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The influence of wave propagation mode on specific absorption rate and heat transfer in human body exposed to electromagnetic wave

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ABSTRACT

In recent years, the utilization of electromagnetic wave in various applications is increasing rapidly because of its advantages. There is concern about the human health due to electromagnetic wave because it can damage human tissue by damaging molecular structure which is interacted with this electromagnetic wave. In this study, the 2-D computational analysis is used to study the distribution of the specific absorption rate (SAR) and temperature on organs in human body exposed to electromagnetic wave which are propagated from source in Transverse Electric mode (TE mode) and Transverse Magnetic mode (TM mode). The mathematical models consist of a coupled electromagnetic wave equation and bioheat equation. In numerical simulation, these coupled mathematical models are solved by using a finite element method (FEM) with thermal and dielectric properties to describe SAR and temperature distributions in the human body. The effects of wave propagation mode, operating frequency, radiated power of electromagnetic wave and exposure time are systematically investigated. This study focuses attention on organs in the human trunk. It is found that the maximum SAR on organs exposed to electromagnetic wave which are propagated in TM mode is higher than that of TE mode for all organs and frequencies of electromagnetic wave. The electromagnetic wave at the frequency of 300 MHz propagated in TM mode is the most significant exposure condition to produce the maximum SAR and temperature increase in fat. Moreover, the maximum SAR and temperature increase are proportional to the power of heating source. The lower frequency of electromagnetic wave has an ability to penetrate through the human body deeper than that of the high frequency.

1. Introduction

Electromagnetic wave is a one heat source that is an attractive alternative over conventional heating methods because electromagnetic wave in range of microwave that penetrates the surface is converted into thermal energy within the material. The utilizations of electromagnetic wave have been used in many industrial and household applications such as heating process or drying process. In recent years, these utilizations are increasing rapidly because of the several advantages of electromagnetic wave heating source such as high speed start up, selective energy absorption, instantaneous electric control, no pollution, high energy efficiency and high product quality [1,2]. Rapid development of electromagnetic energy applications causes an increase in public concern about health risks from electromagnetic energy emitted from various sources [5–8]. The power absorption of electromagnetic wave induces temperature increase on organs in the human body. The specific absorption rate (SAR) criteria have been used to obtain the dosimetric data and to gain further understanding of the biological tissues absorption characteristic of the human body [9]. The temperature increase of organs is one of the main tasks in the evaluation of the human risk related to the exposure to the human body to electromagnetic wave [10].

The computational analysis is used to study the distributions of SAR and temperature in human body because these distributions cannot be measured directly to the alive human body due to ethical consideration. In present day, the experimental data on the correlation of SAR levels to the temperature increase on organs in the human body are still sparse. Most previous studies of a human body exposed to an electromagnetic wave did not consider heat transfer cause an incomplete analysis to result. The earlier studies of heat transfer in human tissues used the general bioheat equation to investigate that [13]. Thereafter, coupled model of Maxwell's equation and bioheat equation were used to model human tissues exposed to electromagnetic wave to explain the electromagnetic wave propagation and heat transfer in tissues in the human body. There are some research have been studied temperature distribution over the surface and various biotissues exposed to electromagnetic wave [14-19]. Nishizawa et al. simulated SAR

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Nomenclature

c_p	specific heat capacity (J/kg K)
E	electric field intensity (V/m)
H	magnetic field intensity (A/m)
f	frequency of microwave (Hz)
k	thermal conductivity (W/m K)
n	refractive index
Q	heat (W/m^3)
s	poynting vector (W/m^2)
t	time (s)
T	temperature (°C)
v	velocity of propagation (m/s)
$\tan\delta$	dielectric loss coefficient

Greek letters

ε	permittivity (F/m)
ε_r	dielectric constant of tissue
μ	permeability (H/m)
ρ	density (kg/m^3)
σ	electric conductivity (S/m)
ω	perfusion rate (1/s)

Subscripts

b	blood
ext	external
met	metabolism

distributions of skin, fat and muscle tissues in human body with three-layer physical model [9]. Keangin et al. studied heat transfer in liver tissue for liver cancer treatment using microwave coaxial antenna [3,4]. However, most studies of temperature increase induced by electromagnetic wave have not been considered in a realistic domain of the human body with complicated organs of several types of tissues. Our research group has tried to numerically investigate the temperature increase in human tissue subjected to electromagnetic fields in many problems, such as Wessapan et al. studied SAR and temperature distributions in the human head and the human eye due to mobile phone radiation at several frequencies [6,7]. Moreover, they used the human body model which has 10 organs in the human trunk to simulate the SAR and heat transfer in these organs exposed to electromagnetic wave at frequencies of 915 MHz and 2450 MHz which are characterized propagation in TE mode [5], and studied the effects of dielectric shield on SAR and temperature increase in the human body at the frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz [8]. However, these works were not considered these effects on organs when the electromagnetic wave propagated from source in different propagation mode.

The work described in this paper is substantially extended from our previous work [6] by further puts the focus on the effects of wave propagation mode, operating frequency, radiated power of electromagnetic wave and exposure time. In this paper, a 2-D human cross section model [11] is used to simulate the distribution of SAR and temperature in these organs exposed to electromagnetic wave. There are four frequencies of electromagnetic wave in range of microwave at 300 MHz, 915 MHz, 1300 MHz and 2450 MHz are chosen to simulate these distributions because the energy of these frequencies can be converted to thermal energy. Each frequency has radiated power of 10 W, 50 W and 100 W. Furthermore, the comparison of biological effects on organs due to particular mode of electromagnetic wave propagation, TE mode and TM mode, are considered. The Maxwell's equation and the bioheat equation are used to investigate electromagnetic wave propagation and heat transfer on organs exposed to electromagnetic wave, respectively. The obtained values provide an indication of limitations that must be considered for temperature increases due to localized electromagnetic wave energy absorption.

2. Numerical simulation

Most of industrial electromagnetic wave heating systems generate high power electromagnetic wave to use in various applications such as industrial microwave system as shown in Fig. 1. The leakage electromagnetic wave from the heating source can cause significant thermal damage on sensitive organs within the human body. Therefore, to approach reality, it is necessary to investigate the temperature distribution on organs in the human trunk due to the leakage electromagnetic wave. It is assumed that the propagation of electromagnetic wave is uniform plane wave. For ethical consideration, it is difficult to measure these distributions directly to the alive human body. The computational analysis is selected to investigate the distributions of SAR and temperature in human body. The system of governing equations as well as initial and boundary conditions are solved numerically using the finite element method (FEM) via COMSOL™ Multiphysics to demonstrate the phenomenon occurs within the human body exposed to electromagnetic wave.

2.1. Human model

Fig. 2 shows the 2-D human body model which is used in this study is obtained by image processing technique from the work of *Shiba* and *Higaki* [11]. The side view cross section through the middle plane of the human trunk model has a dimension of 400 mm in width and 525 mm in height which composes of nine internal organs in human trunk which are skin, fat, muscle, bone, large intestine, small intestine, bladder, stomach and liver. These organs have different dielectric and thermal properties. The thermal properties of tissues are given in Table 1 and the dielectric properties of tissues at the frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz are given in Table 2. The thermal properties of these tissues are constant because there are only a slight change of temperature is noticed along the exposure time.

