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Numerical study of non-Fourier heat conduction in a biolayer spherical living tissue during hyperthermia

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ABSTRACT

Laser interstitial thermal therapy is one of the best methods for tumor treatment. Quality of treatment is highly influenced by the way of temperature control that depends strongly upon the living tissue thermal properties. One-dimensional dual-phase-lag (DPL) in spherical coordinate system numerically has been investigated for bioheat transfer during laser treatment in living biological tissues, which contain tumoral and normal layers. Various behaviors of heat transfer models such as wave, wavelike and diffusion are studied by adjusting the relaxation parameters. Effect of different phase lags values of the heat flux and the temperature gradient and thermal diffusivity on the behavior of heat transfer overshooting phenomenon is also investigated as well. Results indicate variation of the time lag and the thermal diffusivity of the normal and tumoral tissues. Also it has cleared that the geometrical conditions have significant effects upon the thermal response and overshooting phenomenon in biological tissue.

1. Introduction

High-energy beams like laser are being used in medicine, for diagnosing and treating the diseases, which have been highly regarded in recent decades.

Laser-induced interstitial thermotherapy (LITT) which uses to treat some cancers is similar to a cancer treatment called hyperthermia. This technique uses heat to shrink tumors by damaging or killing cancer cells. By applying (LITT), the laser light can be brought into the depth of the tissue for a successful treatment. Therefore, it is possible to irradiate directly inside of tissue which leads to much better therapeutic results (Dua and Chakraborty, 2005). It has been reported that protein denaturation takes place at a temperature range of 40–45 °C for most bio-tissues and cells die at a temperature of about 50–70 °C within few seconds (Nilamani et al., 2013).

Control of energy distribution in the irradiated tissue is one of the benefits of applying laser beams because of their miscellaneous characteristics such as directivity, monochromaticity and ability to be used as pulsed mode (Niemz, 1996). Further laser therapy causes less bleeding and less risk than surgery that associates with less risk of infection.

Classical Fourier conduction law does not apply physically in some cases such as in the heat sources with extremely short duration, very high frequency or quite high heat flux densities. Therefore, the Fourier law, which predicts infinite speed for heat propagation, should be modified. Several models have been presented to describe the thermal conduction. Cattaneo (1958) and Vernotte (1958) presented one of these models in 1958 independently. They proposed a hyperbolic heat conduction model, which is more consistent with experimental data. The heat wave model implies finite speed for the thermal propagation by considering relaxation time for heat flux. However, the hyperbolic heat conduction is not compatible with the second law of thermodynamics in some physical phenomenon (Bai and Lavine, 1995; Barletta, and Zanchini, 1997; Körner and Bergman, 1998). In order to overcome this paradox, Tzou (1995), (1996) proposed Dual Phase Lag (DPL) model by studying micro-scale heat conduction. In their study, two thermal relaxation times were considered for heat flux vector and temperature gradient. Since living tissue is highly non-homogenous, therefore the velocity of heat transfer should be limited.

Several analytical and numerical studies for non-Fourier heat conduction have been reported in the literatures. Antaki (1998), (2000) studied transient heat conduction in a semi-finite slab with surface heat flux in the micro-scale during a short period. Taitel (1972) and Barletta and Zanchini (1997) applied the conventional hyperbolic heat conduction equation to study heat conduction in the solid slab in which the surfaces temperature were suddenly raised. (Moosaie, 2008) studied the hyperbolic heat conduction in a hollow sphere with general linear time independent boundary conditions.

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Nomenclature

c_b	specific heat of blood (J/(kg K))
c	specific heat of tissues (J/(kg K))
k	thermal conductivity of tissue (W/(m K))
q	heat flux vector (W/m^2)
Q	heat source due to (W/m^3)
Q_m	metabolic heat generation (W/m^3)
r	coordinate variable in radial direction (m)
R_{tis}	outer radius of tissue (m)
R_{tum}	outer radius of tumor (m)
T_b	blood temperature (K)
V	speed of the thermal wave (m/s)
w_b	blood perfusion rate (m^3/(m^3 tissue s))

Greek symbols

α	thermal diffusivity (m^2/s)
μ_a	absorption coefficient (m^{-1})
ρ	tissue mass density (kg/m^3)
ρ_b	blood mass density (kg/m^3)
τ_q	phase lag of the heat flux (s)
τ_T	phase lag of the temperature gradient (s)
Δr	size of each control volume in r direction (m)
Δt	time step (s)

