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Analysis and analytical characterization of bioheat transfer during radiofrequency ablation

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ABSTRACT

Understanding thermal transport and temperature distribution within biological organs is important for therapeutic aspects related to hyperthermia treatments such as radiofrequency ablation (RFA). Unlike surface heating, the RFA treatment volumetrically heats up the biological media using a heating probe which provides the input energy. In this situation, the shape of the affected region is annular, which is described by an axisymmetric geometry. To better understand the temperature responses of the living tissues subject to RFA, comprehensive characteristics of bioheat transport through the annular biological medium is presented under local thermal non-equilibrium (LTNE) condition. Following the operational features of the RFA treatment, based on the porous media theory, analytical solutions have been derived for the blood and tissue temperature distributions as well as an overall heat exchange correlation in cylindrical coordinates. Our analytical results have been validated against three limiting cases which exist in the literature. The effects of various physiological parameters, such as metabolic heat generation, volume fraction of the vascular space, ratio of the effective blood to tissue conductivities, different biological media and the rate of heat exchange between the lumen and the tissue are investigated. Solutions developed in this study are valuable for thermal therapy planning of RFA. A criterion is also established to link deep heating protocol to surface heating.

1. Introduction

The modeling of bioheat transfer has been employed extensively in medical thermal therapeutic applications for predicting the temperature distribution (Khaled and Vafai, 2003; Khanafer and Vafai, 2009). Nowadays, cancer is still one of the lowest survival rate diseases. Hyperthermia treatment such as radiofrequency ablation (RFA) (Peng et al., 2011), microwave, laser (Dombrovsky et al., 2012), magnetic fluid (Giordano et al., 2010), etc. is recognized as the fourth adjunct cancer therapy technique following surgery, chemotherapy and radiation techniques. When biological tissues are subjected to high temperatures, which are typically 40–45 °C (Field, 1987), heat shock can cause a cancer cell to lose viability and eventually induce cell death (Kiss et al., 2009). In contrast to resection techniques, which have a poor prognostic outcome, RFA has the potential to improve and to optimize clinical treatment with fewer side effects (Goldberg et al., 2000; Peng et al., 2011). Similar to cryotherapy (Chua et al., 2007), RFA also has a minimally invasive nature. Briefly, RFA induces resistive heating in tissues in direct contact with an ablation electrode (Boronyak and Merryman, 2014). Liu (2001) presented an analytical solution to the Pennes bioheat transfer equation in three-dimensional geometry with practical hyperthermia boundary conditions and random heating. Chung and Vafai (2014) investigated analytically and numerically the effects of hyperthermia on low-density lipoprotein transport and heat transfer within a multi-layered arterial wall accounting for the fluid–structure interaction. However, the thermal responses of a living organ under ablation treatments have not yet been fully evaluated quantitatively in the clinical field. So it is imperative to study the general characteristics of bioheat transfer with medical affiliates in order to demonstrate the relationship between the heating power deposited in the tissue and the resulting tissue status post treatment.

A biological tissue consists of a microvascular bed with blood flow through many vessels. As such it is quite natural to treat the living tissue as a porous medium (Khaled and Vafai, 2003; Khanafer and Vafai, 2006; Zhang, 2009). Thus, the porous media theory can be utilized for bioheat transfer analysis, in which fewer assumptions are needed as compared to other established bioheat transfer models (Khaled and Vafai, 2003; Khanafer and Vafai, 2006, 2009; Nakayama and Kuwahara, 2008; Mahjoob and Vafai, 2009, 2010). Two primary models for analyzing heat transfer in a porous medium are: local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE). The LTE model is based on the assumption that the temperature for tissue phase is equal to that for blood phase, on a local basis, everywhere inside the porous medium. However, the LTE model does not hold for some physical

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Nomenclature

a_{tb}	specific surface area (1/m)
Bi	Biot number, $h_{tb}a_{tb}H^2/k_{t,eff}$
c_b	blood specific heat (J/kg °C)
h_{tb}	blood–tissue interstitial heat transfer coefficient (W/m^2 °C)
H	heating penetration depth (m), R_o-R_i
k_b	blood thermal conductivity (W/m °C)
$k_{b,dis}$	blood dispersion thermal conductivity (W/m °C)
$k_{b,\mathrm{eff}}$	effective thermal conductivity of the blood phase (W/m °C)
k_t	tissue thermal conductivity (W/m °C)
$k_{t,eff}$	effective thermal conductivity of the tissue phase (W/m °C)
n	ratio of the heating probe to the annulus radii, R_i/R_o
Nu	Nusselt number at the probe–organ interface for LTNE model
q_w	imposed heat flux on the organ (W/m^2)
Q_{met}	metabolic heat generation within the biological tissue (W/m^3)
r	radial coordinate (m)
R_i	radius of the heating probe (m)
R_o	radius of the heated annulus (m)
T	temperature (°C)
$T_{b,m}$	blood bulk mean temperature (°C)
T_c	body core temperature (°C)
T_e	arterial blood temperature entering the organ (°C)
T_w	temperature of the probe–organ interface subject to an imposed heat flux (°C)
u	lumen velocity (m/s)
u_e	arterial blood velocity entering the organ (m/s)
z	axial coordinate (m)