2.2. Equation of electromagnetic wave propagation analysis

The mathematical models are developed to predict SAR and temperature distributions within the human body exposed to electromagnetic wave. It is assumed that electromagnetic wave leaks from industrial electromagnetic wave heating system. This electromagnetic wave propagates 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. It is assumed that the electromagnetic wave is plane wave.
2. The human body in which electromagnetic wave interact with human proceeds in free space.
3. The free space is truncated by scattering boundary condition.
4. The dielectric properties of tissues are uniform and constant.

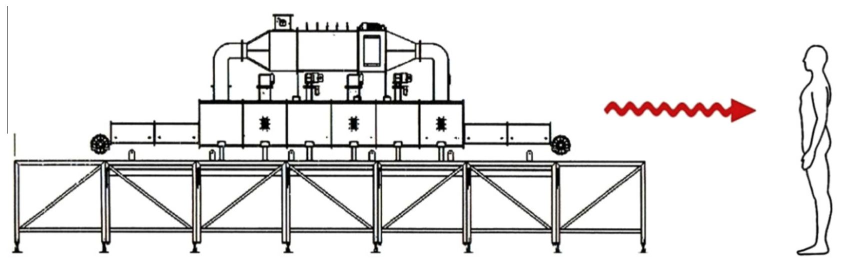

Fig. 1. The leakage electromagnetic wave from the industrial microwave.

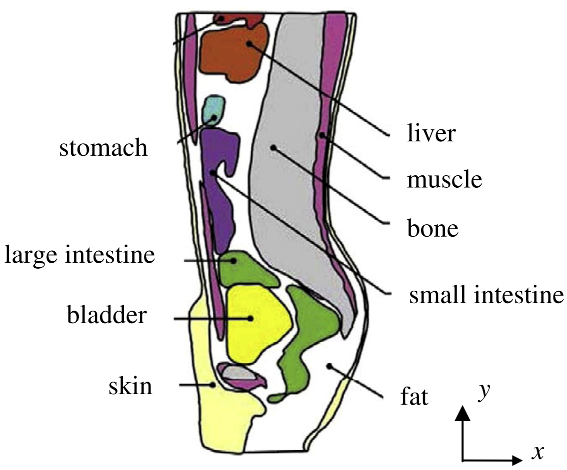

Fig. 2. Cross sectional model of human body.

Table 1
Thermal properties of tissues [8].

Organs	ρ (kg/m^3)	K (W/m K)	c (J/kg K)	ω_b (1/s)
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}

2.2.1. Governing equations

In this study, the two propagation characteristic of electromagnetic wave which leaks from electromagnetic wave heating system to the human body is assumed in two circumstances: (i) TE mode and (ii) TM mode. The induced biological effects on organs in human body due to the two propagation modes of electromagnetic wave are compared. The propagation of electromagnetic wave in human body is calculated by Maxwell's equation [12], which mathematically describes the interdependence between electric and magnetic fields. The general forms of Maxwell's equation are simplified to the following expressions:

- Transverse Electric mode (TE mode) [5,8]

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

- Transverse Magnetic mode (TM mode)

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

where $\varepsilon_o = 8.8542 \times 10^{-12}$ F/m is the permittivity of free space and $j = \sqrt{-1}$ is imaginary number.

2.2.2. Boundary conditions

The electromagnetic wave is emitted from the high power electromagnetic wave heating system and leaks to the environment. It propagates in x-direction to strike in front of the human body and moves through the back. It is assumed that the electromagnetic wave which strikes the human body is characterized by uniform plane wave with the power the same as source. Fig. 3 shows an electromagnetic wave propagation port in the left boundary of considered domain with a specified power,

$$S = \frac{\int^{(E-E_1)} \cdot E_1}{\int_1^E \cdot E_1}. \tag{3}$$

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

$$n \times (H_1 - H_2) = 0. \tag{4}$$

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

Table 2
Dielectric properties of tissues [8].

Organs	300 MHz		915 MHz		1300 MHz		2450 MHz	
	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r
Skin	0.35	48.41	0.92	44.86	1.25	43.56	2.16	41.79
Fat	0.06	6.55	0.09	5.97	0.10	5.80	0.13	5.51
Muscle	1.08	55.45	1.33	50.44	1.42	48.96	1.60	46.40
Bone	2.10	44.80	2.10	44.80	2.10	44.80	2.10	44.80
Large intestine	2.04	53.90	2.04	53.90	2.04	53.90	2.04	53.90
Small intestine	3.17	54.40	3.17	54.40	3.17	54.40	3.17	54.40
Bladder	0.69	18.00	0.69	18.00	0.69	18.00	0.69	18.00
Stomach	2.21	62.20	2.21	62.20	2.21	62.20	2.21	62.20
Liver	1.69	43.00	1.69	43.00	1.69	43.00	1.69	43.00

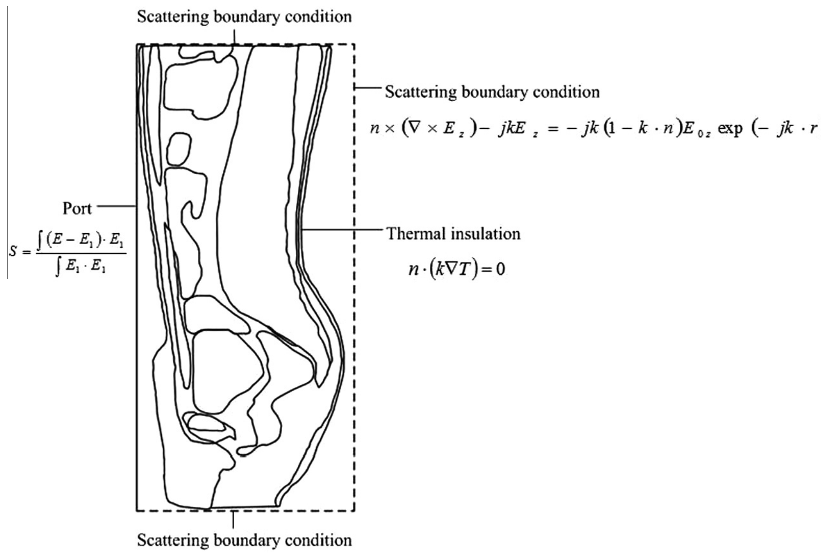

Fig. 3. Boundary conditions for electromagnetic wave propagation and heat transfer.

$$n \times (\nabla \times E_z) - jkE_z = -jk(1 - k \cdot n)E_{oz}e^{-jk\cdot r} \tag{5}$$

2.3. Equation of heat transfer in human body

To solve the thermal problem, the temperature distribution in the human body has been evaluated by the bioheat equation according to Maxwell's equations. The temperature distribution corresponds to the SAR. This is because the SAR within the human body distributes, owing to energy absorption. Thereafter, the absorbed energy is converted to thermal energy, which increases the organs temperature. Heat transfer analysis of the human body is modeled in two dimensions. To simplify the problem, the following assumptions are made:

1. Human organ is bio-material with uniform and constant thermal properties.
2. There is no phase change of substance within the organ.
3. There is no energy exchange throughout the human model.
4. There is no chemical reaction within the organ.

