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Numerical Simulation of Non-Newtonian Blood Flow in A Three-Dimensional Non-Planar Bifurcation with Stenosis

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ABSTRACT: In the present study, numerical simulation of the steady blood flow through the carotid artery with a non-planar geometry model and considering mild (20%), moderate (50%), and severe (80%) occlusion was performed. In this research, the shear-thinning behavior of the blood fluid is incorporated by the Carreau–Yasuda model, and the viscoplasticity of blood was ignored. Furthermore, concentric and eccentric geometries were considered for stenosis. By comparing the non-Newtonian and Newtonian viscosity results, significant differences were found in the secondary flow lines. Shear-thinning behavior affects the secondary flow lines so that the vortices are either not formed or are smaller in size in the middle of the stenosis and subsequent sections. Moreover, axial velocity profiles in the non-planar branch decreased by increasing stenosis percentage, and in estimating the maximum wall shear stress, the Newtonian model had a significant error compared to the non-Newtonian one, and the estimated values by the Newtonian model were less than the non-Newtonian in most cases (up to 37% for an 80% stenosis). In addition, variation of velocity and shear rate caused by stenosis reveals the importance of the non-Newtonian model in calculating streamlines and velocity magnitudes. Plus, as the percentage of stenosis increased, the vessel's curvature effect, which causes the velocity field to deviate to the inner wall, decreased.

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1- Introduction

Blood is a concentrated suspension of red blood cells in plasma occupying 45% of blood volume. These cells play a significant role in the rheological behavior of blood since they represent more than 99% of the blood cellular volume fraction. The elasticity of red blood cells and their biconcave shape leads to the formation of rouleaux (aggregated cells) and increases blood viscosity in low shear rate conditions. On the other hand, if the shear rate increases to a certain value, the rouleaux break up, and viscosity decreases [1]. The pulsatile nature of the blood flow and presence of stenosis provides the necessary condition for altering the viscosity value; thus, blood's non-Newtonian behavior has an undeniable effect on blood flow [2].

From an anatomical perspective, hemodynamics of blood have a major effect on the development of stenosis in the carotid bifurcation. In fact, geometry and non-planarity of the carotid bifurcation alongside the blood rheology governed local hemodynamics [3]. Gijesn et al. [4] conducted an experimental and numerical study on steady blood flow in the carotid artery. They found out that the axial velocity of the non-Newtonian fluid was flattened, had lower velocity gradients at the divider wall and higher velocity gradients at the non-divider wall compared to Newtonian fluid.

The effect of vessel non-planarity was studied by Lu et al. [5]. They proposed a hypothetical geometry for the carotid artery with one planar and one non-planar branch for the first time. Their Computational Fluid Dynamics (CFD) analysis showed that vessel non-planarity significantly affected the velocity profile and Wall Shear Stress (WSS). In addition, Chen and Lu [3] simulated blood flow with the Carreau-Yasuda model in the previous geometry. They showed that curvature of the non-planar branch skewed the velocity profile to the outer wall, creating relatively low WSS at the inner wall.

In the present study, steady blood flow with non-Newtonian behavior (Carreau-Yasuda model) will be simulated in Lu et al. [5] geometry. Also, the influence of eccentric and concentric stenosis on the velocity profiles and WSS will be investigated.

2- Problem Description

Fig. 1. shows a schematic of the stenotic carotid artery based on the hypothetical geometry introduced by Lu et al. [5]. The profile of the occlusion obeys the Gaussian distribution. Three different stenosis severities (mild: 20%, moderate 50%, and severe: 80%) [6] with two different types of occlusion (concentric and eccentric) are considered for numerical

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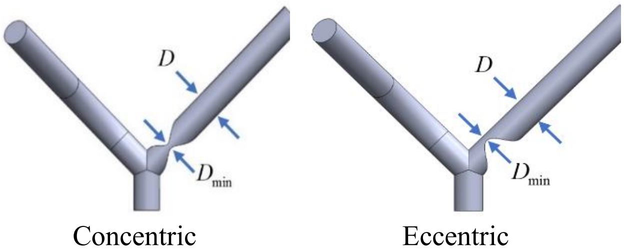


Fig. 1. The geometry concentric and eccentric stenosis

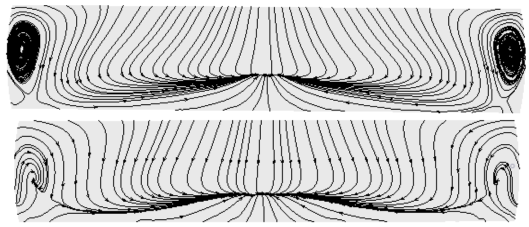
a
b


Fig. 2. Secondary streamlines in 80% AS concentric stenosis in the non-planar branch a) Newtonian, b) non-Newtonian

Table 1. Physical properties of blood (SI units)

Parameter	Value	Parameter	Value
ρ	1410	λ	0.110
μ	0.0029	n	0.392
μ_0	0.022	a	0.644
μ_∞	0.0022		

Table 2. The maximum value of WSS in non-planar stenosis with 80% AS (Pa)

Viscosity model	Eccentric	Concentric
Newtonian	2.37	1.89
non-Newtonian	3.18	2.6
Relative error	34.1%	37.6%

simulation. At the inlet, a fully developed velocity profile with $Re = 270$ is imposed. The walls are assumed rigid with no-slip conditions. At the outlet, zero gauge pressure and zero-gradient velocity are implemented.

