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The Effect of Non-Newtonian Behavior on the Transport of Low Density Lipoprotein Particles in the Vortex Region in the Human Carotid Artery

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ABSTRACT: The common carotid artery is a large vessel which supplies oxygenated blood to the large front of the brain. The artery geometry is extracted from computed tomography angiography images of a healthy 20-year-old volunteer. ANSYS-Fluent commercial software is utilized to simulate the blood transient laminar flow in common, external and internal carotid arteries. In addition to the Newtonian viscosity model, two non-newtonian generalized power law and the modified Casson models have been selected for comparison. The quantitative and qualitative results include the distribution of the low density lipoprotein concentration, the wall shear stress and its fluctuations, and the volume and shape of the recirculation zone. Computations show that the low density lipoprotein Concentration estimated by non-Newtonian models is higher than by the Newtonian model. On the other hand, the carotid bulb and the beginning part of the external carotid artery, contain a large volume of the recirculation flow. Also, the low density lipoprotein particles concentration Comparison between the two modified Casson and Newtonian models in the common carotid artery zone shows the difference of about 12.5 percent. The results of this study show that the vortex region volume and shape are changed during the cardiac period cycle. The findings also reveal that Newtonian and non-Newtonian models present different results in predicting the flow parameters and secondary flow estimation.

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1- Introduction

Nowadays, owing to computer modeling development, estimation of the flow parameters in human blood vessels, has also made significant progress. On the other hand, the findings show that there are indeterminable relationships between parameters such as local Wall Shear Stress (WSS), the flow recirculation, and residence time of the blood cells with vascular diseases, such as aneurysm atherosclerosis, and arterial arrest. Atherosclerosis is a common type of Cardiovascular Disease (CVD) generally found in large and medium arteries [1]. It is well accepted that the situation of atherosclerosis may be because of the unusual accumulation of macromolecules, like Low-Density Lipoproteins (LDLs), in the arterial wall [2]. The macromolecular congestion causes narrowing and blockage of the arteries [3]. So, the knowledge gap is that in case atherogenesis has started with this unusual high accumulation, or that this disorder is just a secondary effect of atherogenesis [4]. In this study, the transient behavior of the volume and location of the recirculation zones in the in-vivo healthy carotid artery are investigated. The effects of the non-Newtonian models on the mean concentration and the Oscillatory Shear Index (OSI) parameters, in four separated parts of the vessel are also discussed. By analyzing the results related to recirculation location and OSI, a direct relationship between them is seen.

2- Methodology

Since the flow streamlines in large vessels are highly dependent on the shape of the artery wall, so, it is essential to extract the artery geometry from a live case. The section below illustrates the geometry extraction procedure. To simulate the blood flow, a total of 670000 elements were produced by using the ANSYS meshing module. The incompressible Navier-Stokes and mass continuity equation, for transient flow with rigid walls, were solved by using the pressure-based ANSYS-Fluent 18.2 solver. The mathematic formulation, which depicts blood flow, is the Navier-Stokes equation [5]:

$$\rho\frac{\partial\vec{v}}{\partial t}+\rho\left(\vec{v}.\nabla\right)\vec{v}=-\nabla\rho+\nabla^{2}\mu\vec{v} \qquad (1)$$

Where $\vec{v}$ is the velocity, ρ is the pressure, μ is viscosity, and is the density of blood. For flow in the artery wall, the porous media approximation, Darcy's law, is used:

$$\nabla P=-\frac{\mu}{K}\vec{v} \qquad (2)$$

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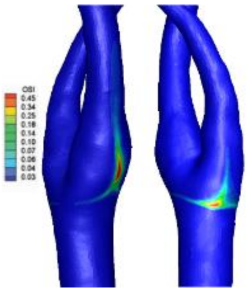

Fig. 1. OSI Contour for Newtonian Model - Left Image: Carotid Bubble View. Right image: ECA medial view

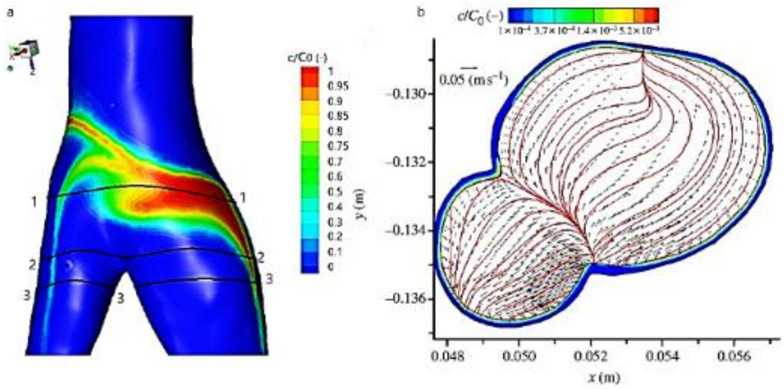

Fig. 3. Same as in Fig. 2, only now for the cross-sectional (2-2) plane carotid artery.

