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Electromagnetic field effects on biological materials

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ABSTRACT

In this study, the effect of an imposed electromagnetic field on biological media is analyzed. The local thermal non-equilibrium (LTNE) is taken into account by solving the two-energy equation model for tissue and blood phases. A comprehensive examination of heat transport through biological media is carried out including thermal conduction in tissue and vascular system, blood-tissue convective heat exchange, metabolic heat generation and imposed heat flux. The primary biological media, i.e., bone, liver, cornea, fat, skin and brain are considered in our analysis. The effects of variations of dimensionless electromagnetic wave power and dimensionless electromagnetic wave frequency on the dimensionless tissue and blood temperature profiles are systematically investigated. Results are obtained for a range of dimensionless electromagnetic wave power from 1 to 500 and dimensionless electromagnetic wave frequency from 0.2 to 2. The coupled equations of electromagnetic wave propagation and heat transfer under LTNE assumption are solved using the finite element method (FEM). This investigation provides the essential aspects for a fundamental understanding of heat transport within biological materials while experiencing an applied electromagnetic field such as applications related to the cancer thermal ablation and can be used as a guideline for these types of treatments.

1. Introduction

The modeling of heat transport within biological materials is quite important and has been used extensively in medical thermal therapeutic applications for predicting the temperature during these processes. In recent years, utilization of an imposed electromagnetic field in various applications has increased since the electromagnetic wave can penetrate the surface and is converted into thermal energy very rapidly within the material. Various electromagnetic wave applications have been used in many industrial and household applications. For example, for drying, pasteurization, sterilization, heating processes, etc. [1]. Recently, electromagnetic wave has been introduced as a rapid method of delivering high temperatures to destroy the cancer cells during thermal ablation [2,3]. The imposed electromagnetic field interacts with the material and results in a variety of thermal effects. Various effects such as an increase in temperature as result of electromagnetic radiation on materials are gaining widespread attention, particularly in biological materials [4,5]. However, the resulting thermo-physiologic response of the biological materials subject to an electromagnetic field is not well understood due to the complexity of the configurations in biological materials. 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 [6]. In order to gain insight into the phenomena occurring within the biological materials subject to an imposed electromagnetic field, detailed knowledge of the electromagnetic radiation absorption is necessary. A detailed investigation is necessary to demonstrate the effects of electromagnetic radiation absorption in biological materials. Furthermore, numerical simulation under various conditions can be utilized to demonstrate and indentify the fundamental parameters as well as provide guidance for different applications.

Studies of heat transport through biological materials, involves thermal conduction in tissue and vascular system, blood-tissue convection and perfusion (through capillary tubes within the tissues) as well as metabolic heat generation [6–10]. Wessapan et al. [6] have carried out a numerical analysis of specific absorption rate (SAR) and heat transfer in human body due to an electromagnetic field leakage. Keangin et al. [10] carried out the numerical simulation of liver cancer treatment using the microwave antenna.

A biological tissue can be represented by a microvascular bed with blood flow through many vessels, through which blood flows and can be regarded as a porous structure [7]. Utilizing porous media theory in modeling heat transfer results in fewer

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Nomenclatures

a_{tb}	specific surface area between the blood and the tissue ($m^2/\ m^3$)
Bi	Biot number, $Bi = \frac{h_{tb}a_{tb}H^2}{K_{t,eff}}$
c_p	specific heat capacity (J/kg °C)
$\vec{E}$	electric field (V/m)
f	electromagnetic wave frequency (Hz)
h_{tb}	interfacial heat transfer coefficient between the lumen and the tissue ($W/m^2\ °C$)
H	height of the biological material (m)
k_0	free space wave number (m^{-1})
K	thermal conductivity (W/m °C)
L	length of the biological material (m)
P	electromagnetic wave power (W)
q_s	heat flux at the surface (W/m^2)
Q	heat source (W/m^3)
T	temperature (°C)
u	lumen velocity (m/s)
x	longitudinal coordinate (m)
y	transverse coordinate (m)

