Computational Analysis of SAR and Temperature Distributions
in Human Body Exposed to Microwave

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Abstract

The utilizations of microwave are used in many industrial and household applications because of the several advantages of the microwave heating source. There is concern about the human health from the leakage microwave because the high power in range several MW of industrial microwave can damage some tissues in human body. For many years, hyperthermia and the related radiometry have been a major subject of interest in investigating biological effects of microwave. The 2-D computational analysis is used to study the distributions of SAR and temperature increase on tissue organs in human body using the Finite Element Method (FEM), the SAR and temperature distributions of nine organs in human trunk are calculated. The influence of frequency, electromagnetic mode of propagation, power of heating source and time exposure are investigated. It is found that the maximum SARs and temperature increases are proportional to the power of heating sources. The low frequency of microwave can penetrates through the human body deeper than that of the high frequency. The microwave which is propagated different electromagnetic mode of propagation, TE and TM mode, cause the different SAR and temperature increase in human body at each frequency and power of heating source.

Keywords: computation, TE and TM mode, SAR, temperature increase, microwave

1. Introduction

Microwave is one of electromagnetic wave which has frequencies ranging from 300 MHz to 300 GHz. It is attractive over conventional to be heating source because the absorbed energy of microwave can be converted to thermal energy within the material volumetrically when it penetrates into the materials. The utilizations of microwave are used in many industrial and household applications such as heating process or drying process [1]. In recent years, these utilizations are increased rapidly because of the several advantages of microwave heating source [2]. There is concern about the human health from leakage microwave heating source because the high power in range

several MW of industrial microwave can damage some tissues in human body. The power absorption of microwave induces temperature increase on tissues in human body, the specific absorption rate (SAR) criteria has been used to obtain the dosimetric data and to gain further understanding of the biological tissue absorption characteristic in human body [3]. The temperature increase on tissues is one of the main tasks in the evaluation of the human risk related to the exposure of human body to microwave [4].

The computational analysis is used to study the distributions of SAR and temperature in human body because cannot measure these distributions directly to the alive human body. Most of previous studies of human body exposed to electromagnetic wave did not consider about heat transfer, resulting incomplete analysis. The earlier studies of heat transfer in human tissues used the general bioheat equation to investigate that [8]. Thereafter, coupled modeling of Maxwell's equation and bioheat equation were used to model the tissues in human body exposed to electromagnetic wave for explanation the electromagnetic wave propagation and heat transfer on tissues in human body. However, most studies of temperature increase induced by electromagnetic wave had not been considered in a realistic domain of the human body with complicated organs of several types of tissues.

In this paper, a two-dimensional human cross-sectional model which has nine types of tissue organs in human trunk composed of skin, fat, muscle, bone, large intestine, small intestine, bladder, stomach and liver is used to simulate the distributions of SAR and temperature on these tissues exposed to microwave, at frequency 915 MHz and 2450 MHz. Each frequency has high power of microwave heating source at 10 MW, 50 MW and 100 MW. Furthermore, the investigation of the maximum SAR and temperature on tissues due to particular transverse electromagnetic mode of wave propagation, transverse electric mode (TE mode) and transverse magnetic mode (TM mode) are compared.

2. Numerical Simulation

The governing equations of boundary conditions and subdomain settings in human body model are solved numerically using finite element method (FEM).

2.1 Human model

This research uses a two-dimension in *x-y* plane of human body model which is obtained by the image from K. Shiba and N. Higaki's work [5]. Fig.1 shows a side view cross sectional human body model in dimension 525 mm $\times$ 230 mm which composed of nine internal organs in human trunk such as skin, fat, muscle, bone, large intestine, small intestine, bladder, stomach and liver.
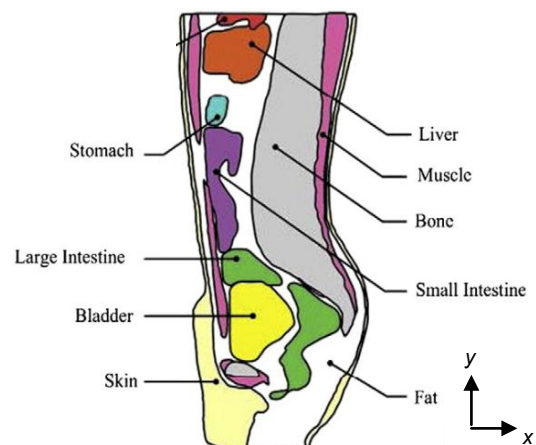