Plus, 1. Area Stenosis (AS) is defined as below where D is normal diameter and D_{min} is the minimum diameter at the maximum stenosis [6].

$$AS = (1 - \frac{D_{min}}{D}) \times 100 \quad (1)$$

3- Governing Equations and Physical Properties

The flow is assumed to be steady and laminar. The governing equations are mass conservation and three-dimensional incompressible Navier–Stokes equations that are given as [3]:

$$\nabla . V = 0 \quad (2)$$

$$\rho (V . \nabla V) = -\nabla P + \nabla . \boldsymbol{\tau} \quad (3)$$

where is the stress tensor and is defined as [3]:

$$\boldsymbol{\tau} = \mu \dot{\gamma} \quad (4)$$

$$\dot{\boldsymbol{\gamma}} = [\nabla V + (\nabla V)^T] \quad (5)$$

In this study, the shear-thinning behavior of blood is accounted for by using the Carreau–Yasuda model for the viscosity as follows [3]:

$$\frac{\mu - \mu_\infty}{\mu_0 - \mu_\infty} = (1 + (\lambda \| \dot{\boldsymbol{\gamma}} \|)^a)^{\frac{n-1}{a}} ; \| \dot{\boldsymbol{\gamma}} \| = \sqrt{\frac{\dot{\boldsymbol{\gamma}}_{i,j} \dot{\boldsymbol{\gamma}}_{i,j}}{2}} \quad (6)$$

The physical properties of the Newtonian and non-Newtonian blood are listed in Table 1. [3].

4- Results and Discussion

Fig. 2. shows the secondary streamlines at the cross-section in the middle of concentric stenosis (80% AS) in the non-planar branch. As can be seen, recirculation areas in the non-Newtonian model decrease due to the shear-thinning behavior of blood. This behavior causes the apparent viscosity to decrease as the blood flow rate increases because of stenosis.

The maximum values of WSS in the stenotic non-planar branch are given in Table 2. Comparison of non-Newtonian and Newtonian results reveals a considerable underestimation made by the Newtonian model in predicting maximum WSS. Therefore, Fig.2 and Table 2. manifest the significance of non-Newtonian blood behavior in determining velocity field and WSS.

The axial velocity profile at the middle of non-planar stenosis in the plane of symmetry (perpendicular to the plane of the paper) is shown in Fig. 3. 80% AS stenosis has the highest maximum velocity compared to other severities. This phenomenon happened due to two main reasons. First, as we expected, velocity increases as the flow cross-section decrease, so mass conservation remains satisfied. Second, increase velocity causes an increased shear rate; thus, the apparent viscosity decreases. This reason acts more profoundly in 80% stenosis compared to other occlusion percentages. Additionally, in 80% AS stenosis, since the viscosity has its lowest value, the velocity profiles are flatter than other stenoses with an M-shaped profile. This result is aligned with the findings of Chen and Lu [3].

In the final step, maximum WSS in the apex and middle of stenosis in the non-planar branch is given in Table 3. As can be seen, an increase in the severity of stenosis changes the location of maximum WSS. In mild and moderate stenosis, the apex has the max WSS, but in severe stenosis, the middle of the stenosis has the max WSS.

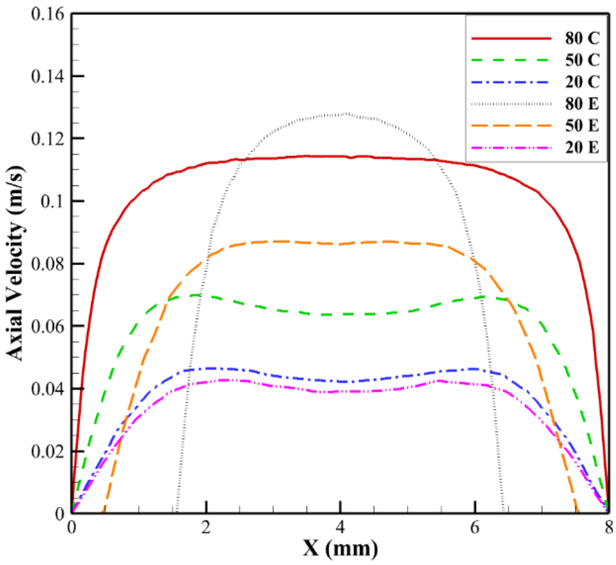


Fig. 3. Axial velocity profile at the middle of stenosis cross-section in the non-planar symmetry plane

Table 3. Maximum WSS in the apex and middle of the stenosis in the non-planar branch (Pa)

	AS	Middle of stenosis	Apex
Eccentric	20%	0.7	4.21
	50%	1.16	2.02
	80%	3.18	2.03
Conccentric	20%	1.28	2
	50%	1.83	2.01
	80%	2.6	2.03

5- Conclusions

Based on the results described above, three concluding remarks are briefly summarized in what follows. First, comparing secondary streamlines and maximum WSS obtained by the Newtonian and non-Newtonian models proves the substantial influence of shear-thinning behavior of blood flow. Second, in the non-Newtonian model, recirculation areas are smaller and the maximum WSS is estimated at least 34% more than the Newtonian model. Finally, as the stenosis severity increases, the shear-thinning behavior of blood becomes more dominant. This conclusion is shown by comparing the velocity profile in Fig. 3. that 80% AS stenosis has the maximum velocity. The maximum WSS location changes from the apex to the middle of the stenosis by increasing the occlusion percentage.

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