The blood temperatures of the mother and fetus are considered separately and vary according to the following equation, in order to satisfy the first law of thermodynamics [15]:

$$T_B(t) = T_{B0} + \int_t \frac{Q_{BTN}(t)}{C_B\rho_B V_B}\,\mathrm{d}t \qquad (4)$$

where T_B is blood temperature of the mother of fetus and T_{B0} is its initial blood temperature. Q_{BTN} is the net rate of heat acquisition of blood from the body tissues, C_B (= 4,000 J/kg·°C) is the specific heat of blood, ρ_B (= 1,050 kg/m^3) is the mass density and V_B is the total volume of blood. V_B is chosen to be 5,000 ml for the mother and 70 ml for the fetus [16].

The thermal constants of the human tissues are identical to those used in our previous study [7] except for those of the fetus tissue, which are taken from [3]. For the thermal parameters, basal metabolic rates in the mother and fetus are 1.4 W/kg and 3.8 W/kg, respectively, which are well within the measured/estimated values of 1.2 W/kg and 3.5-4.5 W/kg [8].

D. Thermoregulatory Response

The thermoregulatory response modeling used here was developed in our previous study [7]. Let us summarize that thermoregulatory response model. The sweating for the adult is modelled based on the formulas in [14]. The sweating rate SW [g min^{-1}] is assumed to depend on the temperature elevation in the skin and hypothalamus according to the equation:

$$SW(\vec{r},t) = \chi(\boldsymbol{r})[\{\alpha_{11}\tanh(\beta_{11}\Delta T_S - \beta_{10}) + \alpha_{10}\}\Delta T_S + \{\alpha_{21}\tanh(\beta_{21}\Delta T_H - \beta_{20}) + \alpha_{20}\}\Delta T_H] \qquad (5)$$

where T_s and T_H are the temperatures of the skin averaged over the body and hypothalamus, respectively. $T_{s,0}$ and $T_{H,0}$ represent set temperatures or upper critical temperature of thermoneutral condition. The dependency of the sweating rate on the body part was considered by introducing the multiplier $\chi(\boldsymbol{r})$ based on Table 2 in [14]. The coefficients of α and β are determined for the average sweating rate based on measurements [7]. In Eq. (5), these coefficients are α_{10}=1.20, α_{11}=0.80, α_{10}=0.19, α_{11}=0.59, β_{20}=6.30, β_{21}=5.70, β_{20}=1.03 and β_{21}=1.98.

$$SW(\vec{r},t) = \gamma(\boldsymbol{r})\chi(\boldsymbol{r})[\{\alpha_{11}\tanh(\beta_{11}\Delta T_S - \beta_{10}) + \alpha_{10}\}\Delta T_S + \{\alpha_{21}\tanh(\beta_{21}\Delta T_H - \beta_{20}) + \alpha_{20}\}\Delta T_H] \qquad (6)$$

For a temperature elevation above a certain level, the blood perfusion rate is increased in order to carry away the excess heat produced. The variation of blood perfusion rate in the

skin through vasodilatation is expressed in terms of ΔT_H and ΔT_S:

$$B(\boldsymbol{r},t) = (B_0(\boldsymbol{r}) + F_{HB}\Delta T_H(t) + F_{SB}\Delta T_S(t)) \cdot 2^{(T(\boldsymbol{r},t)-T_0(\boldsymbol{r}))/6} \quad (7)$$

where F_{HB}, and F_{SB} are the weighting coefficients of signal from the hypothalamus and skin, respectively. The coefficients of F_{HB} and F_{SB} in Eq. (8) were 17,500 $\mathrm{W/m^3/^oC^2}$ and 110 $\mathrm{W/m^3/^oC^2}$ [17]. Blood perfusion in all tissues except the skin was considered as constant, as is similar to [18].

E. Exposure Scenario

As an exposure scenario, the pregnant woman model is assumed to be standing in free space. As an incident wave, a plane wave with a vertical polarization is considered. The plane wave is incident on the body model from the front (along the anteroposterior direction). The frequencies of the electromagnetic wave are chosen as 80 MHz. At this frequency, the whole-body averaged SAR becomes maximal due to standing wave along the body height direction [19]. At that time, the SAR distribution around the fetus becomes maximal. The duration of exposure was chosen as 1 hour. This duration was chosen so as to be longer than the averaging time of 30 min considered in the ICNIRP guidelines [20] and the thermal time constant for the male with a smaller perspiration rate (40-50 min) in our previous study [21]. Note that the duration of MRI is at most 20 min [2].

III. Computational Results

For the thermoneutral condition (ambient temperature of 28ºC), together with a set of thermal parameters given in [7], the heat balance of the mother was maintained [21]. Then, the temperature in the pregnant woman model was calculated for these parameters to reach the thermally steady state. The maternal blood temperature was 37.16ºC while it was set as 37.0ºC for non-pregnant woman model. The fetal blood temperature was 37.41ºC, which is higher than that of the adult. This difference in the blood temperature is attributable to the basal metabolism of the fetus. When paying attention to the brain temperature as core temperature, the brain averaged temperature in the mother and fetus were 37.15ºC and 37.45ºC. The higher temperature in the fetus can also be confirmed from Fig. 3. This temperature difference is in good agreement with the clinical observed data of 0.3-0.5ºC [9]. Note that the difference was marginal (0.1 ºC) when using the modeling in [6].

