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The effect of a bifurcation structure on the heat transfer and temperature distribution of pulsatile blood flow

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ABSTRACT

To analyse the influence of a bifurcation structure on the heat transfer and temperature distribution of pulsatile blood flow, a transient heat transfer model of pulsatile blood flow was constructed. The velocity and temperature distributions of pulsatile blood flow in a bifurcation vessel tree that included a main blood vessel and two branch vessels were simulated using the model. The transient Nusselt number and the time-averaged Nusselt number in branch vessels with different diameters or different boundary conditions were calculated and compared. The results show that the temperature and velocity profiles at the inlet cross section of the branch vessels are non-axisymmetric and pulsatile. There is a low-temperature region at the bifurcation junction of the two branch vessels, and the transient value of the minimum temperature varies with the time of the pulsatile blood flow. Comparing the simulated Nusselt number of pulsatile blood in this study with that of steady-state laminar blood reported in the literature, we found that pulsation does not enhance the heat transfer of blood flow. For the real vessel parameters in a physiological system, the time-averaged Nusselt number in branch vessels, especially for large vessels, is larger than the Nusselt numbers of a fully developed laminar flow for blood. The asymptotic values of the Nusselt number of blood for a uniform heat flux and uniform wall temperature are 4.432 and 3.753, respectively.

1. Introduction

In modern medical and biological research, simulating the heat transfer process in biological tissues is a common research method. For example, to ensure heat treatment efficiency in cancer therapy, the dynamic three-dimensional temperature field of the heated tissue, as obtained by the numerical simulation of the heat transfer process, can be used to predict the treatment outcome [1–3]. One of the most difficult problems in estimating heat transfer in living systems is the assessment of the effect of blood circulation. There is a complex coupling relationship between blood flow and heat transfer in living tissues [4,5]. The structure of a blood vessel tree in living tissue, the blood velocity, and the properties of blood can all significantly affect the heat transfer between the tissues and blood and change the tissue temperature [6]. The cooling effect of a vessel may change the efficiency of therapy [7–9]. In thermal ablative therapies, tumour recurrence occurs more frequently when the tumour is localized near a vessel because cancer cells close to vessels may not reach the required temperature and survive due to the heat sink effect caused by blood flow [10].

A fully coupled method is often used to analyse the heat transfer of blood [11,12]; i.e., the heat exchange between blood and tissue is calculated based on the mass, momentum and energy conservation equations of blood and the energy conservation equation of tissue. However, for a tissue geometrical model containing a complicated vessel tree, the fully coupled simulation of heat exchange between blood and tissue is difficult because of the large number of grids required. In this case, a Nusselt number [13] or a Nusselt number function [14], which represents the convective boundary condition at the tissue-blood interface, can be used to calculate the heat transfer between blood and tissue in place of a fully conjugated method. Some researchers have studied the Nusselt number of blood using experiments or calculations. An experiment was designed by Charm et al. [15] to obtain information about the heat transfer coefficient in small tubes (0.6 mm diameter) in a water bath. Shah et al. [16] designed an instrument to measure the heat convection coefficient on the endothelial surfaces of vessels. Considering the non-Newtonian behaviour of blood, Victor and Shah [17] calculated the Nusselt number in a tube for a uniform heat flux and uniform wall temperature using

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Nomenclature

C	specific heat capacity
d	vessel diameter
Gz	Graetz number
λ	thermal conductivity
Nu	Nusselt number
P	pressure
Pr	Prandtl number
Re	Reynolds number
t	time
T	temperature
T_p	pulse period of blood flow
Q	mean flow rate
x	distance from the inlet section of branch vessel 1
$\vec{u}$	velocity vector

Greek symbols

α	bifurcation angel
ρ	density
η	viscosity
$\dot{\gamma}$	shear rate

Subscripts

m	main vessel
1	branch vessel 1
2	branch vessel 2

a numerical method. Barozzi and Dumas [18] analysed the influence of the plasma layer near the vessel wall on the Nusselt number of blood using a numerical simulation. Chato [19] developed correlation equations for estimating the heat transfer under different configurations and diameters of blood vessels. By simulating the heat transfer process, Luisa et al. [20] proposed a function to evaluate the heat convection coefficient in the portal vein when a portion of its surface is heated.

