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Interstitial hyperthermia treatment of countercurrent vascular tissue: A comparison of Pennes, WJ and porous media bioheat models

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ABSTRACT

Development of appropriate heat transfer models to investigate the thermal behavior of living tissues has become increasingly important in simulations of cancer hyperthermia. In this paper, a review is initially presented of the more important general models developed for heat transfer description of perfused tissues. Comparisons are then made between Pennes' simplified Weinbaum and Jiji “WJ” and the more recent porous media “PM” bioheat models. For this purpose, a mathematical model is developed for the heat transfer in a cylindrical medium containing parallel counter-current pairs of small vessels with characteristics as much as possible similar to those of living tissues. The validity of the models is examined and confirmed using the Pennes in vivo experiments and one-dimensional analytical solutions. For consideration of interstitial hyperthermia treatment the smaller cylindrical zone with typical heat generation, is assumed in the center of the main cylinder. The numerical simulation results revealed that, despite difference in temperature distributions calculated by these three models at normal condition, the heat affected zone at hyperthermic condition predicted by all three models are similar.

1. Introduction

Hyperthermia has found a large number of applications in treating such a wide variety of breast, prostate, and liver cancers, among others, with promising results and only little adverse effects. Hyperthermia of tumors can be categorized in the two external and interstitial treatments. Heat delivery to cancerous tissues in shallow-seated tumors is easily possible. Deep-seated tumors, however, pose serious challenges and require the use of interstitial systems in which the heat source is placed inside the tissue. Recently, the magnetic nanoparticles hyperthermia has proved to be more advantageous than other interstitial methods (Moroz et al., 2002). The major advantage of this method is the remote response of nanoparticles to a magnetic field (Dewhirst et al., 2003). Numerical simulations of interstitial hyperthermia have recently attracted more attention for this purpose. Of special importance for interstitial hyperthermia simulation is the effort to determine the similarities and differences among conventional bioheat models in terms of their capability to predict temperature distribution. In this study, we used the two well-established WJ and porous media bioheat models as well as the classic Pennes model for simulating the thermal behavior of vascular tissue with countercurrent network at normothermic and hyperthermic conditions and compared the results obtained.

In what follows, a review of the most important heat transfer models of perfused tissue is initially presented among which the Pennes, Weinbaum–Jiji and porous media models are selected for numerical comparisons. The similarities between these three models are: relative simplicity, several implications in original and modified forms by various scholars and their capability for general-purpose applications. Using the selected models with original and unmodified form, temperature distributions in tissues with a cylindrical geometry embedded within parallel, counter-current vessel pairs are predicted for normal and hyperthermic conditions and the results are compared. This geometry can provide all required inputs of the selected models. This paper is aimed at comparison and evaluation of these models in their initial and non-modified forms. Presentation of new models or modification of existing models is not in the scope of this paper. The results of the comparisons indicate that, despite the differences in temperature distributions for the cylinder under normal conditions predicted by the three models, they exhibit less differences under hyperthermic conditions in that the predicted temperature distributions are closer within the hyperthermia range. However, it is also found that, for the real physical conditions dominating living tissues, especially muscles, in which blood transport takes place in one direction, the porous medium model is the only model that is capable of capturing this asymmetry.

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Nomenclature

A	cross-section of blood vessel (m^2)
a	specific surface (m^2/m^3)
c	specific heat (J/kg °C)
h	interstitial heat transfer coefficient (W/m^2 °C)
K	thermal conductivity tensor
k	thermal conductivity (W/m °C)
P	circumference (m)
q	volumetric heat source (W/m^3)
r	radius (m)
S	coordinate along the path of blood vessel
T	temperature (°C)
n_p	vessel pair density ($1/m^2$)
g	blood flow (m^3/s)

Greek symbols

ε	porosity
ρ	density (kg/m^3)
σ	shape factor
ω	blood perfusion rate (m^3/m^3 s)

Subscripts and superscripts

a	arterial
b	blood
eff	effective
hyp	hyperthermia
m	metabolic
s	solid-tissue
v	venous

2. Heat transfer models for living tissues

Various models have been developed over the years for heat transfer in living tissues. The original objectives underlying the development of these heat transfer models included the assessment of the thermal behavior of the human body under various conditions, evaluation of skin burns, and determination of blood perfusion rates (Chato, 1981). Harry H. Pennes was the first scientist to study and develop a heat transfer model considering the effect of blood perfusion on tissue temperature (Charny, 1992). His paper published in 1948 has been widely cited in all subsequent studies in the field (Wissler, 1998).

