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DIRECT NUMERICAL SIMULATION OF CELLULAR BLOOD FLOW THROUGH A MODEL ARTERIOLE BIFURCATION

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Introduction

Blood is composed of a suspension of red blood cells (RBCs) suspended in plasma, and the presence of the RBCs substantially changes the flow characteristics and rheology of these suspensions. The viscosity of blood varies with the hematocrit (volume fraction of RBCs), which is a result not seen in Newtonian fluids. Additionally, RBCs are deformable, which can alter suspension dynamics. Understanding the physics in these flows requires accurately simulating the suspended phase to recover the microscale, and a subsequent analysis of the rheology to ascertain the continuum-level effects caused by the changes at the particle level. The direct numerical simulation of blood flow including RBC migration effects has the capability to resolve the *Fåhraeus effect* of observing low hematocrit values near walls, the subsequent cell-depleted layer, and the presence of velocity profile blunting due to the distribution of RBCs.

For flows through bifurcations, the hematocrit and volume flow rate are typically not proportional. This effect is commonly referred to as the *phase separation effect* [1, 2]. The hematocrit distribution in the daughter branches is a function of several variables including the hematocrit of the parent vessel, vessel diameters, and the volumetric flow rate ratio of the daughter to parent vessels [2]. Previous studies [3] indicate that the phase separation effect is not a function of the angle and orientation of the vessels. Another term relative to this phenomena is *plasma skimming*, which refers to observation that the smaller daughter branch of an arteriole bifurcation may 'skim' the cell-depleted layer of its parent arteriole [4, 5]. The phenomena of phase separation and plasma skimming are the motivation for our investigations of cellular flows through model bifurcations relevant to microcirculation.

Bifurcations of arteries throughout mammalian circulatory systems are all unique. However, many studies show that the area ratio between the main and daughter branches of bifurcations follow *Murray's law* [6] which states that the size of daughter branches is such that there is a balance between the metabolic energy of a given volume of blood and the energy required for blood flow [7]. This concept is used to generate theoretical vascular networks with constant wall shear stress. This law was constructed assuming that the vascular walls are rigid, the flow is Poiseuille with a constant pressure gradient, and that blood behaves as a Newtonian fluid. The daughter branch sizes are then determined based on the minimization of dissipated power through the network. Using Murray's law the radii of the daughter branches of a model bifurcation can be chosen such that

$$r_m^3 = r_{d1}^3 + r_{d2}^3 \tag{1}$$

where r_m is the radius of the mother vessel, and r_{d1}, r_{d2} are the radii of the daughter branches. This law is used in the construction of the model geometries used in our investigations of arteriole bifurcations. These model bifurcations are generated in ICEM-CFD and are treated as rigid finite element entities embedded in the fluid domain. An example model bifurcation is given in Fig. 1. For this configuration, the mother branch radius is r_m=21.$\bar{3}$ μm and the daughter branches radii are r_{d1}=18 μm and r_{d2}=15.$\bar{6}$ μm.

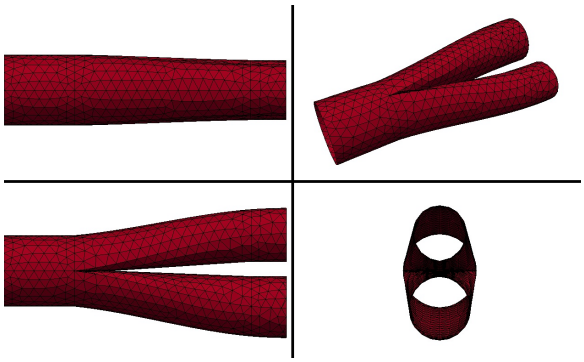

Figure 1. Bifurcation constructed using Murray's law in ICEM-CFD.

Methodology

The method employed for this study combines a lattice-Boltzmann (LB) method with a linear-elastic finite element (FE) method for deformable RBCs. The LB method accurately solves the Navier–Stokes equations at finite Reynolds number and is a readily parallelized algorithm [8]. This 3D LB/FE method shows good agreement to experimental results of blood flow and accounts for the two-phase nature of blood and the deformation of the suspended RBCs [9].

Results

The ensemble averaged axial velocity profile for the mother branch of the bifurcation is given in Fig. 2. The ensemble averaged hematocrit profile for the mother branch of the bifurcation is given in Fig. 3. The velocity profiles show various degrees of blunting for different hematocrit values. From the hematocrit profile, the cell-depleted wall layer observed is approximately 1μm thick. Further analysis of the daughter branches will be given later.

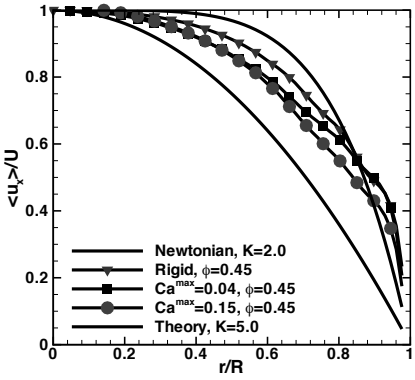

Figure 2. $\langle u_x \rangle / U$ profile for the mother branch of the arteriole bifurcation.

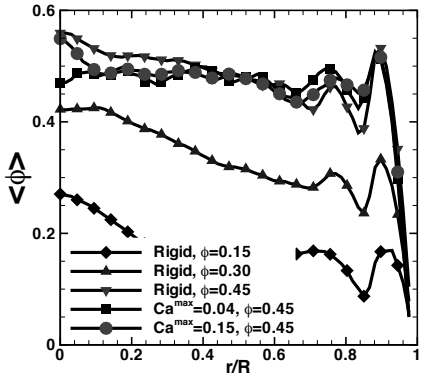

Figure 3. $\langle \phi \rangle$ profile for the mother branch of the arteriole bifurcation.

Acknowledgments

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