2.3.1. Governing equations

The energy of electromagnetic wave is absorbed by tissue organs, when it penetrates into the human body. The temperature of tissues in human body will be increased, according to the absorbed energy is converted to thermal energy. These temperature distributions inside the human model are obtained by Pennes' bioheat equation as Eq. (3). The transient bioheat equation effectively explains the phenomenon of heat transfer within the human body, it can be written as [13]:

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext}. \tag{6}$$

where ρ is the organ density (kg/m^3), C is the heat capacity of organ (J/kg K), k is thermal conductivity of orgas (W/m K), T is the organ temperature (°C), T_b is the temperature of blood (°C), ρ_b is the density of blood (kg/m^3), C_b is the specific heat capacity of blood (J/kg K), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolism heat source (W/m^3) and Q_{ext} is the external heat source term (electromagnetic wave heat-source density) (W/m^3).

In this analysis, the metabolism heat source is negligible, heat conduction and blood flow in each organ is approximated by the term $\nabla \cdot (k\nabla T)$ and $\rho_b C_b \omega_b (T_b - T)$, respectively. For the external heat source, Q_{ext}, this analysis is electromagnetic wave heat source density (W/m^3). It is equal to the resistive heat which is generated by the electromagnetic wave power absorbed, which is defined as

$$Q_{ext} = \frac{1}{2}\sigma_{organ}|E|^2 \tag{7}$$

where $\sigma_{organ} = 2\pi f \varepsilon_r' \varepsilon_o$.

2.3.2. Boundary conditions

Heat transfer is considered only in the human body domain, which is not including the surrounding space. The boundary of human body which contacts the air is considered to be a thermal insulation boundary condition, defined as,

$$N \cdot (k\nabla T) = 0. \tag{8}$$

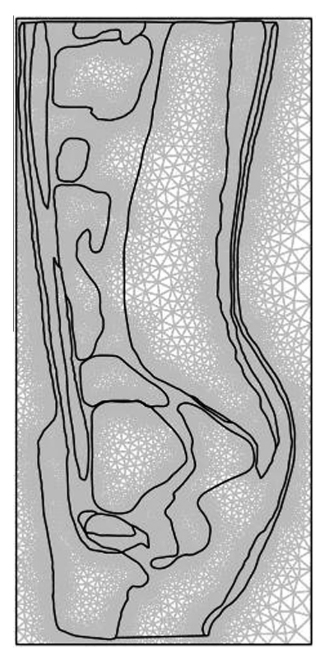

Fig. 4. An initial two-dimensional finite element mesh of human cross section model.

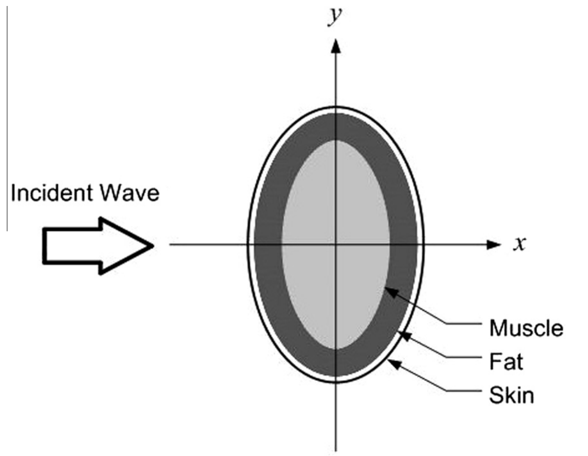

Fig. 5. Geometry of the validation model obtained from the paper [5].

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 continuous.

$$n \cdot (k_u \nabla T_u - k_d \nabla T_d) = 0. \quad (9)$$

2.3.3. Interaction of electromagnetic wave and human organs

Human organs are generally lossy mediums for electromagnetic wave with finite electric conductivity. When electromagnetic wave propagates into these organs, the energy of electromagnetic wave propagation is absorbed by the tissue. SAR of electromagnetic wave energy in organ is defined as a power dissipation rate normalized by organs density [8], which is given by the following equation:

$$\mathrm{SAR} = \frac{\sigma}{\rho}|E|^2. \quad (10)$$

2.3.4. Initial condition for heat transfer

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

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

Table 3
Comparison of the results obtained in the present work with those of Nishizawa and Hashimoto.

Power (W)	Present work	Published work [9]	% difference
SAR_{max} in skin	0.212	0.220	3.63
SAR_{max} in fat	0.198	0.206	3.88
SAR_{max} in muscle	0.116	0.120	3.33

2.3.5. Penetration depth

The penetration depth (D_p) is defined as the distance within material at which the electromagnetic wave density has decreased to 37% of its initial value at the surface [8]:

$$D_p = \frac{1}{\frac{2\pi f}{v}\sqrt{\frac{\varepsilon_r'\left(\sqrt{1+(\tan)^2}-1\right)}{2}}} \quad (12)$$

where ε_r' is the relative dielectric constant, tan δ is the loss tangent which provides an indication of how well the material can be penetrated by an electrical field and how it dissipates electrical energy as heat, and υ is the speed of electromagnetic wave (m/s).

The penetration depth of the electromagnetic wave which penetrates within the material is calculated using Eq. (12), which shows how it depends on the dielectric properties of the dielectric material and frequency of electromagnetic wave. It is shown that the penetration depth is greatly dependent on the frequency of electromagnetic wave, it will be increased if the frequency of electromagnetic wave is decrease.

2.4. Simulation procedure

The finite element method is used to analyze the transient problems. The computational scheme is to assemble a finite element model and compute a local heat generation term by performing an electromagnetic calculation using organ properties. In order

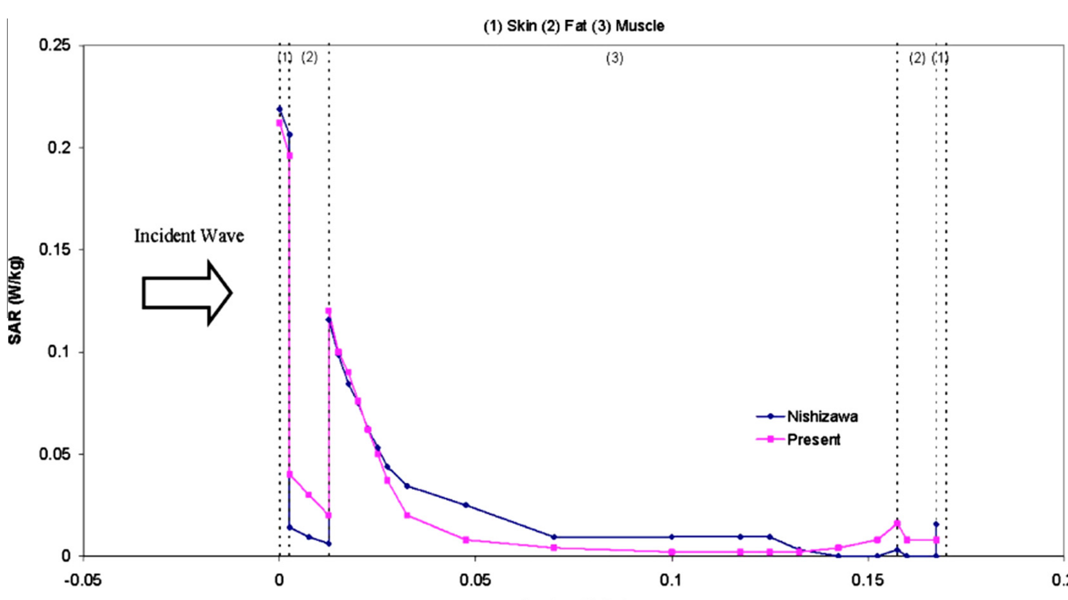

Fig. 6. Comparison of the calculated SAR distribution to the SAR distribution from the paper [5].

