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Laminar blood flow in stenotic microchannels

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ABSTRACT

In this work, Newtonian and non-Newtonian laminar blood flow in rectangular microchannels with symmetric and asymmetric atheroma were numerically studied. It was observed that the impact of symmetry of the atheroma is almost negligible and the non-Newtonian properties of blood leads to higher pressure drops and wall shear stresses than the ones obtained for Newtonian flows.

KEYWORDS : Microchannel; Atheroma; Computational Fluid Dynamics; Wall Shear Stress; Pressure Drop

INTRODUCTION

Over the past few decades, the interest in the atherosclerosis's studies has assumed a prominent place in medicine since this cardiovascular pathology has become one of the major causes of death. The dominant pattern is atherosclerosis, characterized by the formation of atheromas. Most of the times, the formation of an atheroma is accomplished by a thrombus formation. It is thought that the location of higher pressures and velocities promote the endothelium lesion and hence the formation of a thrombus, which normally conduce to a thromboembolism due to the high speeds and pressures¹. Microfluidic devices are becoming one of the most promising new tools for diagnostic applications and treatment of several chronic diseases and the microchannels used in these devices usually have rectangular shape. Hence, it is essential to understand the blood flow behaviour involved in this kind of microchannels.

NUMERICAL SIMULATIONS

The simulations were carried out using the commercial finite-volume package FLUENT[®](v 15.0.7). In the calculations, blood was considered both Newtonian and non-Newtonian fluid, its rheology being described, in the second case, by the Carreau model². The simulations were

carried out in 3D rectangular geometries, Fig. 1. Six channels with distinct stenosis degrees - 15%, 30% and 50% - were studied, 3 of them with symmetric atheroma and the other 3 with asymmetric atheroma.

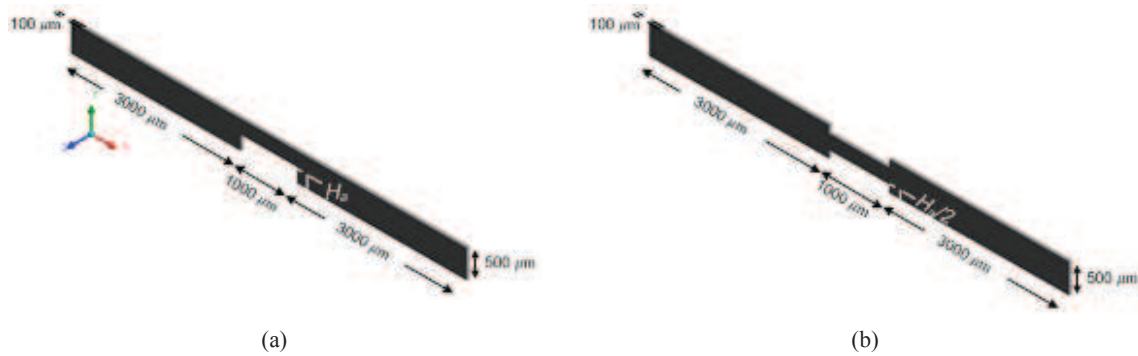


FIGURE 1 Example of computational domains. (a) Asymmetric atheroma and (b) Symmetric atheroma.

Due to the symmetry of the studied microchannels, a symmetry plane was established leading to thinner computational domains. The discretization of these domains was made using meshes constituted by rectangular elements, the mesh being more refined close to the walls, where zero velocity was imposed. In addition to the referred boundary conditions, 6 distinct entry velocities, u_i , were imposed in the plane $x = 0$.

In order to validate the computational fluid dynamics calculations, two tests in the region before the atheroma were performed. First, velocity profiles were compared with the analytical solutions for the Newtonian fully developed flow in a rectangular microchannel³ and it was observed a mean deviation lower than 0.8% for all the channels and operation conditions, Fig. 2.

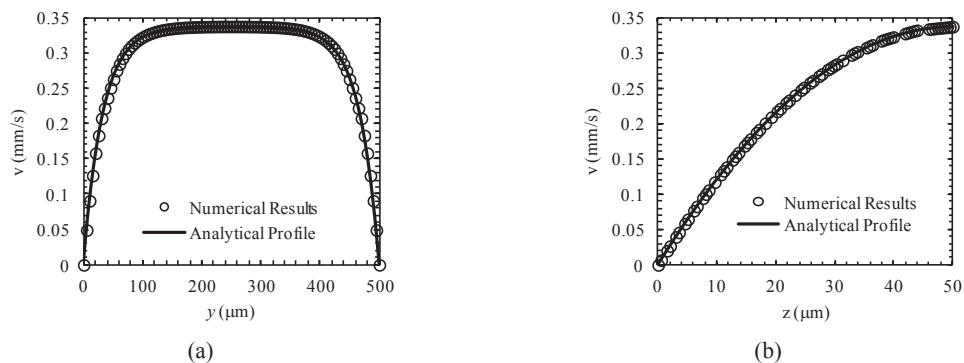


FIGURE 2 Velocity profiles for fully developed flow in the region before the atheroma and $u = 0.198$ mm/s. (a) Symmetry plane ($z = 50 \mu\text{m}$); (b) Central plane ($y = 250 \mu\text{m}$).

