Available online at www.sciencedirect.com
ScienceDirect
Communications in Nonlinear Science and Numerical Simulation 13 (2008) 1615–1626
Communications in Nonlinear Science and Numerical Simulation
www.elsevier.com/locate/cnsns

Numerical investigation of blood flow. Part I: In microvessel bifurcations

A. Jafari [a,*], S.M. Mousavi [b,c], P. Kolari [d]

[a] Department of Energy and Environmental Technology, Lappeenranta University of Technology, Lappeenranta, Finland
[b] Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran
[c] Department of Chemical Engineering, Lappeenranta University of Technology, Lappeenranta, Finland
[d] Laboratory of Computational Fluid and BioFluid Dynamics, Lappeenranta University of Technology, Lappeenranta, Finland

Received 11 May 2006; received in revised form 29 September 2006; accepted 29 September 2006
Available online 19 December 2006

Abstract

In some diseases there is a focal pattern of velocity in regions of bifurcation, and thus the dynamics of bifurcation has been investigated in this work. A computational model of blood flow through branching geometries has been used to investigate the influence of bifurcation on blood flow distribution. The flow analysis applies the time-dependent, three-dimensional, incompressible Navier–Stokes equations for Newtonian fluids. The governing equations of mass and momentum conservation were solved to calculate the pressure and velocity fields. Movement of blood flow from an arteriole to a venule via a capillary has been simulated using the volume of fluid (VOF) method. The proposed simulation method would be a useful tool in understanding the hydrodynamics of blood flow where the interaction between the RBC deformation and blood flow movement is important. Discrete particle simulation has been used to simulate the blood flow in a bifurcation with solid and fluid particles. The fluid particle method allows for modeling the plasma as a particle ensemble, where each particle represents a collective unit of fluid, which is defined by its mass, moment of inertia, and translational and angular momenta. These kinds of simulations open a new way for modeling the dynamics of complex, viscoelastic fluids at the micro-scale, where both liquid and solid phases are treated with discrete particles.

PACS: 47.63.Cb; 87.15.Aa; 47.63.−b

Keywords: Computational model; Blood flow; Bifurcation; Volume of fluid (VOF); Particle simulation

* Corresponding author.
E-mail address: ajafari@lut.fi (A. Jafari).

1007-5704/$ - see front matter
doi:10.1016/j.cnsns.2006.09.017

1. Introduction

Fluid flow in bifurcation is a very complex problem of hydromechanics. It covers many technical and biomedical applications. Many papers have been written about cases of bifurcation, such as bifurcation of vessels, pipes and etc. [1–4], but still it is not completely and clearly described.

From the point of view of biomedical application, the vessel bifurcation is a place where many diseases start. We are not able to change the geometry of vessel bifurcation, but the understanding of blood flow in it helps us to better cure vessel diseases or to anticipate them. Another reason why it is important to deal with blood flow in vessel bifurcation is to learn from it how to design bifurcation for technical application, because we may assume that the geometry of vessel bifurcation is optimal [5].

Blood circulation involves flows through networks of tubes with diameters ranging from 1 cm down to a few μm, driven by the pumping action of the heart [6]. The red blood cell (RBC)-plasma suspension (blood) can be considered to be Newtonian at shear rates above 1000 s^{-1}. High shear rate flows occur in channels with a characteristic diameter of 400 μm. In smaller channels, effects such as migration of RBCs transverse to the main flow could play a key role in flow dynamics. In fact, if aggregation does occur the secondary processes such as sedimentation and syneresis could become the rate-limiting mechanisms. In this light, a simple continuum model is not satisfactory for vessels with diameters well below 400 μm such as microvessels [7].

In the arteriole system the vessels involved are often curved and they branch repeatedly [7]. The area ratio, defined as the combined cross-sectional areas of the daughter branches divided by that of the parent artery, is an important indicator of ''expansion'' or ''narrowing'' in a tree [1]. At a bifurcation the flow in the upstream parent vessel divides into the two daughter vessels so as to bring high velocity blood at the center of the parent vessel in close proximity to the wall of the flow divider [8,9]. When blood flows through a diverging bifurcation, a disproportional fraction of red blood cells generally flows into the branch that receives a higher total flow leading to a higher hematocrit in that branch than in the other [10]. In particular, if the flow into the low-flow branch is sufficiently small, RBCs do not enter that branch. Therefore, that branch skims plasma from the peripheral layer of the flow. Such behavior reflects axial migration of RBCs upstream of the bifurcation, producing a phase separation in the parent vessel, and this physiological phenomenon, which causes heterogeneity in the microcirculation, is caused by a cell-depleted wall layer [11].

The fluid forces directly at a bifurcation can also effect phase separation. Since blood cells are finite size particles, a certain fraction of them will always be found along the dividing stream surface [12]. Only at the branch point the balance of fluid forces will decide which way such cells go, leading to a partial separation of the solid and fluid phase. This process does not require an uneven distribution of the hematocrit in the parent vessel, and is called red cell screening [13].

During the past two decades, the role of the fluid mechanics of blood flow has been implicated in the development of arterial diseases and in the regulation of cellular biology in both normal and diseased arteries [14–16]. Most computer models of blood are motivated by fluid dynamic factors in the development of arterial diseases in large and medium vessels of the circulatory system [2,17]. A common mathematical description of the blood flow treats blood as a homogeneous fluid and solves the full three-dimensional and time-dependent Navier–Stokes equations for incompressible fluids [18]. A number of methods are being used to investigate the dynamic forces in the vascular system, with computational fluid dynamics (CFD) becoming the most prevalent because of its ability to provide more detailed flow information than either in vivo or in vitro experiments. Although significant insight has been gained from CFD simulations in idealized vascular geometries, geometry clearly has a dominant influence on the local dynamics and there is a consequent need for subject specific vascular flow modeling [19].

This paper is focused on blood flow dynamics in branching geometries approaching the microvessels. The organization of the paper is as follows. In Section 2, the mathematical modeling is described. In this part firstly a simple model is developed to investigate the validity of the raster method for mesh generation and then the specific example of flow in a branching where the blood transfers from an arteriole to a venule via a capillary is shown. In Section 2.3, a detailed overview of discrete particle method is presented, and the numerical method is explained in Section 3. This method may be useful for developing a simplified model for particle simulations of microcirculation. This would be the approach to apply to this research topic in the future. Finally, the concluding remarks are presented, providing a correct methodology and a mathematical and numerical framework for the simulation of blood flows in branching.