2.1. Pennes model

The classical bioheat equation known as “Pennes' model” is given by Eq. (1), where the subscripts s and b represent tissue and blood, respectively. q_m is the metabolic heat production and ω_b is the blood perfusion rate per unit volume of tissue (Pennes, 1948).

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \nabla(k_s \nabla T_s) + \rho_b c_b \omega_b (T_a - T_s) + q_m \tag{1}$$

The basic assumption underlying the Pennes model is that heat exchange between blood and tissue occurs basically through the walls of the capillaries. The temperature of the blood delivered into the tissue through the arteries is originally T_a which will immediately reach a thermal equilibrium with that of the tissue inside the capillary bed. It follows then that the temperature of the blood outflow in veins is the same as that of the tissue. He concluded that the amount of heat exchanged serves as a heat source whose magnitude is a product of blood perfusion rate and the difference between blood and tissue temperatures. This heat source of the blood perfusion is expressed by $\rho_b c_b \omega_b (T_a - T)$ in the Pennes model which is still of great significance in the models developed more recently (Bhowmik et al., 2013). Despite the unrealistic concepts used in this model, it has found wide applications in the various fields of hyperthermia for its inherent simplicity and pragmatic results (Nelson, 1998).

2.1.1. Criticisms

Wulff (1974, 1980) was the first to write a critique on Pennes' model. He claimed that convective heat transfer between the blood and the tissue starts out from the arteries and that it must, therefore, be expressed by the vector quantity $(\rho_b c_b) u \nabla T$. His second criticism stated that the spatial and temporal derivatives of temperature and metabolism heat source are local terms while the term for blood–tissue heat exchange is global and, hence, in conflict with other terms.

Following Wulf, Klinger (1974, 1978) also emphasized the convective heat transfer contribution by vascular blood flow and proposed the convective term $(\rho_b c_b)\bar{u}(\bar{r}, t)\nabla T$ as a substitute for the Pennes perfusion term.

2.2. Counter-current bioheat transfer models

Most attention in all the above-mentioned works has been directed to the exchange of heat between a single blood vessel and its surrounding tissue. The actual fact, however, is that counter-current heat exchange seems quite possible due to the temperature difference and the proximity of the venous and arterial blood vessels (Charny, 1992). Scholander and Krog (1957) presented the first mathematical model of counter-current heat exchange. Some 10 years later, Mitchell and Myers (1968) challenged Scholander's concept of counter-current heat exchange which had been assumed to be restricted to the exchange between an arterial-venous pair. They developed a new model in which artery–tissue, vein–tissue, and artery–vein heat exchanges were taken into account. Three years later, Keller and Seiler (1971) developed another model which not only accounted for the counter-current heat exchange between main feeder arteries and collector veins but also introduced an equation for the conservation of energy in their surrounding tissues. Their model may be claimed to be the first of its kind to consider heat exchanges in tissues, arteries, and veins independently. This approach was later used in the models generally known as 'countercurrent bioheat models' proposed by Weinbaum et al. (1984a, 1984b), Baish (1990, 1994), and Charny and Levin (1989). Among these, the one proposed by Weinbaum et al. is of the highest importance.

2.2.1. WJL model

This model laid the greatest emphasis on the role of arterioles smaller than the main arteries in the blood–tissue heat exchange. The authors (Weinbaum, Jiji, and Lemon) initially performed a complete analysis to determine the thermal equilibration length (Le). In their study, the control volume, as shown in Fig. 1, included a pair of thermally significant blood vessels directly connected by capillaries. Based on anatomical observations and thermal measurements, Weinbaum et al. (1984a, 1984b) concluded that the local temperature of blood perfused into tissues mainly depends