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FEM simulation of EM field effect on body tissues with bio-nanofluid (blood with nanoparticles) for nanoparticle mediated hyperthermia

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ABSTRACT

The study of temperature profiles and heat transport within the human body when subjected to electromagnetic waves is crucial for development and improvement of radiofrequency hyperthermia treatments. These treatments being minimally invasive can be a better alternative over surgery and chemotherapy for treatment of cancer. Nanoparticle-mediated hyperthermia for cancer therapy is a growing area of cancer nanomedicine because of the potential for localized and targeted destruction of cancer cells. This treatment is dependent on many factors, including thermal conductivity of bio-nanofluid, volume fraction of nanoparticles,excitation wavelength and power and metabolic heat generation. The present study employs Finite Element Method to investigate and optimize the effects of these parameters on temperature distributions and discuss the heat transport within the human body injected with nanoparticles and subjected to electromagnetic waves. The LTNE (Local Thermal Non Equilibrium) model is used to characterize the bioheat transport through the biological medium. In order to understand the effects induced by imposed electromagnetic field, the specific absorption rate (SAR) of body tissues is also studied. The results obtained have been validated against the pertinent numerical results in the literature. This study provides benchmark numerical solutions for heat transport through biological media thereby, helping in understanding the thermophysiologic response of bio-nanofluid towards imposed electromagnetic radiation.

1. Introduction

The study of transport phenomenon; particularly heat transfer within the human body is of paramount importance in various medical applications, such as thermal therapeutic treatments which rely on the knowledge of temperature variations occuring in the body. Nanoparticles are desirable for biomedical applications because of their distinctive chemical and physical properties, which facilitate the targeting of specific cell types, improve pharmacokinetics and bioavailability, and enhance signal detection [11,12]. Nanoparticle-based therapeutics are not restricted to nanoparticle drug formulations; a growing area of research in cancer therapy is nanoparticle-based hyperthermia [8], in which nanoparticles administered to a tumor are heated in order to kill cancer cells. There has been considerable progress in nano- and biotechnology over the last several years. However, several key challenges have also become apparent, including the need for a better understanding of nanoparticle behavior in vivo and the development of more effective nanoparticle therapeutics [10]. Computational efforts are becoming an important tool in addressing both of these challenges, as well as in generally facilitating and accelerating nanotechnology-based translational research. Nanoparticle-mediated hyperthermia is a form of cancer therapy in which the nanoparticle, rather than a nanoparticle-encapsulated drug, is the basis for treatment.

Electromagnetic (EM) wave energy is the preferred source of heat over other traditional heating methods owing to their penetration capability and conversion into volumetric heat energy within the medium. In recent times, the use of imposed electromagnetic field in various industrial and household applications has been on the rise. For example, milk pasteurization and sterilization, drying and heating processes etc. [7] Choice of energy absorption method, prompt and easy electronic control, non-polluting and being energy efficient are some of the several advantages of microwave heating. In various bio-heat investigations such as bone drilling operation, frictional heating and temperature rise in knee joint replacement, laser surgical treatment of eyes etc., it becomes crucial to assess the thermal side effects [4,9]. With the increased use of high power EM wave, it becomes necessary to determine the threshold limit of safe exposure.

The regulations of exposure of human body to EM field is based on peak spatial average specific absorption rate (SAR). The absorption of power causes an increase in temperature inside tissues. This

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Nomenclature

a_{tb}	specific surface area between vascular and extra-vascular region (m^2/m^3)
Bi	Biot number (–)
c_p	specific heat capacity $(J/kg^{\circ}C)$
E	Electric field intensity (V/m)
f	Frequency of EM wave (Hz)
h_tb	heat transfer coefficient between lumen and tissue $(W/m^{2\circ}C)$
H	Height of the biological medium (m)
k_0	free space wave number (m^{-1})
k	Thermal conductivity $(W/m^{\circ}C)$
L	Length of biological medium (m)
P	Power of EM wave (W)
q_s	Heat flux at surface (W/m^2)
Q	Heat source (W/m^3)
T	Temperature $(^{\circ}C)$
u	lumen velocity (m/s)
x	longitudinal coordinate (m)
y	transverse coordinate (m)

