Rheological Characterization of Blood Flow

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Abstract – The red blood cells are described as deformable closed shell with a membrane characterized by bending rigidity and stretching elasticity. To numerically investigate blood flow and blood associated processes in complex geometries, a highly efficient simulation technique is essential. In this paper we focused on the various modeling techniques of blood flow, the behavior of single and several cells in shear and micro capillary flows, the shear thinning behavior of blood and its relation to the blood cell structure.

Index Terms – Shear Thinning, viscosity, Newtonian solvent, micro capillary flow.

1. INTRODUCTION

Blood performs a large variety of essential functions in our body, ranging from the transport of oxygen to immune response and wound healing. Therefore blood diseases have severe consequences for our health. Prominent examples are plaque formation in arteries which may lead to heart attacks, diabetes as a cause of reduced microcirculation and tissue damage, excessive blood clotting leading to stroke, reduced blood clotting which causes excessive bleeding, etc. therefore, blood flow have attracted the interest of herbal and medical scientists for centuries. With modern tools of chemical analysis, diagnostics and simulation the field has made considerable progress in recent years D.A Fedosov et al.

In order to triumph the numerical problems, several mesoscale hydrodynamics simulation techniques have been developed in the last decades. The Lattice Boltzmann method (LBM) (Succi 2001), dissipative particle dynamics (DPD) (Hoogerbrugge and Koelman 1992; Espanol and Warren 1995), and multi-particle collision dynamics (MPC) (Malevanets and Karpal1999; Kapral2 2008; Gompper et al.2009) have shown a rapid advancement in the recent years, and are now well established techniques for the numerical investigation of the dynamics of complex fluids.

2. METHODS AND MODELS

A variety of methods to model cells and vesicles in flow has been recently applied and developed. These methods are generally mesoscopic, because microscopic modeling of cells is not feasible computationally: here, microscopic modelling refers to a representation on the scale of single atoms and molecules. Furthermore, a flow of cells and vesicles often cannot be described on a macroscopic level, since the properties and dynamics of single cells play an important role in the flow, but enter into macroscopic methods only approximately via constitutive equations D.A Fedosov et.al.

2.1. Modeling Newtonian solvent

Modeling fluid flow of a Newtonian solvent is probably the most developed methodological area out of the three groups identified above. Continuum fluid flow modeling is often performed using the Navier-Stokes equation or its modifications, which has resulted into the development of the computational fluid dynamics (CFD) field (Wendt 2009), fluid flow is described by a set of partial differential equations and satisfies the conservation laws and continuum assumptions. The equations can be solved numerically using various discretization techniques (e.g. finite difference, finite element), initial and boundary conditions. The advantages of continuum modeling include speed and robustness of methods and rather well established numerical techniques and codes. However, in these methods, it may be non-trivial to include some features present at the micro and mesoscale, for instance thermal fluctuations. There also exist several other numerical methods, which do not strictly belong to the continuum or particle-based methods groups, but they can be used to efficiently model fluid flow. These include the Lattice Boltzmann method (LBM) (Succi 2001) and Brownian dynamics (Ermak and McCammon 1978), which are often considered to be mesoscopic. In LBM, the Boltzmann equation is solved on a pre-defined lattice leading to proper fluid hydrodynamics.

2.2. Red blood cell model

Human red blood cells (RBCs) are biconcave with a diameter of about 8 µm and a thickness of 2 µm. a RBC is composed of a membrane filled with a viscous cytosol (hemoglobin solution), which is usually assumed to be a Newtonian fluid with a viscosity several times larger than that of blood plasma under physiological conditions. The RBC membrane consists

of a lipid bilayer re-enforced by two-dimensional spectrin-protein cytoskeleton attached to the back side of the bilayer. The lipid bilayer is fluidic and area-preserving (Fung 1993), while the spectrin network supplies RBC elastic resistance, which is re quired to sustain large deformations when passing through relatively narrow capillaries with the diameter down to 3 µm.

The network model of a RBC is built by a set of points which form a two dimensional triangulated network on a RBC surface (Fedosov et al. 2010a; Noguchi and Gompper 2005a; Dupkin et al 2007 ; Discher et al. 1998 ; Li et al.2005; Pivkin and Karniadakis 2008; Fedosov et al. 2010c). The potential energy of this system is defined as

$$U(\{X_i\}) = U_S + U_b + U_a + U_v$$

where U_s is the spring's potential energy, U_b is the bending energy, and U_a and U_v correspond to the area and volume conservation constraints, respectively. The U_S part of the total RBC energy mimics membrane viscosity response of the network similar to RBC membrane viscosity. The curvature energy term supplies bending resistance of the lipid bilayer, while the area and volume conservation constraints mimic the area incompressibility of the lipid bilayer and incompressibility of a cytosol, respectively. The RBC biconcave shape is also characterized by the reduced volume $V^* = V_0/(4/3\ \pi\ R_0^3)$, where V_0 is the RBC volume and $R_0 = (A_0/4\pi)^{\wedge 0.5} = 3.5$ µm , with A_0 being the area of a RBC. The reduced volume of a healthy RBC is about $V^*=0.6$; at this reduced volume, the discocyte shape minimizes the curvature energy of a fluid lipid vesicle (Deuling and Helfrich 1976).