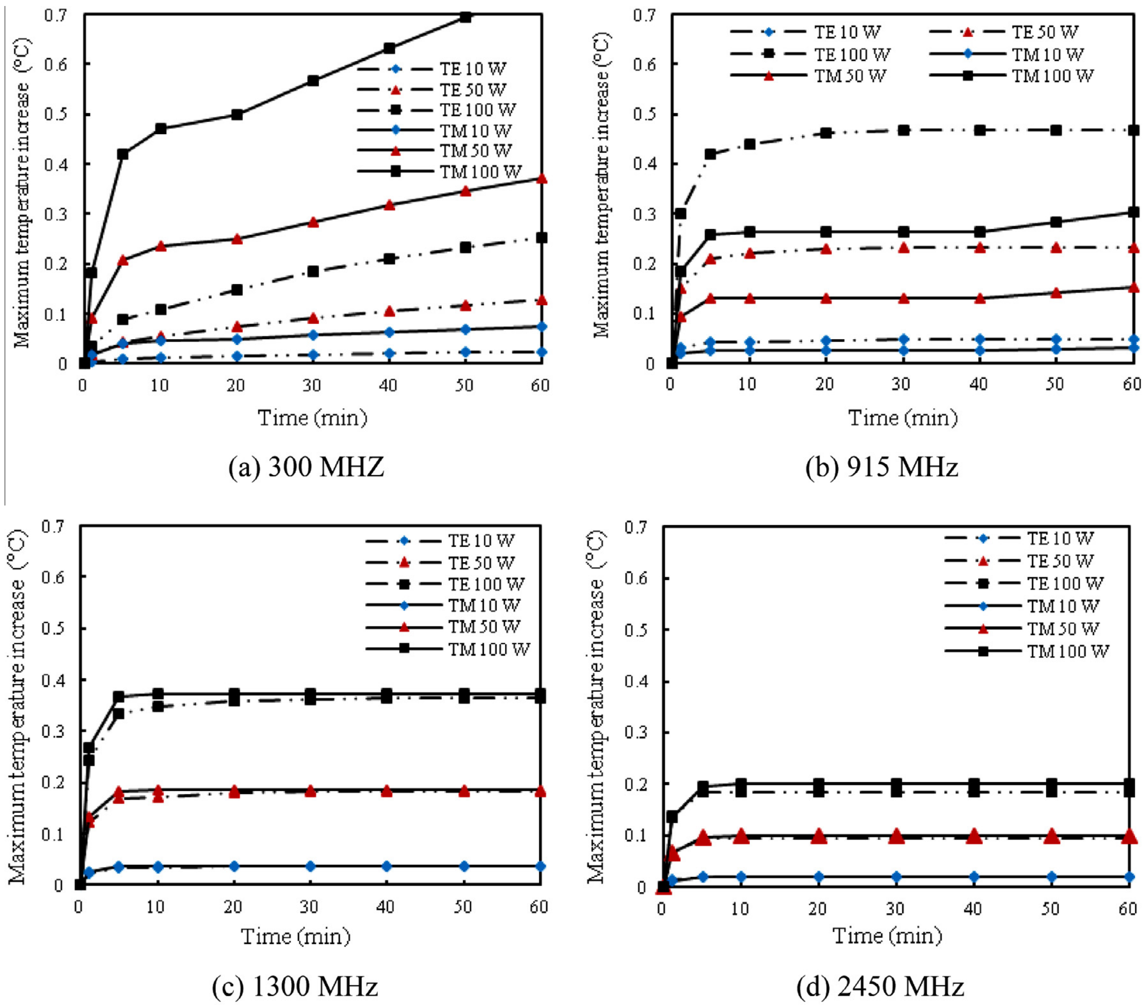

Fig. 7. The maximum temperature increase on organs in human body due to electromagnetic wave at frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz in various exposure time.

to obtain a good approximation, a fine mesh is specified in the sensitive areas. This study provides a variable mesh method for solving the problem as shown in Fig. 4. The model of bioheat equation and Maxwell's equation are solved. All computational processes are implemented using COMSOL™ Multiphysics, to demonstrate the phenomena that occur within the human body exposed to electromagnetic fields. The electromagnetic power absorption at each point is computed and used to solve the time-dependent temperature distribution. All steps are repeated, until the required exposure time is reached. The 2-D model is discretized using triangular elements and the Lagrange quadratic is used to approximate temperature and SAR variation across each element. Convergence tests are carried out to identify a suitable number of elements required. The convergence test leads to a grid with approximately 90,000 elements. It is reasonable to assume that, with this element number, the accuracy of the simulation results is independent of the number of elements and therefore save computation memory and time.

3. Results and discussions

The coupled mathematic models of heat transfer and electromagnetic wave propagation is used to simulate SAR and temperature distributions on organs in human body exposed to electromagnetic wave which have four frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz. The influence of wave propagation mode, operating frequency, and radiated power of the electromagnetic wave source are systematically investigated.

3.1. Verification of the model

It must be noted in advance that it is not possible to make a direct comparison of the model in this study and the experimental results. In order to verify the accuracy of the present numerical model, the simple case of the simulated results is then validated against the numerical results with the same geometric model obtained by *Nishizawa* and *Hashimoto* [9]. The horizontal cross section of three-layer human tissues as shown in Fig. 5 is used in the validation case. In the validation case, the leakage power density exposed to the electromagnetic frequency of 1300 MHz is 1 mW/cm^2. The results of the selected test case are illustrated in Fig. 6 for SAR distribution in the human body. Table 3 clearly shows good agreement in the maximum value of the SAR of tissues between the present solution and that of *Nishizawa* and *Hashimoto*. This favorable comparison lends confidence in the accuracy of the present numerical model. It is important to note that there may be some errors occurring in the simulations that are generated by the input dielectric properties and the numerical scheme.