The pressure drop, ΔP , was estimated resorting to the correlation $f = PoRe^{-1}$, where f is the Fanning friction factor, Re the Reynolds number and Po the Poiseuille's number, which assumes the value 19.0^4 for the studied region. The relative errors for ΔP ranged between 0.01 and 0.1%.

RESULTS

As expected, the influence of the symmetry of the atheroma in the pressure decrease with the decrease of the stenosis degree (Fig. 3(a)). In Fig. 3(a) it can be observed that pressure for Newtonian flow is higher than the one obtained for the non-Newtonian flow. Fig. 3(b) shows that pressure drops are higher for the non-Newtonian flows and the impact of non-Newtonian properties on this flow property decrease with the increase of mean velocity, u .

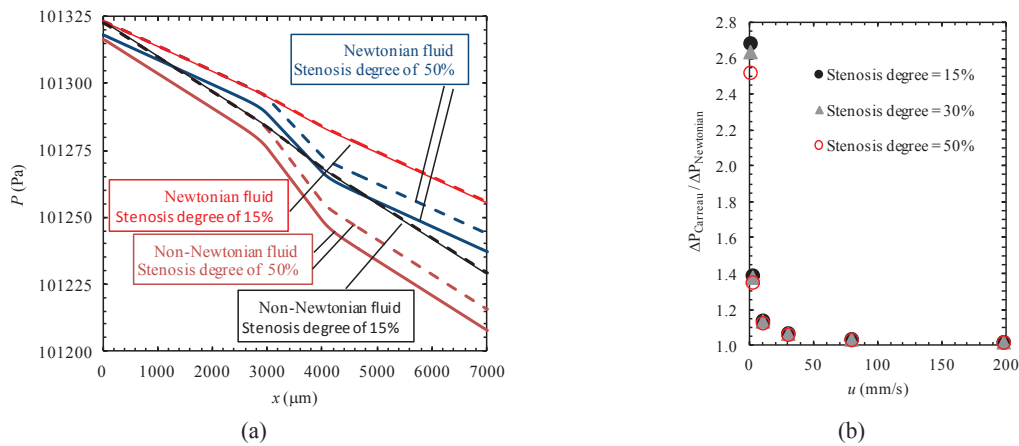


FIGURE 3 (a) Pressure along channels for $u = 1.98$ mm/s: (---) symmetric atheroma; (—) asymmetric atheroma. (b) Ratio between pressure drop of non-Newtonian and Newtonian fluids.

The wall shear stress (WSS) along the channels for both Newtonian and non-Newtonian flows have been analyzed and it was verified that the maximum value was reached at the symmetry plane in the corner of the atheroma (Fig. 4).

The asymmetry of the WSS profile is more pronounced for the asymmetric atheroma, being this asymmetry less pronounced for lower velocities (Fig. 4). In the opposite side of the atheroma, Line 2 (Fig.4(b)), the presence of this obstruction is also felt, as can be observed in Fig.4(b).

The impact of non-Newtonian blood properties in the WSS was studied and it was concluded that WSS for Carreau fluid are higher than the ones developed for the Newtonian fluid and this impact increases with the decrease of mean velocity.

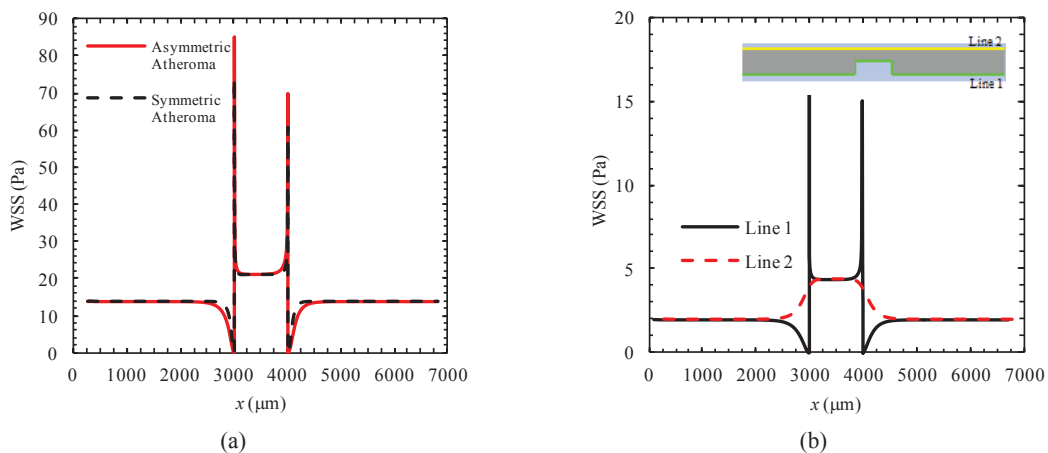


FIGURE 4 (a) WSS along Line 1 for 30% of stenosis degree, Newtonian fluid for $u = 79.2\text{mm/s}$. (b) WSS in top and bottom of the channel with 50% of stenosis degree for the Carreau fluid for $u = 9.9\text{ mm/s}$.

CONCLUSIONS

With this study, the influence of blood's non-Newtonian properties, stenosis degree and symmetry of atheroma in laminar flow's properties in stenotic rectangular microchannels were analyzed. It was possible to conclude that in the range of studied mean velocities, local velocity is not affected by the used rheological model or symmetry of the atheroma. The non-Newtonian properties of blood leads to higher pressure drops and wall shear stress being this effect more pronounced for lower velocities.

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