Greek symbols

ϵ	Porosity (ratio of volume fraction of vascular to extra-vascular space) (–)
η	Dimensionless co ordinate(–)
ϕ	Dimensionless heat generation (–)
κ	Ratio of effective blood thermal conductivity to tissue thermal conductivity ( )
ρ	Density (kg/m^3)
θ	Dimensionless temperature (–)
γ	Permittivity (F/m)
σ	Electric conductivity (S/m)

Subscripts

b	Blood phase
c	Cut-off
$eff,\ ev$	Effective value
em	External
f	base fluid (blood)
mb	Metabolic
p	nanoparticle
r	relative
t	Tissue phase

temperature increase can have an adverse effect on the normal functioning of the biological organs. A small increase in temperature (1–5 °C) can result in malfunctioning of various processes and systems within the body including short term infertility, change in hormone production and blood chemistry along with suppression of immunity response.

As such, it becomes important to explore the effect that absorption of EM radiation causes in biological materials. An analysis for different cases can be used to show and recognize the critical parameters along with providing guidelines for different applications.

Wessapan and Rattanadecho [33] conducted a numerical study of SAR and heat transfer occuring in human body when exposed to different frequencies of EM radiation. Numerical study of liver cancer treatment was done by Keangin et al. [16]. Many researchers have studied the heat transport in biological material; taking into account the thermal conduction in tissues, convective flow of blood inside the tissue along with perfusion and heat generation through metabolism. A biological tissue can be considered as a microvascular bed with blood flowing through numerous blood vessels [17]. It can thus, be best modelled as a porous structure. The porous media theory involves less assumptions in comparison to various other bioheat transfer models, making it an effective choice for the present study. Heat transfer through a porous media has been illustrated by many researchers in the past [31]. The two models used for studying the heat transfer inside a porous media are LTE (Local Thermal Equilibrium) and LTNE (Local Thermal Non-Equilibrium) model. The LTE model is also described as one equation model because it assumes that the temperature of the tissue phase and the blood phase is the same throughout the porous media. This is an unsuitable assumption for a number of real life physical settings. Hence, in the past couple of decades, the LTNE model has gained increased attention of researchers for demonstrating the heat transfer in biological media [1,19,31,32,34,35]. The LTNE model recognizes the thermal non-equilibrium between the tissue and the blood phase. It takes into account the heat exchange due to convection between the two phases. The energy equation for the particular phase is obtained using the volume averaging technique. The alternative modelling to this kind of problem was provided by Baxter and Jain [3] and Soltani and Chen [30]. Under independent studies, they modelled the flow, mass and heat transfer in a biological tissue using the theory of porous media combined with a multiscale approach which helped in prediction of interstitial fluid flow pattern in solid tumors and surrounding tissues. As the present study does not involve the modelling of tumor tissue, the authors have used the LTNE model to study temperature distributions. Mahjoob and Vafai [21] provided the analytical characterization of transport of heat through the human body in context of hyperthermia treatment. They used the LTNE model for their study, obtaining detailed temperature profiles for both blood and the tissue. Another study conducted by Mahjoob and Vafai [22] focused on analyzing the bioheat transport through the dual layer biological media. They achieved the detailed exact solutions for temperature profiles under the effect of metabolic heat generation. Belmiloudi [5] used the LTNE model to analyze the impact of porous media for biofluid heat transfer, in context of thermal therapy. In the study of bioheat transfer through porous media, Nakayama and Kuwahara [26] extended the two-energy equation model to three-energy equation version accounting for the countercurrent heat transfer between closely spaced arteries and veins in the circulatory system.

Radio frequency ablation (RFA) has the capability to enhance and optimize medical treatment with less side effects [14,27]. During RF cardiac ablation, thermal effect on tissue and blood needs to be modelled effectively and with a fast response in order to ensure that the induced heat only destroys the abnormal tissue without damaging the rest of the heart. A number of medical implants such as pacemakers, medical pumps, neuromodulation systems etc. need electrical energy for their proper functioning. This energy is stored in the batteries. Over time, this stored energy depletes and thus, must be recharged. One method is through transcutaneous recharge of such neurostimulation systems. It is important to supervise both the blood and tissue temperature throughout the process in order to avoid damage to tissues and organs. Keangin et al. [16] used the Finite Element Method to solve the coupled equations and generate temperature profiles for blood and tissue at different electromagnetic wave power and electromagnetic wave frequencies. They considered six different biological media in their study. Nabil et al. [24] conducted numerical simulations of flow, mass and heat transport in the tumor microenvironment for nano-based cancer hyperthermia. Nabil and Zunino [25] conducted a