Figure1 Cross-sectional model of human body

The thermal properties of these internal organs are constant because they are slightly change of temperature distribution, the dielectric properties of tissue depend on frequency of electromagnetic wave which can be shown as table 1 and table 2 [2], where ρ , k , c , ω_b and ε_r are density (kg/m^3), thermal conductivity (W/m·K), specific heat (J/kg·K), blood perfusion rate (1/s) of tissues and relative permittivity (F/m), respectively.

Table 1 Thermal properties of internal organs

organs	ρ	k	c_p	ω_b
skin	1125	0.35	3437	2.00×10^{-2}
fat	916	0.22	2300	4.58×10^{-4}
muscle	1047	0.60	3500	8.69×10^{-3}
bone	1038	0.44	1300	4.36×10^{-4}
large intestine	1043	0.60	3500	1.39×10^{-2}
small intestine	1043	0.60	3500	1.74×10^{-2}
bladder	1030	0.56	3900	0.000
stomach	1050	0.53	3500	7.00×10^{-3}
liver	1030	0.50	3600	1.72×10^{-2}

Table 2 Dielectric properties of internal organs

organs	915 MHz		2450 MHz	
	σ	ε_r	σ	ε_r
skin	0.92	44.86	2.16	41.79
fat	0.09	5.97	0.13	5.51
muscle	1.33	50.44	1.60	46.40
bone	2.10	44.80	2.10	44.80
large intestine	2.04	53.90	2.04	53.90
small intestine	3.17	54.40	3.17	54.40
bladder	0.69	18.00	0.69	18.00
stomach	2.21	62.20	2.21	62.20
liver	1.69	43.00	1.69	43.00

2.2 Governing equations

2.2.1 Equation of microwave propagation

It is assumed that the microwave which leaks from industrial microwave heating source is propagated in x-direction and penetrates into the human body from front to back of human body as shown in Fig.1. To simplify the computational analysis, some of the following assumptions are used in this paper:

1. Microwave is plane wave.
2. Microwave interacts directly to human body in the open region.
3. The computational analysis is truncated by the scattering boundary condition.
4. The dielectric properties of tissues are constant.

The characteristic of microwave which propagate from the heating source to the human body is divided two transverse electromagnetic modes, TE and TM mode. The propagation of microwave in human body is calculated by Maxwell's equation [6]. The general forms of Maxwell's equation are simplified to demonstrate the electromagnetic fields of microwave penetrate in the human body as the following equations:

- Transverse Electric mode (TE mode)

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times E_z \right) - \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o} \right) k_o^2 E_z = 0. \quad (1)$$

-Transverse Magnetic mode (TM mode)

$$\nabla \times \left(\left(\frac{1}{\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}} \right) (\nabla \times H_z) \right) - \mu_r k_o^2 H_z = 0. \quad (2)$$

Where E_z and H_z are the electric field and the magnetic field intensity which propagate in z-direction, respectively, $\varepsilon_o = 8.8542 \times 10^{-12}$

F/m is the permittivity of free space, ε_r is the relative permittivity (F/m), μ_r is the relative magnetic permeability, σ is the electric conductivity (S/m), and $j = \sqrt{-1}$ is imaginary number.

2.2.2 Equation of heat transfer in human body

When the microwave penetrates into the human body, the energy of microwave is absorbed by the tissues. The temperature of the tissues will be increased due to the absorbed energy is converted to thermal energy. These temperature distributions inside the human model are obtained by Pennes' bioheat equation [7]. The transient bioheat equation effectively explains the phenomenon of heat transfer within the human body can be written as:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext}. \quad (3)$$

Where ρ is the internal organ density (kg/m^3), c is the heat capacity of internal organ (J/kg·K), k is the thermal conductivity of internal organ (W/m·K), T is the organ temperature (°C), T_b is the blood temperature (°C), ρ_b is the blood density before entering ablation region (kg/m^3), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolism heat source density (W/m^3) and Q_{ext} is microwave heat source density (W/m^3). It is equal to the resistive heat which is generated by microwave power absorbed, defined as

$$Q_{ext} = \frac{1}{2} \sigma_{tissue} |E|^2 . \quad (4)$$

Where $\sigma_{tissue} = 2\pi f \varepsilon_r' \varepsilon_o$ is the conductivity of tissue. In this analysis, the metabolism heat source (Q_{met}) is negligible and

heat conduction between organs and blood flow is approximated by the term $\rho_b C_b \omega_b (T_b - T)$.