Greek Symbols

ε	porosity (the ratio of the volume fraction of the vascular space to the space occupied by the extra-vascular space) (–)
η	dimensionless transverse coordinate, $\eta = \frac{y}{D}$
Φ	dimensionless heat generation within the biological material, $\Phi = \frac{(1-\varepsilon)HQ_{met}}{q_s}$
κ	ratio of the effective blood thermal conductivity to that of the tissue, $\kappa = \frac{K_{b,eff}}{K_{t,eff}}$
ρ	density (kg/m^3)
θ	dimensionless temperature, $\theta = \frac{K_{t,eff}\langle\langle T\rangle - T_s\rangle}{q_s H}$
μ	magnetic permeability (H/m)
γ	permittivity (F/m)
σ	electric conductivity (S/m)
ω	angular frequency (rad/s)

Subscripts

b	blood phase
c	cut off
eff	effective property
ext	external
met	metabolic
r	relative
s	surface
t	tissue phase
tb	tissue to blood
0	free space, initial condition

Abbreviations

FEM	finite element method
LTNE	local thermal non-equilibrium

assumptions as compared to different established bioheat transfer models [7–9]. Depiction of heat transport through a porous medium has been of interest for many decades. Two different models are used for analyzing heat transfer in a porous medium; local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) [11–15]. The LTE model is based on the assumption that the tissue phase temperature is equal to blood phase temperature everywhere in the porous medium and referred to as the one equation model [7,11–13]. This assumption is not suitable for a number of physical situations [7]. In recent years, the LTNE model has received more attention to demonstrate the heat transport in biological media [7–9,16,17]. Utilizing the porous media theory, LTNE between the tissue and the blood phase is addressed and the tissue-blood convective heat exchange is taken into account. Volume averaging over each of the tissue and blood phases results in energy equations for each individual phase. Studies of heat transport under LTNE in biological media has been established in the literature [8,9]. Mahjoob and Vafai [8] analyzed characterization of heat transport through biological media incorporating hyperthermia treatment, utilizing the LTNE model. They had obtained detailed exact solutions for the tissue and blood temperature profiles. Mahjoob and Vafai [9] analyzed characterization of bioheat transport

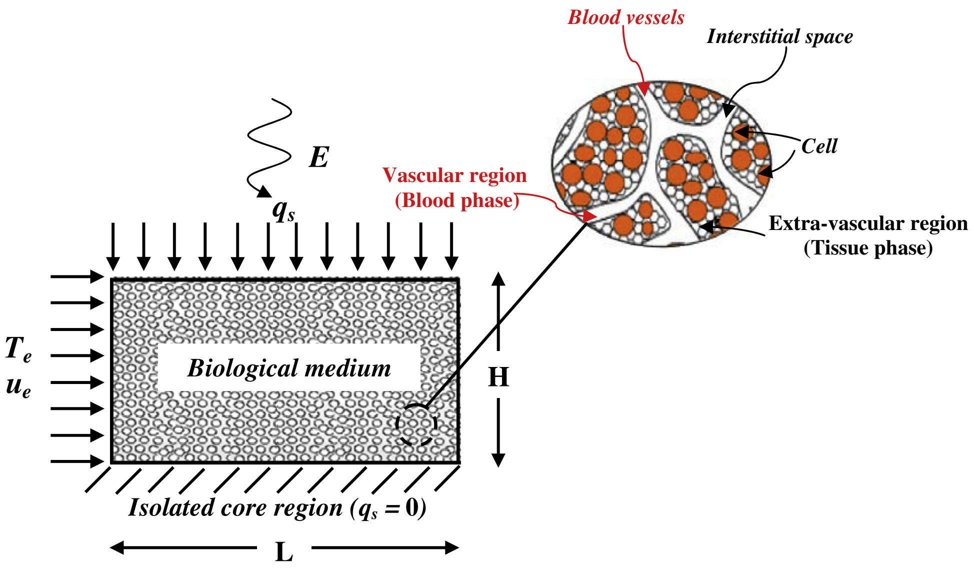

Fig. 1. Schematic diagram of a biological medium subject to an electromagnetic field.