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Analysis of thermal conductivity in living biological tissue with vascular network and convection

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ABSTRACT

Based on the blood circulatory system, a model is established for living biological tissue represented by a vascular network and surrounding tissue. In this paper, we analyze the heat transfer in living biological tissue and present an analytical model for the effective thermal conductivity of living biological tissue by taking into account the effects of geometric structures of branching vascular network and convection caused by blood flow. The proposed model is expressed as a function of the thermal conductivities of solid tissue matrix and blood, structural parameters of branching vascular network, porosity and properties of blood. It is found that the effective thermal conductivity of living biological tissue decreases with the increase of branching levels, length ratio and diameter ratio. It is also found that there exists a thermal conductivity ratio, at which the effective thermal conductivity is same for different porosities, below which the effective thermal conductivity increases with the increase of porosity, and above which the effective thermal conductivity decreases with the increase of porosity. A good agreement is obtained between the proposed model predictions and available experimental data for living tissue. The present results show that blood flow plays an important role in increasing the effective thermal conductivity, and the proposed model with blood flow is more reasonable and can reveal more physical mechanisms of heat transfer in living biological tissue.

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1. Introduction

With the development and progress of science and technology as well as modern medical treatment, research on the biological heat transport has received widespread attention in the fields of biological science and medicine, such as hyperthermia, cryosurgery, organ transplantation frozen storage, biological tissue cutting and welding, disease diagnosis, food preservation and thermal comfort analysis, etc. Study of biological heat transport has become one of the hot topics in the international academic circles. Heat transfer through living biological tissue is a complicated process, which is involved in heat conduction in solid tissue matrix and blood vessels, convective heat transfer between tissue and blood (blood perfusion), as well as metabolic heat generation [1]. The thermal conductivity of biological tissue (especially in vivo) is not only pivotal to deeply study heat transfer characteristics and mechanisms but also important in the clinical medicine applications [2,3]. For example, in an effective hyperthermia treatment [4–6], in order to precisely predict and control temperature distribution in therapy region and ensure that the tumor is mandated in the therapy temperature and the surrounding normal tissue is in safe temperature, an important aspect is the knowledge of the thermal conductivity of tissue. Heat transport in biological tissue is usually expressed by bio-heat models, such as Pennes [7] bio-heat transfer equation, Weinbaum and Jiji's [8] model, Wissler's [9] model, Baish's [10] model, Xuan and Roetzal's [11] model, etc, which are the basis of the human thermotherapy and the human thermoregulation system [12,13]. For establishment and validation of such bio-heat transfer models, the selection for the thermal conductivity of biological tissue is a key issue. Thermal conductivity is mainly determined by experiments, e.g., the guarded hot plate technique was proposed by Hill et al. [14], and this technique is a steady-state method only used to measure the thermal conductivity of dead tissues. The step-temperature technique was developed by Valvano and Bowman et al. [2] and the pulse delay method was presented by Chen et al. [15], both of which are transient thermal techniques mainly to measure the thermal conductivity of living tissue. However, the data of thermal

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Nomenclature

A	cross-sectional area of the entire living biological tissue of a unit cell
A_{eb}	equivalent cross-sectional area of the vascular network
d	branching diameter of the vascular network
d_0	diameter of the 0th branching level (capillaries)
d_k	diameter of the kth branching level
d_f	diameter of liquid molecule
h	heat convection coefficient
h_0	heat convection coefficient of the 0th branching level
h_k	heat convection coefficient of the kth branching level
l_0	length of the 0th branching level
l_k	length of the kth branching level
l_m	length of the mth branching level
L_0	representative length of the vascular network
m	total number of branching levels
Nu	Nusselt number
n	branching number (=2 in this paper)
$2n^{m-k}$	total number of branching channels at the kth branching level
Pr	Prandtl number
Q_{cv}	heat convection caused by blood flow in the vascular network
R_b	total thermal resistance by heat conduction in the vascular network
R_k	thermal resistance of a single channel of the kth level
R_m	total thermal resistance by heat conduction in the solid tissue matrix
R_t	total thermal resistance by heat conduction in vascular network and solid tissue matrix
S	total heat convection area of the vascular network
S_k	heat convection area of the kth branching level
T	temperature
ΔT	temperature difference

Greek symbols

α	ratio of the length of the channels at two successive branching levels
β	ratio of the diameter of the channels at two successive branching levels
θ	branching angle
λ_b	thermal conductivity of blood
λ_m	thermal conductivity of solid tissue matrix (tissue)
λ_{cd}	effective thermal conductivity by heat conduction in vascular network and solid tissue matrix
λ_{cv}	equivalent thermal conductivity by heat convection caused by blood flow
λ_{eff}	total effective thermal conductivity of the entire living biological tissue
λ_{cd}^{+}	dimensionless effective thermal conductivity by heat conduction
λ_{cv}^{+}	dimensionless equivalent thermal conductivity by heat convection
λ_{eff}^{+}	total dimensionless effective thermal conductivity of the entire living biological tissue
ε	porosity
δ_T	thickness of the thermal boundary layer of heat convection caused by blood flow

Subscripts

k	rank of channel
e	equivalent
b	blood
m	solid tissue matrix (tissue)
t	total
eff	effective
cd	conduction
cv	convection

conductivity of biological tissue are seriously insufficient due to the limitations of existing testing technology and the notable difference among the data reported in the literature. So the estimation of thermal conductivity has received much attention [16–20]. As Roetzel and Xuan [21] points out, the lack of experiment data for thermal conductivity of biological tissue should not hinder us from applying the present bio-heat models to certain cases using estimated values. In this work, we establish a theoretical model to predict the effective thermal conductivity of biological tissue based on the blood circulatory system.

Biological medium can be treated as a fluid saturated porous medium as the blood vessels can be considered as pores in the medium, in which the blood permeates and the extra-vascular tissue can be considered as a solid tissue matrix [22–24] (see Fig. 1(a)). The blood vessels in tissue are often connected in the form of branching structure called branching vascular tree [25–29]. Fig. 1(b) shows a branching vascular tree of arteries or veins [30,31]. A large number of studies showed that the branching structure is statistically self-similar and has fractal characteristics in the range of a certain scale, and can be described by fractal-like tree branching network [18,32]. Masters [28] demonstrated that the vascular tree in the normal human retina has statistical self-similar fractal structure, and the fractal dimension of the blood vessels is approximately 1.7. Buijs et al. [33] also studied the geometrical and fractal properties of the rat hepatic portal vein tree and found that the mean fractal dimension is 1.37. Furthermore, some experimental studies [2,34–36] showed that the blood flow via blood vessels has great effect on the thermal conductivity of living biological tissue. For instance, Liang et al. [35] measured the thermal conductivity of a dead and a living snake and found that the thermal conductivity increases from 0.494 W m^{-1} K^{-1} (without blood flow) to 0.58 W m^{-1} K^{-1} (with blood flow). Thus, in this paper, we establish an analytical model for the effective thermal conductivity of living biological tissue by considering the effects of geometric structures of branching vascular network and blood flow.

This paper is organized as follows. After the introduction, Section 2 gives a brief description of the models for living biological tissue based on the blood circulatory system. Then in Section 3, an analytical expression for the effective thermal conductivity of living biological tissue based on the blood circulatory system is derived by considering the effects of geometric structures of branching vascular network and blood flow. The results and discussions of the proposed model are shown in Section 4. Finally, the conclusions are presented in Section 5.

2. Description of the model for living biological tissue

Fig. 2(a) shows a sketch of artery and vein surrounding by solid tissue matrix [24], (b) shows the schematic of the model for living biological tissue represented by a vascular network and

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