Hemorheology and hemodynamics: modeling and simulations

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Abstract

The blood circulation in the cardiovascular system depends not only on the driving force of the heart and the architecture and mechanical properties of the vascular system, but also on the mechanical properties of blood itself. Whole blood is a concentrated suspension of formed cellular elements including red blood cells (erythrocytes) white blood cells (leukocytes) and platelets (thrombocytes). Blood cells are suspended in plasma, an aqueous ionic solution. Experimental investigations over many years show that blood flow exhibits non-Newtonian characteristics such as shear-thinning viscosity, thixotropy, viscoelasticity and yield stress, and its rheology is largely due to three aspects of erythrocytes behavior: their ability to form a three dimensional (3D) microstructure at low shear rates, their deformability, and their tendency to align with the flow field at high shear rates. An understanding of the coupling between the blood composition and its physical properties is essential for developing suitable constitutive models to describe blood behavior.

Hemodynamic factors such as flow separation, flow recirculation, and low and oscillatory wall shear stress are recognized as playing important roles in the localization and development of important vascular diseases. Therefore, mathematical and numerical simulations of blood flow in the vascular system can ultimately contribute to improve clinical diagnosis and therapeutic planning. However, meaningful hemodynamic simulations require constitutive models that can accurately model the rheological response of blood over a range of physiological flow conditions. Experimental evidence on the stability of the 3D microstructure of erythrocytes suggests that it is probably reasonable to treat the blood viscosity as constant in most parts of the arterial system of healthy individuals, due to the high shear rates found in these vessels and the length of time necessary for the blood microstructure to form. However, in diseases states in which the stability of the aggregates is enhanced or for diseases in which the arterial geometry has been altered to include regions of recirculation (e.g. saccular aneurysms), this simplifying assumption may need to be relaxed and a more complex blood constitutive model should be used. In addition, even in healthy patients, the non-Newtonian characteristics of blood can play an important role in parts of the venous system.

In this talk we present a short overview of some constitutive models that can mathematically characterize the rheology of blood and some numerical simulations to illustrate its phenomenological behaviour [1, 2]. Some numerical simulations obtained in geometrically reconstructed real vessels will be shown to illustrate the hemodynamic behavior using Newtonian and non-Newtonian inelastic models under a given set of physiological flow parameters. Moreover, using a mesoscopic lattice Boltzmann flow solver for non - Newtonian shear thinning fluids, we present a three-dimensional numerical study of the dynamics of leukocytes rolling and recruitment by the endothelial wall, based on in vivo experimental measurements in Wistar rat venules [3]. Preliminary numerical results obtained for a comprehensive model of blood coagulation and clot formation, that integrates physiologic, rheologic and biochemical factors will also be presented [4].

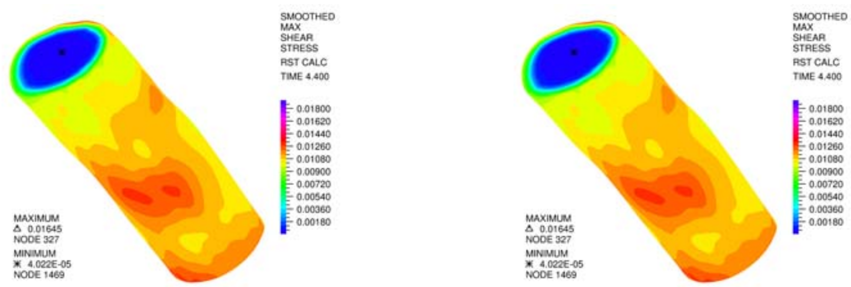

Figure 1: Wall shear stress distribution for a non-Newtonian Carreau-Yasuda model (left) and for a Newtonian model at high shear rate viscosity (right).

Keywords: blood rheology, blood cells, non-Newtonian models, numerical simulations.

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