For the whole-body averaged SAR of 0.4 W/kg and 2 W/kg, the temperature variation of maternal and fetal blood was investigated in Fig. 4. As seen from Fig. 4, the maternal and fetal temperature elevations at 1 h were identical at 0.05 ºC for whole-body averaged SAR of 0.4 W/kg. Thus the temperature difference between the mother and fetus is almost identical for the condition without exposure. For the whole-body averaged SAR of 2.0 W/kg, the maternal and fetal temperatures were 37.56 ºC and 37.91 ºC, respectively, Thus, their difference becomes 0.35 ºC, which is larger than that at the initial state of 0.21 ºC.

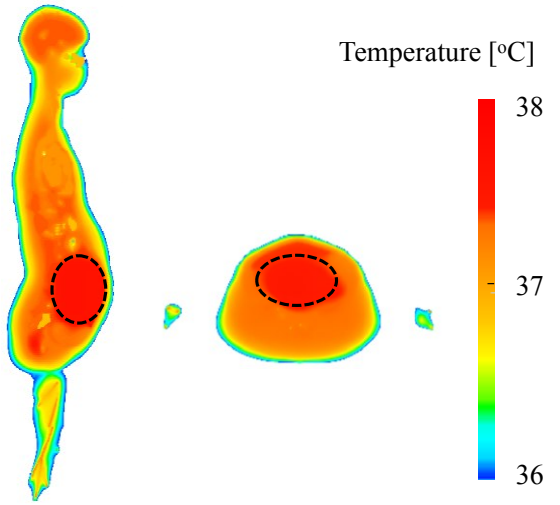
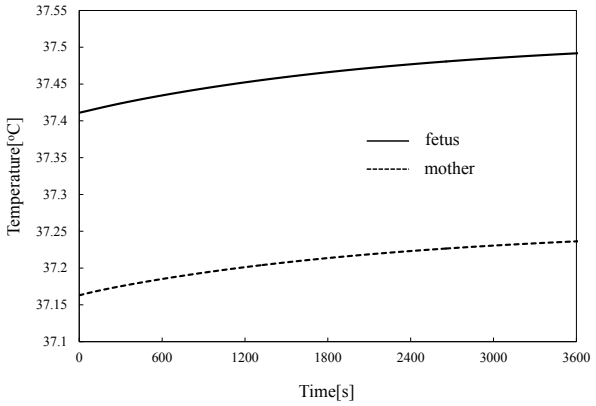
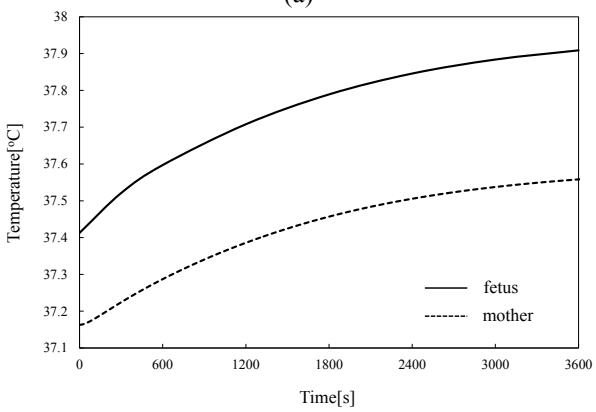


Fig. 3. Temperature distribution in the adult female model with pregnancy.



(a)



(b)

Fig. 4. Blood temperature variation in the fetus and mother for exposure at whole-body averaged SAR of (a) 0.4 W/kg and (b) 2.0 W/kg.

IV. Summary

The present study investigated temperature elevation in the fetus for radio-frequency exposure. First, a new thermal modeling in the pregnant woman model was proposed. The thermal modeling is then applied to the temperature variation

in the fetus and its mother for plane wave exposure at 80 MHz. From computational results, the temperature in the fetus was 37.5°C in the thermoneutral condition, which is larger than that of the mother by 0.35 °C and coincident with measured data. When the pregnant woman model is irradiated by the plane wave at 80 MHz with the whole-body averaged specific absorption rate of 2 W/kg for 1 hour, the temperature elevation in the fetus is 0.50 ºC, which is 0.11 ºC larger than that in the mother. This difference was not observed by the computational modeling presented in previous study [3, 6]; the core temperature elevation in the mother and fetus is the same when using the modeling in [6]. Even though computational results at different frequencies are not presented to avoid repetition, the temperature elevation in the fetus was higher than that in the mother.

Future research includes the investigation of the temperature elevation for exposure to the radio-frequency field in a realistic MR system.

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