2.2.3 Interaction of microwave and human tissues

Human tissues are generally lossy medium, microwave energy can be converted to thermal energy. When microwave propagates into these tissues, the energy of microwave will be absorbed. The specific absorption rate (SAR) of microwave energy in tissue is defined as a power dissipation rate normalized by tissue density. It is given by equation

$$SAR = \frac{\sigma}{\rho} |E|^2 \quad (5)$$

Where E is the root mean square electric field (V/m), σ is the conductivity (S/m) and ρ is the mass density of the tissue (kg/m^3).

2.3 Boundary Conditions

2.3.1 Boundary conditions for microwave propagation

The microwave radiation is emitted from the high power microwave heating source. It propagates in *x*-direction to strike in front of the human body and moves through the back. It is assumed that the human body is in the region extending farther than two wavelengths away from the source, far-field, and the microwave radiation propagate in lossless medium from the source to the body. Therefore, microwave radiation which strikes the human body is characterized by uniform plane wave with the power the same as source. The microwave port in the left boundary of considered domain has a specified power,

$$S = \frac{\int (E - E_1) \cdot E_1}{\int E_1 \cdot E_1}. \qquad (6)$$

For the boundary conditions along the interfaces between different medium such as air and tissue or tissue and tissue, they are considered as a continuity boundary condition,

$$n \times (H_1 - H_2) = 0. \qquad (7)$$

For the outer sides of the tissue boundaries are truncated as scattering boundary conditions,

$$n \times (\nabla \times E_z) - jkE_z = -jk(1 - k \cdot n)E_{oz}e^{-jk \cdot r} \quad (8)$$

2.3.2 Boundary conditions for heat transfer

The analysis of heat transfer is considered only in the human body domain, which is not including the surrounding space. The boundaries of human body which contact the air are considered as a thermal insulation, defined as,

$$n \cdot (k\nabla T) = 0. \qquad (9)$$

It is assumed that no contact resistance occurs between the internal organs in human body. Therefore, the boundary conditions of the internal organs are assumed to be a continuity boundary condition,

$$n \cdot (k_u \nabla T_u - k_d \nabla T_d) = 0 \qquad (10)$$

2.4 Initial condition for heat transfer

In this analysis, the temperature distribution inside human body is assumed to be uniform. The thermoregulation mechanisms and the metabolic heat generation of each tissue have been neglected to illustrate the clear temperature distribution. Therefore, the initial temperature of the human body is defined as

$$T(t_o) = 37 \;\; ^\circ\mathrm{C} \qquad (11)$$

3. Results and Discussions

In this research, the finite element method (FEM) is used to analyze the transient problem. The computational scheme is to assemble finite element model and to compute a local heat generation term by performing microwave calculation using tissue properties. The coupled mathematic models of heat transfer and microwave propagation is used to simulate SAR and temperature distributions on tissues in human body exposed to microwave which have two frequencies, 915 MHz and 2450 MHz, usually use in industries. The influence of frequency, mode of electromagnetic propagation, power of heating source and time exposure are investigated.

3.1 Verification of the model

This research is extended from the work of *T.Wessapan et.al* in 2011 [2], it was found that if the number of mesh elements were higher than 90,000 elements, the temperature of skin will be converged. To save the resources of computer and time to study, the suitable numbers of mesh elements which used in this study are 92,469 elements.

