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

Apichart Siriwitpreecha, Phadungsak Rattanadecho *, Teerapot Wessapan

Center of Excellence in Electromagnetic Energy Utilization in Engineering (CEEE), Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani 12120, Thailand

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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

* Corresponding author. Tel.: +66 2564 3001 9; fax: +66 2564 3010.
E-mail address: ratphadu@engr.tu.ac.th (P. Rattanadecho).

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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.