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Porous media based bio-heat transfer analysis on counter-current artery vein tissue phantoms: Applications in photo thermal therapy

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ABSTRACT

The present work deals with the determination of transient variation of temperature distributions inside laser irradiated biological tissue phantoms consisting of an artery–vein counter current arrangement. An optical inhomogeneity that is absorbing in nature and embedded inside an otherwise homogenous medium has been employed to model the abnormal cells. The surrounding tissue region has been modeled as a porous medium consisting of solid and fluid matrices. Separate energy equations for solid and fluid matrices of the porous tissue regions have been solved as part of the bio-heat transfer model. A short pulse laser has been employed to irradiate the phantom. A numerical model coupling the Discrete Ordinates Method (DOM) for solving the transient form of Radiative Transport Equation (RTE) with that of the porous media based bio-heat transfer model has been developed and benchmarked. The convective cooling effects of blood flow through a single blood vessel as well as counter current blood vessels under local thermal non-equilibrium (LTNE) conditions have been investigated. Thermal response of the porous tissue phantom with respect to the changes in the Reynolds number ($Re = 1$ and 10) and for varying porosity levels has been presented. The effect of blood vessel diameter on the resultant temperature distribution within the body of the laser irradiated tissue phantom has been studied. Results have been presented in the form of temporal variations of temperature distributions, local variations in the heat transfer rates (Nusselt numbers) along the spatial dimensions of various interfaces present in the physical domain. Finally, the influence of the position of the embedded inhomogeneity with respect to the point of laser irradiation on the temperature rise at the location of the inhomogeneity has been investigated. The study reveals a strong dependence of the maximum possible temperature rise on the relative position of the embedded abnormal cells for a given set of laser parameters.

1. Introduction

The technique of laser induced photo thermal therapy has gained considerable attention in the past few decades for the destruction of cancerous cells embedded inside biological tissue samples. The technique employs a laser source to target radiation on a tumor region, for the purposes of inducing a local hyperthermia to destroy the cancerous cells. It has been observed that upon raising the cell temperature beyond 43 °C for a specified amount of time, complete necrosis of the biological cells can be achieved [1]. Further, coupled with the temperature rise, successful destruction of the cancerous cells also requires a specified exposer time [2]. Robinson et al. [3] observed that a local temperature rise beyond 53 °C for an exposure time of up to 1 s would ensure complete destruction of cancerous cells. Therefore, the success of the photo thermal therapy lies in the ability to accurately determine the temperature distributions inside the body of the laser irradiated tissue phantoms. The numerical model must take into consideration an accurate representation of the physical tissue phantoms along with the different physical processes that take place inside the biological tissue phantoms. In addition, the technique of photo thermal therapy should maximize the damage to the cancerous cells, with a minimum possible collateral damage to the neighboring healthy tissues. In this context, the study of various heat transfer processes such as diffusion, convection and radiation transfer inside the body of the tissue phantoms need to be studied carefully and modeled accurately.

In order to predict the temperature distributions inside the tissue phantoms, the first objective would be to develop a concrete understanding of light propagation inside the tissue phantoms. The turbid nature of the tissue phantoms coupled with the fact that the biological tissues are porous in nature consisting of numerous blood vessels of various diameters, make the job of determination

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Nomenclature

c	speed of light in medium
c_p	specific heat of the tissue
C/F	Forchheimer number
G	incident intensity
h	heat transfer coefficient
I	intensity
I_b	blackbody intensity, $\sigma T^4/\pi$
k	thermal conductivity
K	permeability
M	number of discrete directions
P	pressure
q	radiative heat flux
s	distance traveled by beam
$\hat{s}$	unit direction vector
S	volumetric source term
T	temperature
t	time

Greek symbols

$d\Omega'$	control angle
ε	emissivity/porosity
κ	absorption coefficient
σ	scattering coefficient or Stefan–Boltzmann constant
β	extinction coefficient, $\kappa + \sigma$
μ, ζ	direction cosines in x and y direction respectively
Φ	scattering phase function
ω	weight in discrete direction m
ρ	density of the medium