Greek symbols

ε	porosity (volume fraction of the vascular space)
ζ	dimensionless position of the annulus regulated from 0 to 1, $\eta-\eta_i$
η	dimensionless radial coordinate, r/H
θ	dimensionless temperature, $k_{t,eff}(T-T_w)/q_wH$
$\theta_{b,m}$	dimensionless bulk mean blood temperature
θ_c	dimensionless body core temperature, $k_{t,eff}(T_c-T_w)/q_wH$
κ	ratio of the effective blood thermal conductivity to that of the tissue, $k_{b,eff}/k_{t,eff}$
λ	$=\sqrt{(1+\kappa)\mathrm{Bi}/\kappa}$
ξ	dimensionless axial coordinate, z/H
ρ_b	blood density (kg/m^3)
Φ	dimensionless heat generation within the biological tissue, $(1-\varepsilon)HQ_{met}/q_w$
ψ	ratio of the radius of the heating probe to the heating penetration depth, R_i/H

Subscripts/superscripts

b	blood phase
c	body core
i	inner surface of the heated annular region
o	outer surface of the heated annular region
t	tissue phase
w	probe surface

Symbol

$\langle\rangle$	intrinsic volume average of a quantity

situations when the temperature difference between the two phases is not negligible (Khaled and Vafai, 2003). In such cases, the LTNE model should be utilized to investigate the blood temperature changes as a result of tissue-blood convective heat exchange and blood perfusion (Xuan and Roetzel, 1997; Lee and Vafai, 1999; Alazmi and Vafai, 2000; Zhang, 2009; Mahjoob and Vafai, 2009, 2010; Rattanadecho and Keangin, 2013). Mahjoob and Vafai (2009) carried out a comprehensive investigation of bioheat transport through the tissue/organ incorporating hyperthermia treatment using LTNE, and had established exact solutions for the tissue and blood temperature profiles during surface heating.

In a separate work, Mahjoob and Vafai (2010) investigated characterization of bioheat transport through a dual layer biological media. Dombrovsky et al. (2013) conducted numerical simulations on laser-induced hyperthermia of superficial tumors. Keangin et al. (2013) highlighted the effects of electromagnetic field on biological materials. In their study, the coupled equations of electromagnetic wave propagation and heat transfer under the LTNE assumption were solved by the finite element method. Peng et al. (2011) presented a two-equation coupled bioheat model to investigate thermal energy exchange between the blood and its surrounding peripheral tissue. Zhang (2009) obtained dual-phase bioheat equations by analyzing non-equilibrium heat transfer in a living biological tissue. Most recently, Keangin and Rattanadecho (2013) investigated the transient distribution of tissue and blood temperatures inside a porous liver during microwave ablation process.

Analytical solutions in this area are very useful as they provide an effective route for parametric studies when a large number of variables are involved. Nevertheless, most of the existing analytical solutions are concentrated on surface heating in planar geometry. For deep hyperthermia treatments such as RFA, the heating domain is approximately an annulus. To the authors' knowledge, no work has been performed analytically in the open literature on heat transfer within an annular biological medium while incorporating the LTNE condition.

The present study aims at predicting the blood and tissue temperature distributions within biological media as well as heat transfer behavior during RFA. The influence of the pertinent parameters such as vascular volume fraction, the effective thermal conductivity ratio, metabolic heat generation, etc. is analyzed. A criterion is also constructed to bridge the bioheat transfer for deep heating such as RFA and that for surface heating (Mahjoob and Vafai, 2009, 2010) through a geometrical analysis.

2. Mathematical modeling

2.1. Problem description

Biological tissue generally contains blood vessels, cells and interstitial space (Mahjoob and Vafai, 2009), which can be categorized as vascular and extra-vascular regions, as shown in Fig. 1(a). As such, the whole anatomical structure can be modeled as a porous matrix through which the blood infiltrates. Generally, the pressure is uniformly higher throughout the tumor as compared to the peripheral values, which leads to an extremely slow interstitial flow inside the tumor (Wu et al., 2009). Hence, the blood flow within the tumor region can be represented by the Darcy flow model (Wu et al., 2009; Mahjoob and Vafai, 2009, 2010; Cookson et al., 2012). In this study, hydraulically and thermally fully developed condition is assumed. The flow is steady and incompressible. Natural convection and radiation