It is shown that the maximum SAR of organs calculated in the present study and Nishisawa's models are in good agreement, the

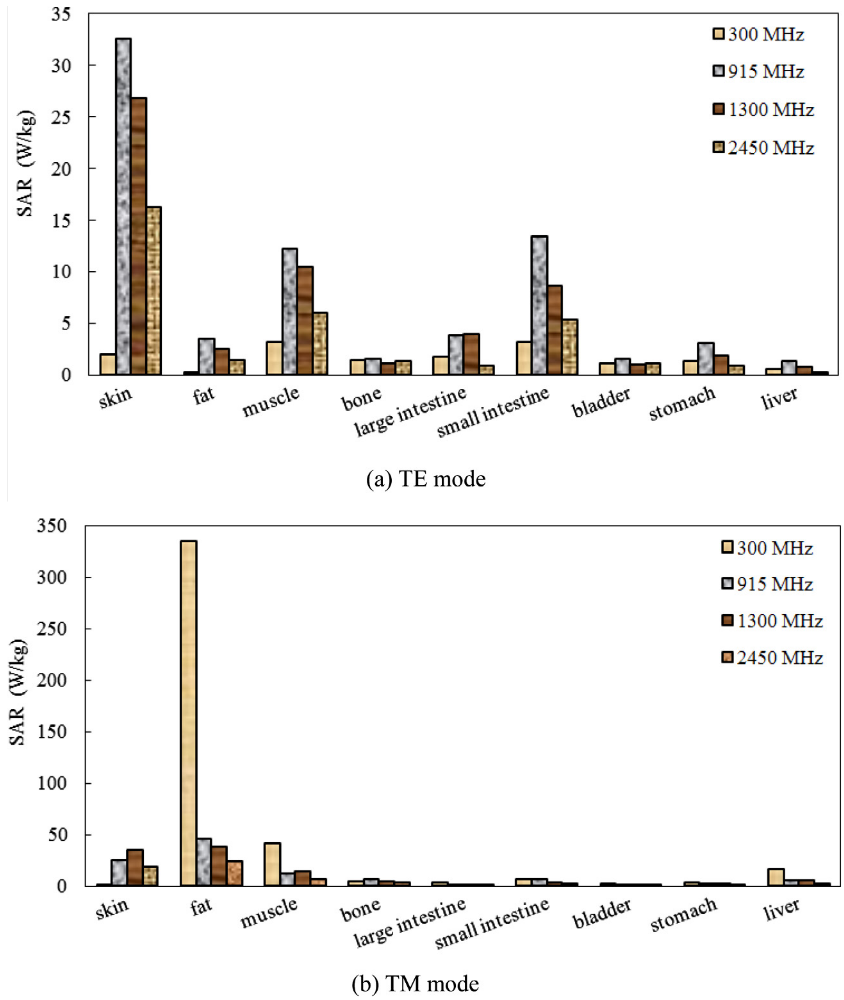

Fig. 8. SAR distribution on organs in human body exposed to electromagnetic wave which are propagated in (a) TE mode and (b) TM mode at power 100 W and exposure time 20 min in various frequencies.

maximum difference is 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. Influence of exposure time of electromagnetic wave

Fig. 7 shows the maximum temperature increases in human body exposed to electromagnetic wave propagation in TE and TM mode plane wave at the frequency of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz in various exposure times. It is found that the maximum temperature increases in the human body at these frequencies are approach to steady state after five minutes of exposure time, except for the frequency of 300 MHz from both of propagation mode, the temperature is rising continuously. This is because the high penetration depth of the 300 MHz frequency causes localizing thermal runaway in deep organs which is shown in Eq. (12). The SAR distributions at low frequency are higher than that of high frequency, but at 300 MHz has low SAR value because its penetration depth is too high compared to that of other frequencies. The electromagnetic wave can penetrate into the human body and the absorbed energy is distributed in each organ of the human body as shown in Fig. 8.

The maximum temperature increases at the high frequency of 1300 MHz and 2450 MHz for both TE and TM mode propagation have a very similar distribution trend at each radiated power as shown in Fig. 7(c) and (d). This is because in this frequency range they have low penetration depth of the electromagnetic wave into the human body. While at the low frequency of 300 MHz, the maximum temperature increases in case of TM mode, is higher than that of TE mode. This is because the resonance of standing wave is becoming a dominant phenomenon in the fat (which will be discussed later). The energy of this resonance ability to be absorbed in the fat, thereafter, it is converted to thermal energy and its transfer to other organs. This phenomenon causes significant high temperature increase within organs.

At the frequency of 915 MHz, it is illustrated the different behavior of the maximum temperature increases to the frequency of 300 MHz. It is found that the temperature increases of TE mode are higher than that of TM mode. This is because the maximum SAR obtained from TE mode occurred in the skin, is very different from fat as shown in Fig. 8(a). Therefore, a significant amount of thermal energy transfers from skin to fat. It is found that the maximum temperature occurs in the fat because it has low thermal conductivity and low blood perfusion rate. While the maximum SAR obtained from TM mode occurs in the fat, but not much different from the contiguous organs. This is because thermal energy spread out from fat to these organs. Thus, the maximum temperatures of organ in human body exposed to electromagnetic wave at 915 MHz of TM mode are lower than that of TE mode.

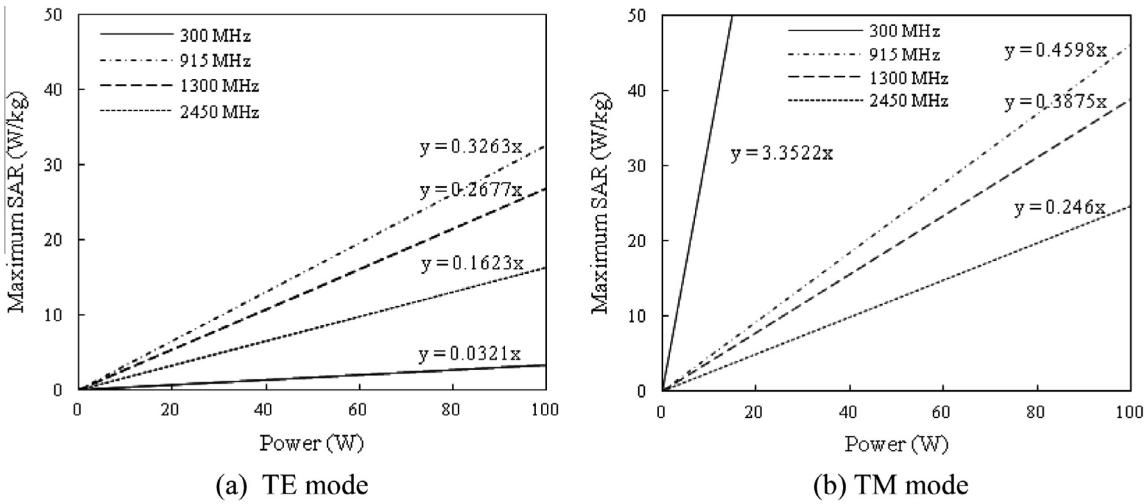

Fig. 9. The maximum SAR on organs of each electromagnetic wave power of heating source which are propagated in (a) TE mode and (b) TM mode.

