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A study on DPL model of heat transfer in bi-layer tissues during MFH treatment

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ABSTRACT

In this paper, dual-phase-lag bioheat transfer model subjected to Fourier and non-Fourier boundary conditions for bi-layer tissues has been solved using finite element Legendre wavelet Galerkin method (FELWGM) during magnetic fluid hyperthermia. FELWGM localizes small scale variation of solution and fast switching of functional bases. It has been observed that moderate hyperthermia temperature range (41–46 °C) can be better achieved in spherical symmetric coordinate system and treatment method will be independent of the Fourier and non-Fourier boundary conditions used. The effect of phase-lag times has been observed only in tumor region. FCC FePt magnetic nano-particle produces more effective treatment with respect to other magnetic nano-particles. The effect of variability of magnetic heat source parameters (magnetic induction, frequency, diameter of magnetic nano-particles, volume fractional of magnetic nano-particles and ligand layer thickness) has been investigated. The physical property of these parameters has been described in detail during magnetic fluid hyperthermia (MFH) treatment and also discussed the clinical application of MFH in Oncology.

1. Introduction

Cancer is a major cause of death in human life. It is characterized by uncontrolled growth and spread of the abnormal cells. It is caused by both external factors (tobacco, infectious organism, chemical and radiation, etc.) and internal factors (inherited mutations, hormones, immune condition, and mutation that occur from metabolism) [1]. On the basis of International agency for Research on cancer's notion [2], remarkable progress has been recorded in diagnosis [3] and treatment of cancer over the last few years. An effective thermal treatment is one which selectively destroys the tumor without disaffecting neighboring healthy tissues. The thermal treatment of cancer has been extensively studied in pre-clinical models and in human clinical trials [4]. Hyperthermia, thermal ablation, cryoablation and cryosurgery are names of the few thermal treatment modalities which are used for selectively destroying the tumor [5]. Magnetic fluid hyperthermia (MFH) is one of the ideal modalities for treatment of tumor using magnetic nanoparticles (MNPs). In this process, the fluid of MNPs are localized at tumor region. After that, an alternative magnetic field is applied which heats MNPs by the mechanism of Néel–Brownian relaxation or magnetic hysteresis losses.

Bi-layer denotes two adjacent layers, first layer is of cancerous cells with injected nano-particles and second one consists of normal (healthy) tissue region. The heat transfer in bi-layer tissue is a complex process [6]. It involves different phenomenological mechanisms including conduction in tissues, advection (blood perfusion) and diffusion through micro-vascular beds and metabolic heat generation [7]. Several mathematical models have been derived in order to model this complex process. Pennes [8] derived the bioheat transfer model for the analysis of tissue and arterial blood temperature in the resting forearm. This model is used commonly in medical and engineering field for the interpretation of thermal data. Pennes bioheat model is based on Fourier's law which depicts infinite speed of thermal signal. Biological tissues have highly non-homogeneous inner structure, so infinite speed of thermal signal is not realistic one [9–11].

In order to overcome this unrealistic situation, Cattaneo [12] and Vornotte [13] independently proposed the single-phase-lag (SPL) constitutive relation which results in finite speed of thermal signal. SPL constitutive relation when combined with energy equation gives thermal wave bioheat transfer model. Thermal wave bioheat transfer model captures micro-scale responses in time only. In order to capture micro-scale response in both time and space, a phase-lag time for temperature gradient has been added in SPL constitutive relation by Tzou [14] which is known as dual-phase-lag (DPL) constitutive relation. The DPL bioheat transfer model is obtained when DPL constitutive relation is combined

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Nomenclature

T	temperature of tissue, °C
T_b	arterial temperature, °C
T_w	wall temperature at the boundary, °C
T_f	ambient temperature, °C
h	reference heat transfer coefficient, W/m^2 °C
q	heat flux, W/m^2
q_w	reference heat flux, W/m^2
r	space coordinate, m
L	length of tissue, m
t	time, s
τ_q	phase lag due to heat flux, s
τ_T	phase lag due to temperature gradient, s
w_b	perfusion rate of blood, 1/s
ρ	density of tissue, kg/m^3
ρ_b	density of tissue, kg/m^3
c	specific heat of tissue, J/kg °C
c_b	specific heat of blood, J/kg °C
k	thermal conductivity of tissue, W/m °C
q_m	metabolic heat generation, W/m^3
q_r	spatial heating source, W/m^3
K_a	magnetocrystlline anisotropy constant, J/m^3
τ_0	average relaxation time response due to thermal fluctuation, s
μ_0	permeability of free space, T m/A
H_0	amplitude of alternating magnetic field, A/m
f	frequency of alternating magnetic field, 1/s
δ	ligand layer thickness, m
D	diameter of MNPs, m

