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Flow and heat transfer in biological tissue due to electromagnetic near-field exposure effects

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ABSTRACT

Electromagnetic fields (EMF) have been a vital part of our daily life over the past decade. Therefore, people are continuously exposed to electromagnetic (EM) sources in their vicinity generated by electronic devices such as those emitted by Wi-Fi, mobile phones, portable wireless router and other wireless services. This study aims to investigate the SAR, fluid flow and heat transfer in biological tissue due to EM near-field exposure. In a tissue model, the effects of distance to an EMF source and tissue permeability on natural convection in the biological tissue are systematically investigated. The specific absorption rate (SAR), fluid flow and the temperature distributions in the tissue during exposure to EM fields are obtained by numerical simulation of EM wave propagation and heat transfer equations. The EM wave propagation is expressed mathematically by Maxwell's equations. The heat transfer model used in this study is developed based on bioheat model and porous media model. By using the porous media model, the distribution patterns of temperature are quite different from the bioheat model by the strong blood dissipation effect of the porous media model. The exposure distance significantly influences the SAR, velocity field and temperature distribution. Moreover, the tissue permeability also affects the temperature distribution patterns within the tissue. The obtained results may be of assistance in determining exposure limits for the power output of the wireless transmitter, and its distance from the human body. The results can also be used as a guideline to clinical practitioners in EM relates the interaction of the radiated waves with the human body.

1. Introduction

During recent years there has been increasing public concern on potential health risks from radiation emission from wireless communication systems. All wireless electronic devices generate electromagnetic field (EMF). EMF travel indefinitely through space and disturb other electromagnetic changes in their vicinity. The user of these electronic devices is exposed to electromagnetic (EM) radiation in the near field of the EM source. However, recommendations on EM exposure limits are specified in terms of the far-field parameters. The recommendations which limit the exposure have been issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] and the Institute of Electrical and Electronics Engineers (IEEE) [2]. Moreover, available study on the SAR, heat transfer and fluid flow in biological tissues exposed in the near-field are very limited.

At microwave frequencies, the main biological effect of EM near-filed exposure is heating. Most previous studies of the interaction between EMF and the biological tissue were mainly focused on SAR and have not been considered heat transfer and blood flow causing an incomplete analysis to the results. Actually, the severity of the physiological effect produced by small temperature increases can be expected to worsen in sensitive organs. An increase of approximately 1–5 °C in human body temperature can cause numerous malformations, temporary infertility in males, brain lesions, and blood chemistry changes. Even a small temperature increase in human body approximately 1 °C can lead to altered production of hormones and suppressed immune response [3]. Therefore, the realistic modeling of the complex phenomena associated with the heat transport is needed in order to completely explain the actual process of interaction between EM field and the biological tissue.

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Nomenclature

C	specific heat capacity (J/(kg K))
E	electric field intensity (V/m)
f	frequency of incident wave (Hz)
H	magnetic field (A/m)
j	current density (A/m^2)
k	thermal conductivity (W/(m K))
n	normal vector
p	pressure (N/m^2)
Q	heat source (W/m^3)
T	temperature (K)
u	velocity (m/s)
t	time
Greek letters	
β	volume expansion coefficient (1/K)
μ	magnetic permeability (H/m)
ε	permittivity (F/m)
ε_p	porosity
σ	electric conductivity (S/m)
ρ	density (kg/m^3)
ω	angular frequency (rad/s)
ω_b	blood perfusion rate (1/s)
μ	dynamic viscosity (N s/m^2)
Subscripts	
b	blood
ext	external
eff	effective
met	metabolic
r	relative
s	solid
ref	reference
0	free space, initial condition

Recently, transport models of biological tissue have been rapidly developed and have been used extensively in studies of the health implications of exposure to EMF and prediction of therapeutic responses to EMF. The most widely used bioheat model was introduced by Pennes [4]. Due to simplifications of Pennes' bioheat model, other workers have established mathematical bioheat models by extending or modifying Pennes model [5–7]. Some bioheat models are also established and examined for countercurrent heat transfer in arterial–venous blood vessels [8,9]. Recently, there has been an increasing attention to using porous media in modeling flow and heat transfer in biological tissues [10–13,29]. The theory of porous media for heat transfer in biological tissues is found to be most appropriate since it contains fewer assumptions, are stressed by Khaled and Vafai [14], Nakayama and Kuwahara [15], and Khanafer and Vafai [16,13]. The volume averaging method has also been widely used to develop the transport equation for countercurrent bioheat transfer between terminal arteries and veins in the circulatory system [15]. Advances in modeling of transport process in biological tissue subjected to hyperthermia have been recently carried out [17,18].

Our research group has numerically investigated the temperature increase in human tissue subjected to EM fields in many problems [19–30]. Wessapan et al. [19,20] utilized a 2D finite element method (FEM) to obtain the specific absorption rate (SAR) and temperature increase in the human body exposed to leaked EM waves. Wessapan et al. [21,22] developed a 3D model of the human head in order to investigate the SAR and temperature distributions in the human head during exposure to mobile phone radiation. Wessapan et al. [23–26] investigated the SAR, fluid flow and temperature distributions in the eye during exposure to EM waves using porous media theory. Keangin et al. carried out a numerical simulation of liver cancer treated using a mathematical model that considered the coupled model of EM wave propagation, heat transfer, and mechanical deformation in the biological tissue in the couple's way [27]. They also include more advanced applications in the model such as the different types of antennas [28] and include the porous media effects into their model [29]. Keangin et al. proposed a model to investigate the effect of EMF on biological tissue using porous media theory based on thermal non-equilibrium (LTNE) model [30].

Although porous media involves natural convection in biological tissue have been used in the previous biomedical studies [29,30], most studies of biological tissue exposed to EMF have not been considering the porous media approach especially in near-field problems. Therefore, the actual thermo-physiologic response of the biological tissues subject to a near-field EMF is still not well understood due to the physical complexity associated with transport in biological tissue and EMF propagation.

The present study utilizes the porous media theory to analyze SAR, fluid flow and heat transfer in biological tissue subjected to a near-field EMF. The dipole antenna is the most common design for omnidirectional antennas and is used as an EM source in this study. The EM wave propagation emitted from the antenna propagate through the tissue is expressed mathematically by Maxwell's equations. In the tissue model, the effects of distance to an EMF source and tissue permeability on natural convection in the biological tissue is systematically investigated. The SAR, fluid flow and temperature distributions in the tissue during exposure to EM fields are obtained by numerical simulation of the EM wave propagation and heat transfer equations. In particular, the results obtained from the porous media model, considered natural convection, are compared with the results obtained from a convectional bioheat model. The exposure frequency of 900 MHz is selected because of it is frequently used in various industrial, medical and wireless transmitters. The obtained results may be of assistance in determining exposure limits for the power output of the wireless transmitter, and its distance from the human body. The results can also be used as a guideline to clinical practitioners in EM relates the interaction of the radiated waves with the human body.

2. Formulation of the problem

In general, total personal exposure consists of contributions from near-field and far-field sources with respect to the human body. These EM energy can lead to temperature rise produced in body tissue which can cause a number of adverse human health effects. Near-field sources such as mobile phones and portable wireless router operate in close vicinity of the body and can cause temporarily high local exposure. For adequate study of transport phenomena in the human tissue caused by EM near-field exposures, the contribution of different EM sources to the human exposure of different body tissues is required. Fig. 1 shows human exposure to near-field EM radiation.

This study investigates the effect of EM near-field exposure on SAR, fluid flow and heat transfer in biological tissue. Due to ethical