Previous studies regarding the heat convection coefficient or Nusselt number of blood all used a single vessel as the research object, and the effect of a bifurcation structure on heat transfer was not considered in those papers. Yue et al. [21] found that the structure, size, and position of a bifurcation vessel significantly affects the heat transfer process in magnetic fluid hyperthermia treatment. Zhang and Xie [22] also analysed the effect of a bifurcation structure on the Nusselt number of blood. The blood flow through the bifurcation vessels studied in these investigations was assumed to be under steady-state conditions. However, in a real physiological system, the blood flow in vessels is pulsatile due to fluctuations from the pumping action of the heart. Studies of the heat transfer of pulsatile blood flow have focused on describing the effect of a single vessel on the tissue temperature [23–26]. The present paper presents the flow and heat transfer of pulsatile blood flow in a bifurcation vessel tree simulated by solving a three-dimensional heat transfer model of blood. The dynamic velocity profile and temperature profile of this bifurcation structure in a pulse cycle were obtained, and the effect of bifurcation on the Nusselt number of pulsatile blood flow was analysed.

2. Heat transfer model of pulsatile blood in a bifurcation vessel tree

2.1. Geometry of a bifurcation vessel tree

According to morphometrical investigations, the number of branches at each bifurcation point in a vessel tree is almost two [27]. Therefore, a binary bifurcation vessel tree including a main vessel and two branch vessels was used in this study (Fig. 1). x is the distance from the inlet of branch vessel 1. α is the angle between two branch vessels and is termed the bifurcation angle. As vascular walls are elastic muscular tissue, round corners were used in the joint between the main vessel and branch vessels to accurately simulate the actual vessel structure. The sizes of the vessels studied in this paper ranged from terminal arterial branches to large arteries, which are thermally significant blood vessels [28] and have a significant cooling effect on therapy. The lengths of these vessels were selected based on the diameter-to-length ratios in the vasculature [6]. The angle α was 90°. The parameters of the bifurcation vessel tree used in this paper are presented in Table 1. The diameter of branch vessel 2 was calculated using Murray's law [29], Eq. (1):

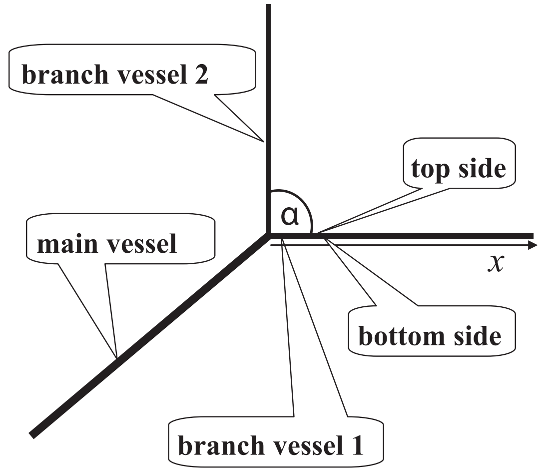

Fig. 1. Schematic of the bifurcation vessel tree.

$$d_m^3 = d_1^3 + d_2^3 \tag{1}$$

2.2. Assumptions

The assumptions of this heat transfer model of pulsatile blood flow in a bifurcation vessel tree are as follows. Vessel tapering and wall distensibility are overlooked. The blood flow is laminar with constant properties, except viscosity. The pulsatile blood flow is treated as a non-Newtonian fluid, and its viscosity property is described by Carreau's shear-thinning model [30], as shown in Eq. (2).

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (k\dot{\gamma})^2]^{(a-1)/2} \tag{2}$$

Here, $\dot{\gamma}$ is the shear rate. η_0 and η_∞ are the zero shear viscosity and the infinite shear viscosity, respectively, with $\eta_0 = 0.056$ Pa s, and $\eta_\infty = 0.00345$ Pa s. k is the time constant: $k = 3.313$ s. a is a consistency index: $a = 0.3568$.