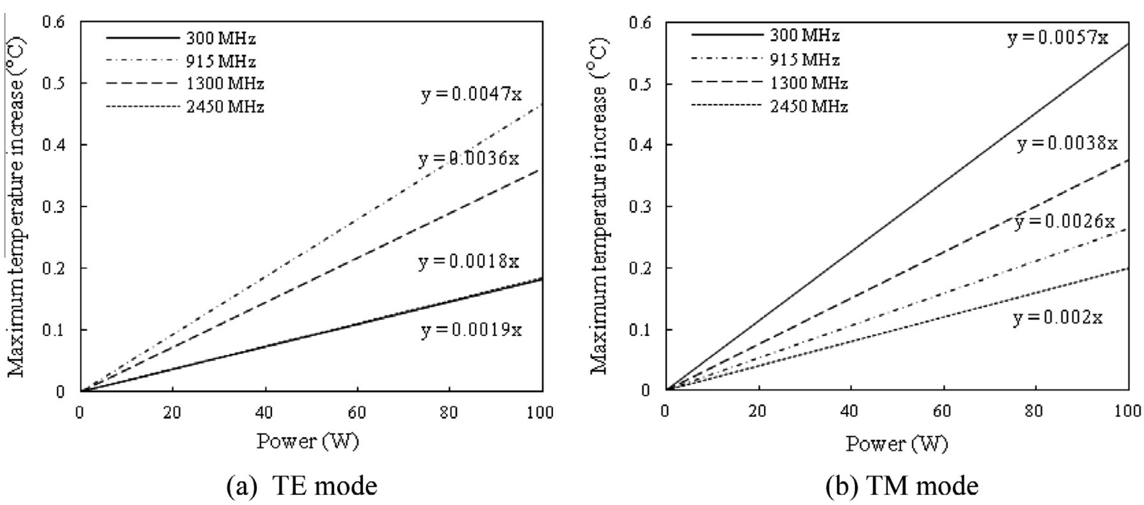

Fig. 10. The maximum temperature increase on organs of each power of heating source which are propagated in (a) TE mode and (b) TM mode.

3.3. Influence of the power of electromagnetic wave

The relation between the maximum SAR and electromagnetic wave radiated power which is propagated in TE and TM mode is shown in Fig. 9. The exposure times at 20 min are selected to study because the maximum temperature increases in human body due to electromagnetic wave are steady for both of frequencies and propagation mode, except at 300 MHz which are shown in Fig. 7.

Fig. 9 shows the maximum SAR depends on the radiated power, it will be increased if the radiated power is higher. The increasing is inversely to the frequency of electromagnetic wave, because the penetration depth in human body of the lower frequency is high, except at frequency 300 MHz in TE mode, it is the most slowly increasing of the maximum SAR because it is very high of penetration depth. This is because the energy of electric field distributes many organs in human body. The maximum SAR at frequency 300 MHz in TM mode is the most rapidly increasing in various powers of source, because the resonance of the electric field standing wave in the fat is very strong due to the large different thermal and dielectric properties with each others as shown in Tables 1 and 2. From electromagnetic theory, the reflection to the first medium and the transmission to the next medium of electromagnetic wave can be occurred at the surface when it propagates in discontinuous medium. The standing wave of electric or magnetic field will be occurred at the first medium due to the combination of incident and reflected field if they have opposite phase, normally when it propagates from low density to strike high density medium. The dominant standing wave of electromagnetic field which is propagated in TE mode is magnetic field, while propagated in TM mode is electric field. These fields will be increased in the medium which has many standing waves due to the resonance of these standing waves inside. Thus, the total electric and magnetic field of each organ are from the penetration field and the resonance. Therefore, SAR value of organ is obtained from electric field, its dielectric property and density as shown in Eq. (10). Moreover, the maximum SAR from TM mode is higher than that of TE mode at each frequency because the dominant standing wave of TM mode is electric field which causes to SAR value.

For consideration of the maximum temperature increases, it is found that most of them are corresponding to the maximum SAR as shown in Fig. 10. For TE mode, the maximum temperatures at the extremely high and low frequencies are slowly increases, while at 915 MHz is the most rapidly increase in this propagation mode. For TM mode, the maximum temperature increase at 300 MHz is

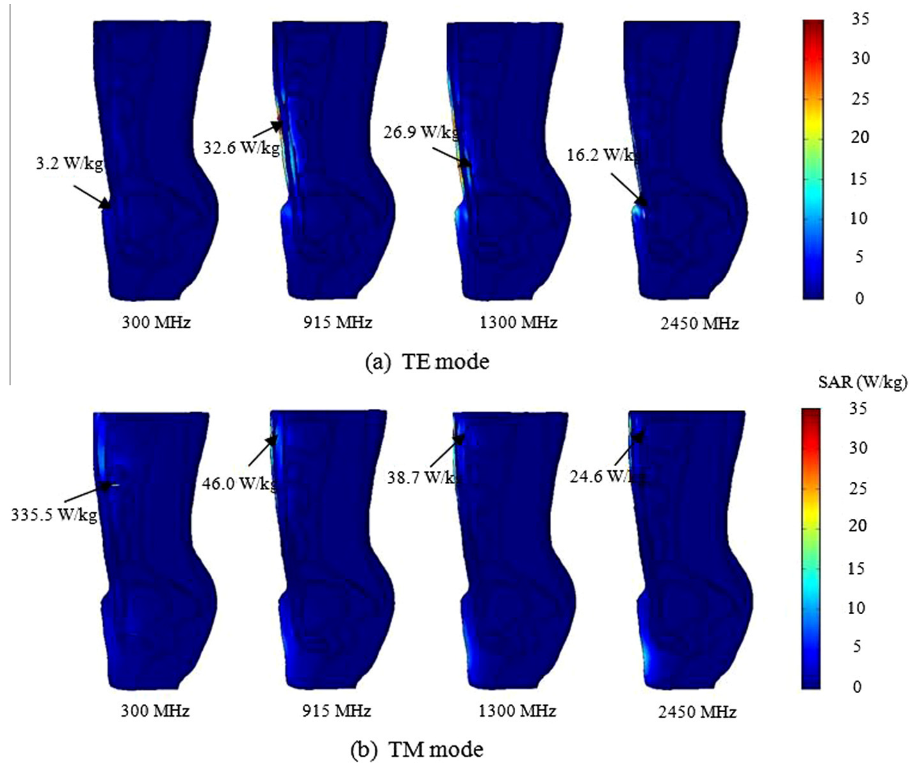

Fig. 11. SAR distribution of human body exposed to electromagnetic wave at frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz which are propagated in (a) TE mode and (b) TM mode at power 100 W and exposure time 20 min.

the most rapidly while 2450 MHz is the most slowly temperature increase, corresponding to the maximum SAR.

3.4. SAR distribution in human body

Fig. 11 shows the SAR distribution evaluated on the vertical section of the human body in which the maximum SAR value occurs. For consideration of the SAR distribution on organs in human body exposed to electromagnetic wave at frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz, the cases of 100 W and exposure time at 20 min are investigated. It is evident that the dielectric properties, as shown in Table 2, can become significant to SAR distributions in human organ when electromagnetic energy is exposed in these organs. The electric field is attenuated within the human body, owing to the energy absorbed in organs. The SAR in particular organ is given by Eq. (10), it is found that the high values of SAR occur in the periphery region of the body, skin and fat. The SAR distributions at low frequency are higher than that of high frequency of electromagnetic wave in the same organs, because the penetration depth of low frequency is high. But at frequency 300 MHz in TE mode has low SAR because it is very high penetration depth of this frequency when compares with other frequencies, the electromagnetic wave can moves through many organs in human body and distributes the energy on each organ, as shown in Fig. 11(a).