For validation of the models, it is difficult to measure SAR and temperature distributions directly to the alive human body. In order verify the accuracy of the models, the simulation results which used these models were compared with the numerical results from the same geometric models which were obtained by Nishizawa and Hashimoto [3]. It was shown that the maximum SAR of tissues which simulated between these model and Nishisawa models

were good agreement, the maximum difference was about 3.88%. This comparison lends confidence in the accuracy of these models to simulate SAR and temperature distributions in human body in this study.
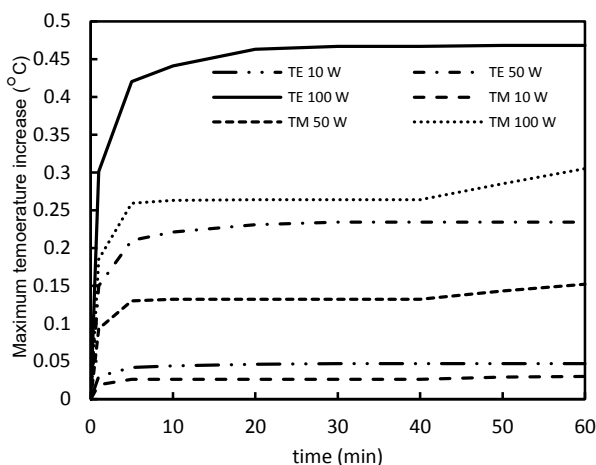
3.2 Time exposure of microwave

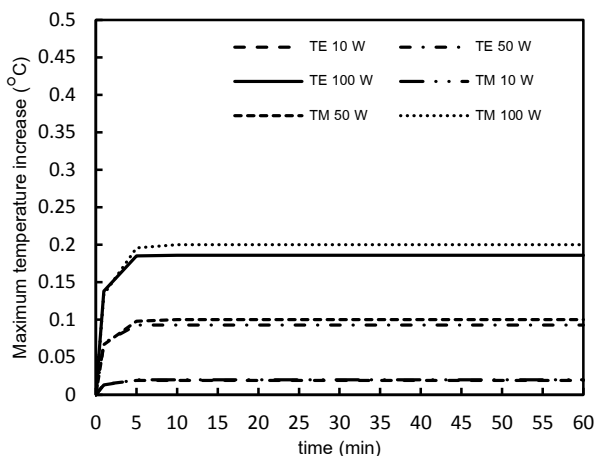**Figure 2** Maximum temperature increase on tissues in human body due to microwave at 915 MHz

Figure 3 Maximum temperature increase on tissues in human body due to microwave at 2450 MHz.

Figs. 2 and 3 shows the maximum temperature increases in human body exposed to microwave which are propagated in TE mode and TM mode at frequencies 915 MHz and 2450 MHz in various times. It is found that the

maximum temperature increases are steady after five minutes of exposure time. The maximum temperature increases at frequency 2450 MHz of TE and TM mode are little different at each power as shown in Fig.3, while the maximum temperature increases at 915 MHz of TE mode are higher than that of TM mode at each power as shown in Fig.2. The maximum temperature increases of 915 MHz are higher than that of 2450 MHz because the low frequency can penetrates into the medium better than that of high frequency, more absorbed energy which is converted to thermal energy. The temperature increases in human body of TE mode are higher than that of TM mode because the SAR distribution on tissues in human body from TE mode are higher that from TM mode as shown in Fig. 5.
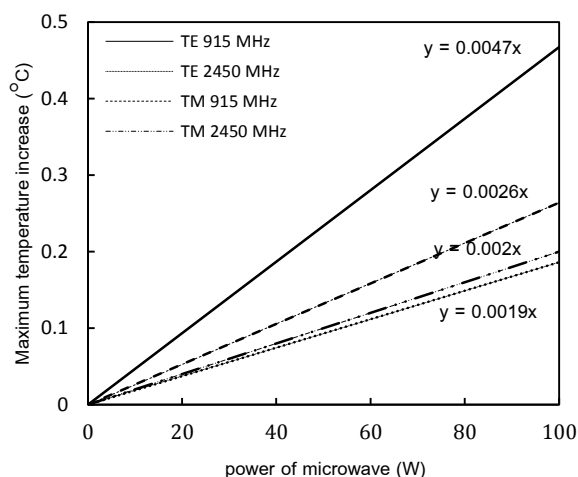
3.3 Power of microwave heating source

Figure 4 Maximum temperature increase on tissues of each microwave power.

It is found that from Figs. 2 and 3, the maximum temperature increases depend on power of heating source, frequency and mode of propagation. The maximum temperature

increases in various power at time exposure 20 minutes, steady state time, due to TE mode at 915 MHz is the most rapidly increase while TE and TM mode at 2450 MHz are slowly increase as shown Fig. 4.