3. BLOOD RHEOLOGY AND STRUCTURE

Rheological properties of blood are governed by RBCs due to their high volume fraction. RBCs in whole blood are able to form aggregate structures called "Rouleaux," which resemble stacks of coins (Merrill et al. 1963, 1966; Chien et al 1970). The RBC aggregation is associated with the plasma proteins (Merrill et al.1966; Chien et al. 1970) such that an increase in fibrinogen concentration leads to a significant increase in blood viscosity (Merrill et al 1966). Moreover, whole blood appears to exhibit a yield stress (a threshold stress for flow to begin) (Merrill et al.1963; Cokelet et al. 1963; Copley etal.1973).In simulations, blood is modeled as a suspension of RBCs, which is characterized by a bulk hematocrit H_t.

3.1. Blood viscosity and RBC aggregation forces

The viscosity of whole blood and non-aggregating RBC suspension has been measured at physiological temperature 37^0Cfor different H_t values in several rheological experiments (Merrill et al. 1963; Chien et al 1966; Skalak et al. 1981). The blood viscosity in simulations (Fedosov et al. 2011b) has been obtained from a RBC suspension in simple shear flow. The blood viscosity was computed over a wide range of shear rate $\dot{r}$ from $0.001s^{-1}$ to approximately $1{,}200.0\ s^{-1}$.

The strength of RBC aggregation in simulation was calibrated based on the viscosity values for a single shear rate, since exact RBC aggregation forces are not know (Fedosov et al. 2011b).

4. BLOOD FLOW AND RBC CLUSTERING

Fahraeus-Lindqvist effect

The Fahraeus-Lindqvist effect (Fahraeus-Lindqvist effect 1931) describes a decrease in the apparent viscosity with decreasing tube diameter found in the experiments of blood flow in glass tubes (Pries et al. 1992). The apparent viscosity is calculated as follows

$$\eta_{App} = (\pi\ \Delta P\ D^{\wedge 4})/\ (128QL) = (\ \Delta P\ D^2)/\ (32\ \bar{v}\ L)$$

where $D = 2R_{cap}$ is the tube diameter, Q is the flow rate, and $\Delta P/L$ is the pressure drop in a tube of length L. For the higher hematocrit H_T , the apparent viscosity increases, since higher cell crowding leads to a larger flow resistance. For convenience, we define the relative apparent viscosity as

$$\eta_{rel} = \eta_{\ app} / \eta_0\ ,$$

where η_0 is the plasma viscosity.

5. RESULTS AND DISCUSSIONS

Figure 1 Graph between tube diameter Vs apparent viscosity of blood.

The figure 1 is a graph between the tube diameter and the apparent viscosity of blood which is taken from The Fahraeus-Lindqvist effect, when we take a close look at the graph we can see in the left part of the graph, that when the diameter of the tube is decreasing the apparent viscosity of blood is increasing.

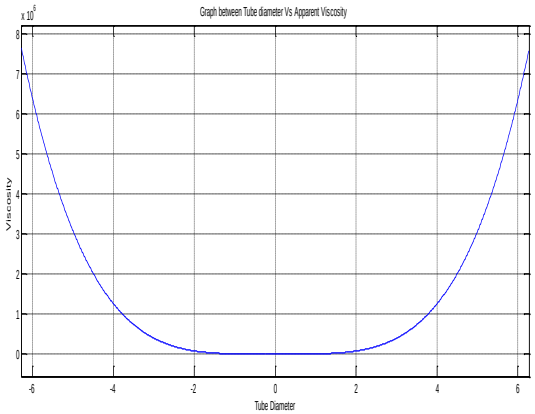

Figure 2 Graph between pressure difference and apparent viscosity of blood.

In the Figure.2 we can see that the trend of the graph is linear, the graph is in between pressure difference and the apparent viscosity of the blood, the graph is plotted by using the Fahraeus-Lindqvist effect, we can see that the viscosity is decreasing when the pressure difference is increasing. Before reaching the zero the viscosity is increasing with the increasing in pressure which is purely a theoretical concept, because the pressure can be negative but the viscosity of the blood cannot be negative.

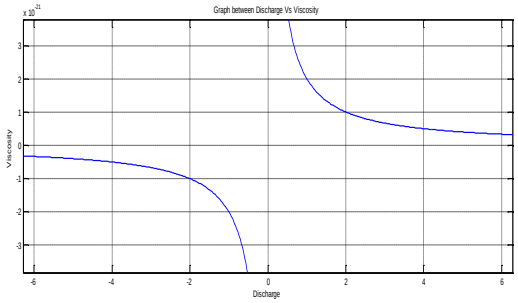

Figure 3 Graph between discharge and viscosity of blood.

The figure.3 is in between discharge and apparent viscosity of blood, the graph is plotted in accordance with the Fahraeus-Lindqvist effect, it has been observed that when the discharge is decreasing the viscosity of blood is also decreasing up to a certain value than it follows a path where it is becoming constant.

6. CONCLUSION

This paper has been developed to move ahead on the voyage to know the real and actual processes in the human body, so that we can be able to find the real problems with the prominent data and hence we can solve the problems efficiently with the provided resources. On the other hand if we do not even know the real problem, in that circumstance it is unrealistic to get the true result and the true solution. Therefore these kinds of researches are beneficial for finding the real solutions. All the four graphs have been developed by using MATLAB 7.10.0 (2010a), to show the behaviour of the blood in different conditions, by using the equations for finding the apparent viscosity of blood, which are mentioned in the paper above.

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