For TM mode, it is found that the SAR values on each organ which is exposed to electromagnetic wave in TM mode are higher than that of TE mode for all organs and frequencies. This is because the standing wave on each organ can be occurred by the summation of the transmitted electromagnetic field from previous organ and reflected electromagnetic field from the boundary of the next organ. It contributes to the resonance of standing wave in each organ, the energy of the resonance of standing wave will be absorbed by organs. The dominant standing wave on organs from wave propagation in TE mode is magnetic field, while from wave propagation in TM mode is electric field. Thus, the absorbed energy from electric field on each organ which exposed to electromagnetic wave in TM mode is higher than that of TE mode. Fig. 11(b) shows the SAR value at frequency 300 MHz in TM mode is too high on fat when compares with other frequencies and organs, because the dielectric constant of fat is too different from the contiguous organs while the others are similar to each contiguous organ as shown in Table 2, the reflected coefficient of electric field is very high, it causes strong standing wave on fat. The resonance of standing wave on fat at frequency 300 MHz in TM mode is significant because it has high penetration depth and strong standing wave, it has very high SAR when compare to other organs, frequencies of electromagnetic wave and propagation mode.

3.5. Temperature distribution in the human body

Fig. 12 shows the temperature distribution in the 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 each organ is converted to thermal energy. Although the SAR on the inner organs are quite different from the periphery organs of the body as shown in Fig. 8, but the temperature increases are not quite different. Not only SAR is important value to cause the temperature increase in the human body, but the thermal and dielectric properties which are shown in Tables 1 and 2 are also important. The bioheat equation in Eq. (6) shows that thermal energy can be transfer to the contiguous organs due to conduction and blood perfusion terms. The heat source of each tissue is SAR, while heat sink is heat transfer to other organs by factors of thermal conductivity and blood perfusion rate.

For TE mode, the maximum temperature increases are inversely to frequency, except at 300 MHz because it has low SAR in this case. The maximum temperature of high frequencies of 915 MHz

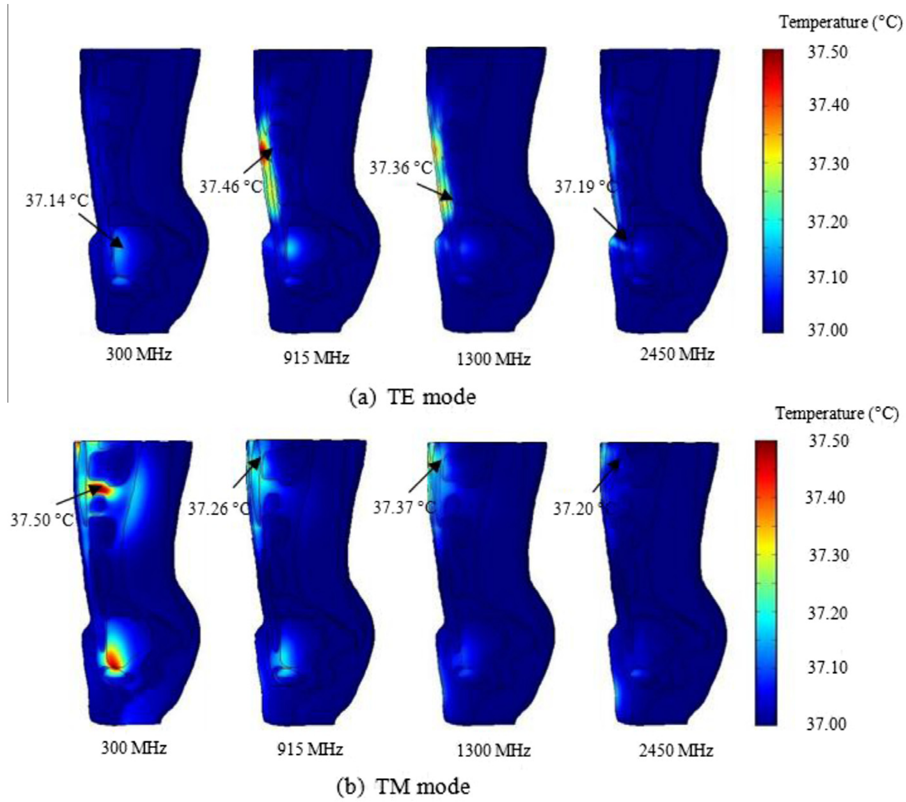

Fig. 12. Temperature distribution of human body exposed to electromagnetic wave at frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz which are propagated in (a) TE mode and (b) TM mode at power 100 W and exposure time 20 min.

and 1300 MHz are occurred on fat at 37.46 °C and 37.36 °C, respectively. For the frequency of 2450 MHz is occurred on skin at 37.19 °C as shown in Fig. 13(a). This is because fat has low thermal conductivity and blood perfusion rate as shown in Table 1, causes low heat sink on fat. While the maximum temperature at frequency 300 MHz is occurred on bladder, 37.14 °C. This is because this frequency has high penetration depth, it can penetrate into bladder. This organ is very large and do not have blood perfusion rate.

For TM mode, the most of maximum temperature is obtained from 300 MHz at 37.50 °C on fat because it has very high SAR on fat. Fig. 13(b) shows that the temperature increases on organs of 300 MHz are not quite different, although the SAR value on fat is very high when compare with other organs. This is because of heat transfer from fat to the contiguous organs. The maximum temperatures which are obtained from 915 MHz, 1300 MHz and 2450 MHz are occurred on skin at 37.26 °C, 37.37 °C and 37.20 °C, respectively. It is found that the temperature increases which are obtained from both of TE mode and TM mode at high frequency are not different. The maximum temperature increase from all frequencies and propagations mode in this work is 0.50 °C, this temperature is much lower than the thermal damage temperature within the range of 1–5 °C.

3.6. The maximum SAR and temperature on organs in the human body

From the previous section, the steady state temperature after exposure for 20 min at the radiated power of 100 W, are selected to study the organs which have the maximum SAR and temperature. Tables 4 and 5 show the organs which have the maximum SAR and temperature from TE mode and TM mode, respectively. It is found that the maximum SAR from TE mode at frequencies of 915 MHz, 1300 MHz and 2450 MHz occur in the skin. These values are 32.6 W/kg, 26.9 W/kg and 16.2 W/kg, respectively. Thereafter, thermal energy transfers from skin to fat, the maximum temperatures occur on fat, because at low conductivity and blood perfusion rate on fat. These values are 37.46 °C, 37.36 °C and 37.19 °C, respectively. At 300 MHz, which has high penetration depth, the maximum SAR occurs on muscle, 3.2 W/kg, and the maximum temperature occurs on the next organ, bladder, 37.14 °C.