3.4 SAR and temperature distributions

For the consideration of SAR and temperature distributions on tissues in human body exposed to microwave, the cases of time exposure 20 minutes and 100 W of heating source power are investigated. Fig. 5 shows the distribution of SAR on tissues, it is evident that the dielectric properties as shown in table 2 are significant on SAR distribution in human body due to microwave. The electric field of microwave is attenuated within the human body, the energy of microwave will be absorbed, the specific absorption rate of energy is given by Eq.5. The areas which have high value of SARs occur in the periphery region of the body, skin and fat. The maximum SARs on tissues are obtained from both of TE and TM mode at frequency 915 MHz, because of the penetration depth of microwave and dielectric properties of tissues.

Fig. 6 shows the temperature increases on tissues in human body at the same cases of the SAR consideration. It is found that the temperature increases are corresponding to the SAR distributions because the absorbed energy on tissues is converted to thermal energy. Although the SAR on the inner tissues are quite different from the periphery tissues of the body as shown in Fig.5, but the temperature increases are not quite different because the thermal energy can be transfer to the contiguous

tissues due to thermal conductivities as shown in table 1. The maximum temperature increases both of TE and TM mode are obtained from 915 MHz, 0.46°C for TE mode on fat and 0.26°C for TM mode on skin. At the frequency of 2450 MHz, the maximum temperature increases are 0.18°C on skin for TE mode and 0.20°C on skin for TM mode. These are much lower than the thermal damage temperature of tissues in human body within the range of 1-5°C.
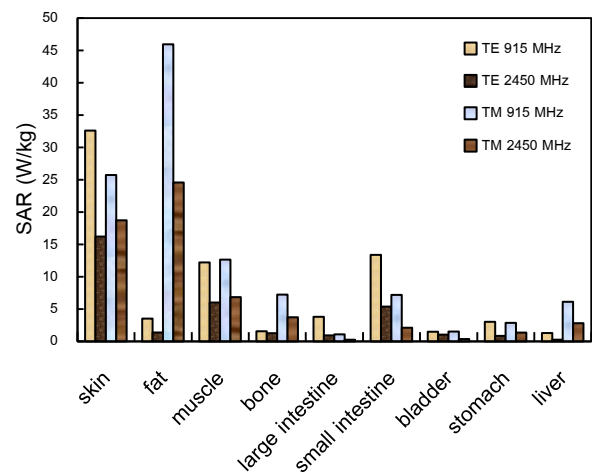

Figure 5 SAR distribution on tissues in human body exposed to microwave with power 100 W and time 20 minutes.
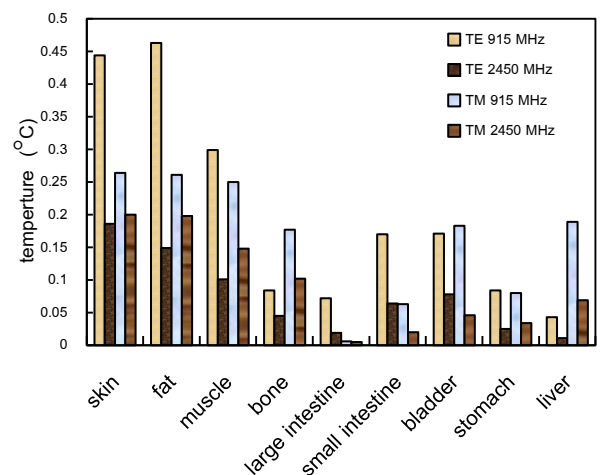

Figure 6 Temperature distribition on tissues in human body exposed to microwave with power 100 W and time 20 minutes.

4. Conclusions

This study presents the computational simulation SAR and temperature distributions on tissues in human body exposed to microwave at frequencies 915 MHz and 2450 MHz which are propagated in TE and TM mode. It is found that the maximum temperature increases in human body proportional to the power of heating source, at 915 MHz of TE mode is the most rapidly increase while both of TE and TM mode at 2450 MHz slowly increase. For the exposure time, SAR and temperature increase due to microwave are steady after five minutes. For SAR distributions, the maximum SAR occur at the periphery region of body, the inner tissues are higher SAR when exposed by lower frequency because it has high penetration depth. For temperature distribution, the maximum temperature increases occur at the periphery region of body but don't much different from the inner tissues because heat transfer from the tissues to the others.

5. Acknowledgement

6. References

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