Mitra et al. (1995) carried out an experiment on processed meat which suggested the existence of non-Fourier heat conduction in non-homogenous materials. They also determined the relaxation time of heat flux in the processed meat about 15 s, which is much larger than those reported for metals with pico-second relaxation times. The high value of the relaxation time is due to microstructure of non-homogenous materials as found in meat and biological tissues. Note that the dual-phase-lag model of heat conduction proposed by Tzou (1995), (1996) also provided incorrect predictions in some cases. Scott et al. (2009) studied whether or not a model of non-Fourier heat conduction is needed to correctly capture the thermal behavior of tissue. However the non-Fourier conduction problem is closely related to the problem under consideration in the present study. Banerjee et al. (2005) measured the thermal response of meat under laser irradiation. Zhou et al. (2009a), (2009b) used an implicit numerical solution to study the dual-phase-lag bioheat conduction in one-dimensional Cartesian and axisymmetric coordinate systems for laser heating of living tissues. Liu and Chen (2009) developed a hybrid numerical scheme for solving the dual-phase-lag (DPL) bioheat model during magnetic tumor hyperthermia treatment in spherical tissue. Afrin et al. (2012) adopted a generalized DPL bioheat model based on non-equilibrium heat transfer in bio-tissue to study thermal damage induced by laser irradiation numerically. Nilamani et al. (2013) investigated non-Fourier effects in bio-tissues during laser assisted photo thermal therapy. They reported the surface temperature effects observed during near infrared (NIR) irradiation of tissue-mimics, with and without embedded nanostructures.

As far as accurate prediction of temperature distribution is concerned, this study uses numerical simulation to investigate the effect of different thermal, biological and geometrical properties of tissue on thermal wave propagation behavior in a two-layer concentric spherical region, which is induced by laser irradiation. In addition, it considers blood perfusion and metabolic heat generation. First, the problem is formulated using the DPL model in general form. Then the DPL heat conduction is derived for heat flux. The governing equations discretized by using the control volume method associated with staggered grid. Finally effect of different phase lag values and thermal properties of tumoral and normal tissue such as diffusivity as well as geometry is investigated on the behavior of wave propagation.

2. Physical modeling

A small tumor as a solid hemisphere with the radius R_{tum} is located in the center of a normal tissue. Therefore, the system is composed of two concentric layers with different Thermo-physical properties. Yuan (2008) showed the blood vessel with diameter larger than 30 µm has substantial influence on the temperature distribution and the rate of heat transfer. In this study, it is assumed there is no significant blood vessel in the tissue. Hence, the flows effect can be neglected. Perfusion is assumed uniform through time and space. The geometrical model of the tissue under treatment is shown in Fig. 1.

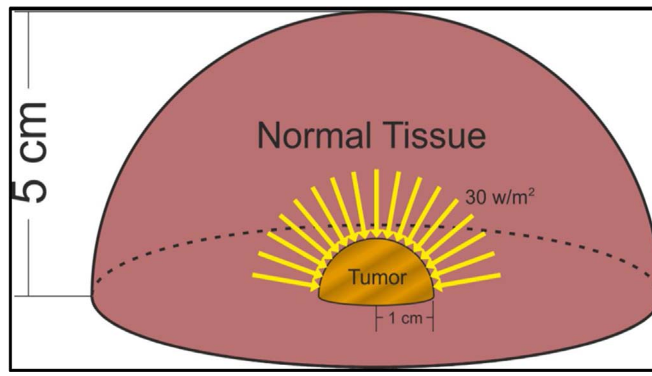

Fig. 1. Schematic of the tumoral and normal tissue layers under heat flux.

3. Mathematical model

Pennes (1948) proposed a mathematical model of heat transfer in the living tissue, follows:

$$\rho c\frac{\partial T}{\partial t} = -\nabla.\, q + \omega_b\rho_b c_b(T_b - T) + Q_m + Q \tag{1}$$

Here ρ, c, q and T are density, specific heat, heat flux and temperature of the tumoral and normal tissue, respectively. In addition, ρ_b, c_b, and ω_b are density, specific heat and perfusion rate of the blood, respectively. T_b is the arterial temperature and is assumed constant. Q_m is the metabolic heat generation and Q is the external heat source. It is also assumed the tissue temperature is initially uniform at 37 °C.

The tumoral tissue placed in the center region ($0 < r < R_{tum}$) and the thermo-physical properties of this region belongs to the thermo-physical properties of the tumoral tissue and the normal tissue placed on the outer region ($r > R_{tum}$) and the thermo-physical properties belongs to the normal tissue.

Mathematically, the equation of dual-phase-lags (DPL) model follows (Tzou, 1995, 1996):

$$q(\vec{r}, t + \tau_q) = -k\nabla T(\vec{r}, t + \tau_T) \tag{2}$$

where τ_q and τ_T are the phase-lag time for the heat flux vector and