For TM mode, it is found that the maximum SARs occur on fat at all frequencies, because of the resonance of the electric field standing wave is very strong. These values are 335.5 W/kg, 46.0 W/kg, 38.7 W/kg and 24.6 W/kg, respectively. The maximum temperatures occur in the skin because thermal energy from fat spread out to the contiguous organs, except at 300 MHz is still on fat because of very high SAR when compared to the others. These values are 37.50 °C, 37.26 °C, 37.37 °C and 37.20 °C, respectively.

Comparing to the ICNIRP limit [20], SAR value for occupational exposure is 10 W/kg. It is found that most of the resulting of SAR values are exceeded the ICNIRP limit for all cases of frequencies and propagation modes when the electromagnetic radiated power is 100 W, especially at 300 MHz in TM mode.

4. Conclusions

This study presents the numerical simulation of SAR and temperature distributions on organs in human body exposed to electromagnetic wave at the frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz. The influence of electromagnetic wave propagation mode at each frequency in various exposure time and power of electromagnetic wave are investigated. The results show that the maximum temperature are approch to steady after

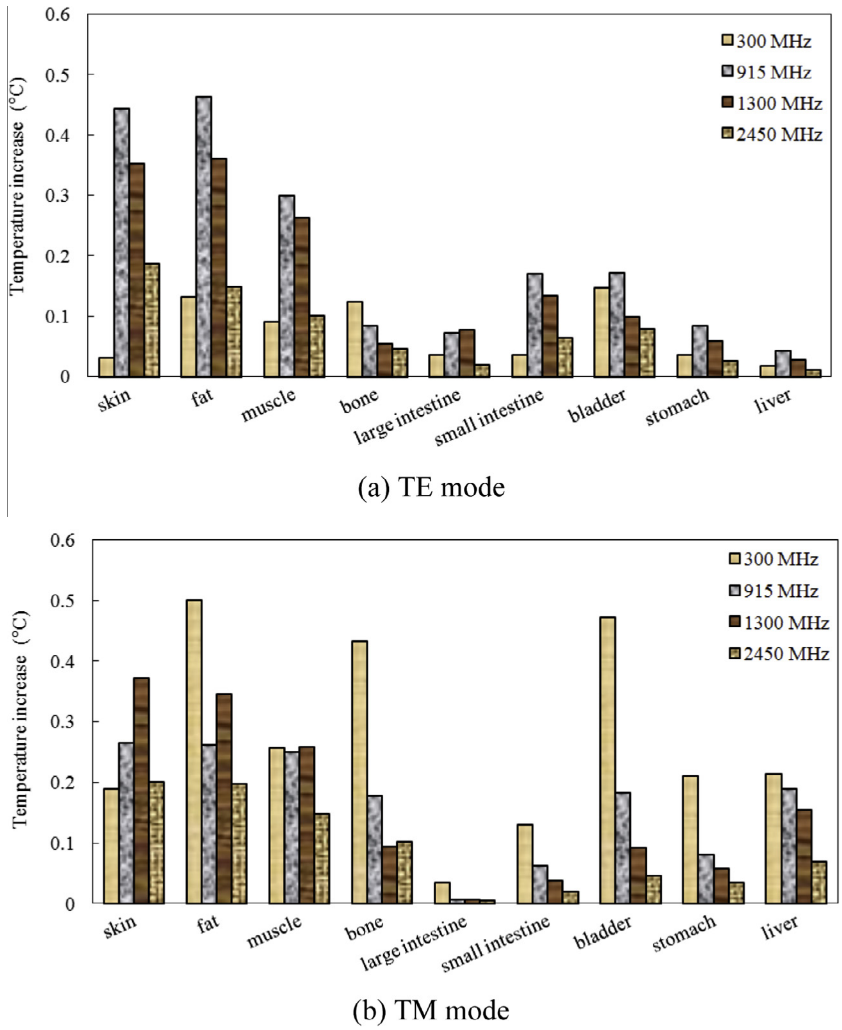

Fig. 13. Temperature distribution on tissues in human body exposed to electromagnetic wave at frequencies of 300 MHz, 915 MHz, 1300 MHz and 2450 MHz which are propagated in (a) TE mode and (b) TM mode at power 100 W and exposure time 20 min.

Table 4
The organ in human body which has the maximum SAR and temperature in TE mode.

Power (W)	300 MHz		915 MHz		1300 MHz		2450 MHz	
	SAR	*T*	SAR	*T*	SAR	*T*	SAR	*T*
10	Muscle	Bladder	Skin	Fat	Skin	Fat	Skin	Fat
50	Muscle	Bladder	Skin	Fat	Skin	Fat	Skin	Fat
100	Muscle	Bladder	Skin	Fat	Skin	Fat	Skin	Fat

Table 5
The organ in human body which has the maximum SAR and temperature in TM mode.

Power (W)	300 MHz		915 MHz		1300 MHz		2450 MHz	
	SAR	*T*	SAR	*T*	SAR	*T*	SAR	*T*
10	Fat	Fat	Fat	Skin	Fat	Skin	Fat	Skin
50	Fat	Fat	Fat	Skin	Fat	Skin	Fat	Skin
100	Fat	Fat	Fat	Skin	Fat	Skin	Fat	Skin

5 min of exposure time, it depends on the power of electromagnetic wave.

For the distribution of SAR consideration, the maximum SARs within the human body which are exposed to electromagnetic wave propagation in TM mode are higher than that of TE mode at each frequency for all cases of radiated power. The maximum SARs occur at skin when electromagnetic wave propagated in TE mode for all frequencies, except at the frequency 300 MHz. It occurs at muscle because it has high penetration depth. In TM mode, they occur at fat for all frequencies because of the resonance of electric field standing wave on fat. These maximum SAR values are proportional to the power of electromagnetic wave but the power of electromagnetic wave is not affected to the organs which have the maximum SAR, it is the same organ for all frequencies and propagation modes even though the power of electromagnetic wave is increasing.

For the distribution of temperature consideration, the maximum temperatures in the human body occur at the contiguous organs of the organs which have the maximum SAR, because of heat transfer of these organs. They occur at bladder from the frequency 300 MHz and fat from the frequencies of 915 MHz, 1300 MHz and 2450 MHz for all powers of electromagnetic wave in TE mode. These organs has the lareg size, the effect of heat is increasing of temperature more than transfer to other organs. While they occur at skin from the frequencies of 915 MHz, 1300 MHz and 2450 MHz for all powers of electromagnetic wave in TM mode. This is because fat is a tiny region at the position of the maximum SAR. Except at the frequency 300 MHz in TM mode, the maximum temperature still occurs at fat. This is because it has very high SAR and the large size of fat.

Moreover, it is found that the temperature distribution is not related only electric field, but the dielectric property, thermal property, blood perfusion and penetration depth of organs at each frequency of electromagnetic wave are significant too. However, mode of electromagnetic wave propagation is important to cause the SAR and temperature distributions. The electromagnetic wave at frequency 300 MHz which is propagated in TE mode is little affected to SAR and temperature distributions in human body, while 300 MHz in TM mode is significant to cause the SAR and temperature distributions.

For the future work, these models will be developed for 3-D simulation for better understanding of the realistic situation of the interaction between the electromagnetic wave and the organs in human body. Moreover, these effects will be calculated from other electromagnetic sources such as electromagnetic wave which is propagated from high power transmission lines.

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