Dimensionless variable and similarity criteria

x	dimensionless space coordinate
F_o	Fourier number or dimensionless time
F_{oq}	dimensionless phase lag due to heat flux
F_{oT}	dimensionless phase lag due to temperature gradient
θ	dimensionless local tissue temperature
θ_b	dimensionless arterial blood temperature
θ_w	dimensionless wall temperature at boundary
θ_f	dimensionless ambient temperature
P_f	dimensionless blood perfusion coefficient
P_r	dimensionless external heat source coefficient
P_m	dimensionless metabolic heat source coefficient
K_i	Kirchhoff number
B_i	Biot number
ϕ	volume fraction of MNPs
Γ	the number to classify coordinates

Subscript

1	indication for tumor
2	indication for normal tissue

with energy equation. In DPL bioheat transfer model, Antaki [15] interpreted τ_q as the delay time for contact resistance between tissues particle. On the other hand, τ_T was interpreted as a measure of the conduction that occurs within tissue particles. Non-Fourier models may play an important role in the thermal-neural behavior of skin tissue; the wave behavior thermal-neural response may play an important role in the phenomenon of latency; it is τ_q, rather than τ_T, that dominates [16]. The relaxation time (τ_q) also depends on non-homogenity of material used and the biological materials are highly non-homogeneous in nature [15] so that the non-Fourier model is more suitable in case of biological contents. The measured value of lag times is found to match the theoretical non-Fourier hyperbolic predictions very well. The superposition of waves occurring inside the meat sample due to the hyperbolic nature of heat conduction is also proved experimentally [17]. The large discrepancies are found to exist amongst the prediction of Pennes model, thermal wave model and DPL model, while different bioheat transfer models give similar predictions [18]. Among other bioheat transfer models, DPL bioheat transfer model is closest to experimental observation [19], and also has greater degree of freedom $(\tau_q$ and $\tau_T)$ [15]. So DPL bioheat transfer model provides the best results in comparison to others. Heat transfer in multi-layered tissue is induced by pulse irradiation energy passing the interface of two layers using dual-phase-lag heat conduction equation [20]. In DPL bioheat transfer model, Fourier boundary condition is considered as the insulated inner surface and the outer surface irradiated with an axial symmetric heat flux [21].

Candeo and Dughiero [22] have studied the treatment of tumor during MFH with the help of Pennes bio-heat transfer in a cylindrical bi-layer system. Magnetic nanoparticle hyperthermia cancer treatment has been studied with the help of Pennes bio-heat transfer in a spherical coordinate system in bi-layer tissues by Mital and Tafreshi [23]. Lin and Liu [24] studied estimation for the heating effect of magnetic nanoparticles in perfused tissues in Pennes bio-heat transfer equation in a spherical bi-layer tissues. Moroz et al. [25] studied magnetic fluid hyperthermia, and they used maximum potential for such selective (tumor) region. Many recent studies have investigated the heating ability of MNPs to determine their suitably as MFH. The heating intensity strongly depends on size of MNPs [26,27], concentration of MNPs [28], the amplitude of the applied alternating field [29], etc. Salloum et al. [30] measured the temperature elevation in muscle tissue of rat hind limbs induced by intramuscular tissues injection of magnetic nanoparticles during in MFH experiments. Electromagnetic field induced by two external electrodes and temperature field resulting from electrode action in the domain of biological tissue being a composition of healthy region and a tumor is considered by Majchrzak and Paruch [31]. Muhammad and Ng [32] studied the physical perspective of capacitive hyperthermia treatment of tumor. The idea consisting in the introduction of nano-particles to the tumor region is very effective, and obtained the maximum temperature in tumor domain [33]. Pennes bioheat transfer model with induced heating effects of embedded micro/nanoparticles on human body subject to external medical electromagnetic field is studied by Lv et al. [34] during MFH. Different kinds of MNPs were studied for their movement and heating responses in a known physical setting [35].

Due to complexity of the solution of bioheat transfer model in bi-layer tissues, the approximate numerical methods are often considered for solving the bio-heat transfer equation. Analytical and numerical solutions of Pennes heat conduction equation are available for single and multi-layer region subjected to MFH [36–38], they must be augmented with additional consideration about realistic conditions. In available literature, the bioheat transfer models are solved by using different types of numerical methods like finite difference method [39], finite element method [22], finite volume method [40], finite element based software package [41], finite difference–decomposition method [42], Galerkin method with B-polynomial [43], general boundary element method [11,44], hybrid numerical method [24] etc. These methods