Subscripts

f	clear fluid/blood
fp	fluid matrix in porous medium
sp	solid matrix in porous medium
sf	solid to fluid matrix

of the laser intensity distributions extremely difficult. Chandrasekhar [4] developed the Radiative Transport Equation (RTE) for explaining the process of light propagation inside the biological samples. The balance of photons inside a control volume due to all the possible events results in the generation of an integro-differential equation. The analytical solutions of RTE are extremely difficult, and are possible only for situations involving relatively simple geometries and boundary conditions. Thus, RTE has to be solved by employing suitable numerical methods. Various researchers have developed numerical methods for solving the RTE based on techniques of Finite Volume Method [5], Discrete Ordinates Method [6], Discrete Transfer Method [7] and Monte Carlo based statistical technique [8]. Literature also reports studies undertaken to compare the effectiveness and feasibility of different numerical methods for solving the radiative transport [9]. Mishra et al. [9] studied the solution of RTE inside one dimensional domains, by employing the different numerical models, and performed a comparative study.

For photo thermal therapy related applications, where the focus of the study is on the determination of temperature distribution inside the body of laser irradiated tissue phantoms, the temporal evolution of the light intensity and temperature distributions are required. Thus, the transient form of the RTE needs to be considered. The addition of the transient terms poses certain challenges to the numerical method. In this regard, the studies of Kumar and Srivastava [10] and Nirgudkar et al. [11], where the development of the numerical models by considering the transient form of RTE were presented, need to be considered.

The next step involved in the determination for temperature response of the laser irradiated tissue phantoms is the development of a suitable form of the energy equation to determine the resultant temperature distribution. The energy equations which predict the temperature fields for these applications are commonly referred to as the bio-heat transfer equations. Many forms of the bio-heat transfer equations have been proposed by numerous researchers to account for the different anatomical and bio-physical heat transfer aspects inside the tissue. Each of these developed models is associated with its inherent advantages and drawbacks. The earliest form of the bio-heat transfer equation was developed by Pennes [12] that considered the tissue to be a homogenous solid body with blood perfusing inside the body of the tissue. It was assumed that the temperature of the perfusing blood was equal to the venous blood temperature along the entire spatial domain of the tissue phantom. However, the Pennes bio-heat transfer equation does not consider the porous nature of the biological tissues and also neglects the presence of thermally significant blood vessels inside the tissue phantoms. Thus the temperature distributions as obtained by employing the Pennes bio-heat transfer model are prone to errors.

The subsequent bio-heat transfer models developed by Wulff [13], Klinger [14], Chen and Holmes [15] and other researchers proposed improvements to the Pennes model. It has to be noted here that these bio-heat transfer models do not consider the effects of porosity of the tissue. In order to consider the effect of the porous nature of the tissue on temperature distributions, Nakayama and Kuwahara [16] proposed a bio-heat transfer model to obtain the temperature distributions inside the porous tissue regions and the blood vessel regions of a tissue phantom. By employing the volume averaging theory, a set of volume averaged governing equations for the temperature distribution and blood flow were developed by the authors [16]. They further considered the counter current nature of the blood vessel inside the tissue phantoms, thus the model is generally referred to as the 3 energy equation model, as it tries to separately determine the temperatures associated with artery, vein and the tissue regions. By utilizing a similar set of governing equations, Roetzel and Xuan [17] determined the temperature distributions inside the human limbs.

It is to be noted that in addition to the porous nature of the biological tissue samples, the challenges associated with the development of any numerical model get compounded due to the presence of blood vessels, e.g. arteries, veins etc. thus the model must take into account the coupled effects of thermal diffusion through the body of the porous tissue as well as the convective heat transfer effects of the blood flowing through the blood vessels embedded inside the biological samples. Thus, the accuracy of the numerical predications strongly depends on how one handles the blood vessel–tissue interface. In this regard, the studies reported in the literature on the development of strong interface modeling at the porous tissue–blood vessel interfaces have now been discussed.

Numerous researchers published analytical solutions and also developed numerical models for the heat transfer and fluid flow across the porous–clear fluid interface, by considering test problem similar to Joseph–Beavers problem. Alazmi and Vafai [18] presented a comparative study of temperature and velocity profiles under different interface conditions, which are used to model the exchange of momentum and energy across the porous–clear fluid interfaces. Chikh et al. [19] considered a channel geometry in the presence multiple heated porous blocks, and studied the heat