Where k is the Darcy constant. The transport of LDL is described by the advective diffusion equation:

$$\frac{\partial c}{\partial t}+\vec{v}.\nabla c=D\nabla^2 c \qquad (3)$$

Where c is the concentration of LDL and D is the diffusion constant. The last equation in the mathematical model is the mass conservation equation given by

$$\nabla.\vec{v}=0 \qquad (4)$$

The OSI is defined [6] as:

$$OSI=0.5\left(1-\frac{\left|\int_0^T \overrightarrow{\tau_w}dt\right|}{\int_0^T\left|\overrightarrow{\tau_w}\right|dt}\right) \qquad (5)$$

3- Results and Discussion

Fig. 1 shows the OSI contour for the Newtonian model with the maximum value of 0.2. The arterial cross sections at three characteristic locations, shown in figures 2a, 3a, and 4a are analyses next. The intensity of the secondary flow is depicted by contours of the axial by superimposed corresponding stream traces (Figs. 2b, 3b, and 4b).

4- Conclusions

In this study, a computational fluid dynamics tool was used to estimate the unstable and slow behavior of blood flow in the human carotid artery extracted from Computed Tomography (CT) angiography images. Two comprehensive models of general law and modified caisson law are also considered to consider the non-Newtonian property of blood. Finally, after reviewing the results, some general conclusions are presented as follows:

1-The concentration obtained from non-Newtonian models is more than Newtonian and this difference is more for the Casson model than the power law model. The percentage difference between the Casson and Newtonian models in the common carotid artery is about 12.5 percent.

2- The OSI parameter, in addition to indicating the shear stress fluctuations, is a variable to describe the residence time of the blood cells and also the existence of the recirculation region. In this simulation, the maximum value of the OSI for the Newtonian fluid was observed in three regions of the carotid bulb, the bifurcation apex, and the medial part of the ECA. These zones for the non-Newtonian fluid are limited to two zones of the carotid bulb and bifurcation apex.

3- The STWSS Comparison between the two modified Casson and Newtonian models in the bifurcation zone shows a difference of about 11.5 percent.

4- The results of local and general non-Newtonian importance factors showed that the non-Newtonian behavior of the fluid is more important in the middle parts of the vessel

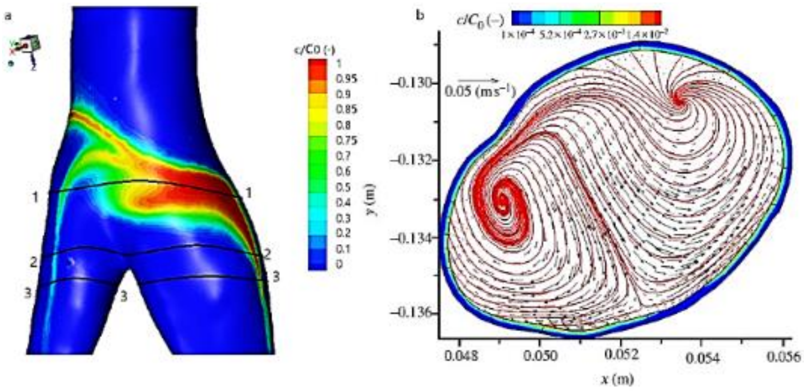

Fig. 2. (a) The contours of the non-dimensional LDL concentration (c/C_0) along the lumen–endothelium interface and locations of the cross sections (1-2-3) (zoom-in). (b) Superimposed velocity vectors of the secondary motion and stream trace inside the lumen and contours of the non-dimensional LDL concentration (c/C_0) within the artery wall in the cross-sectional (1-1) plane.

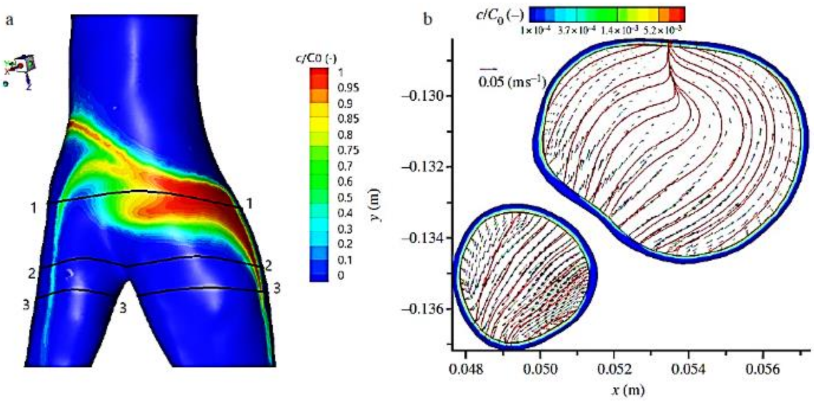

Fig. 4. Same as in Fig. 2, only now for the cross-sectional (3-3) plane carotid artery.

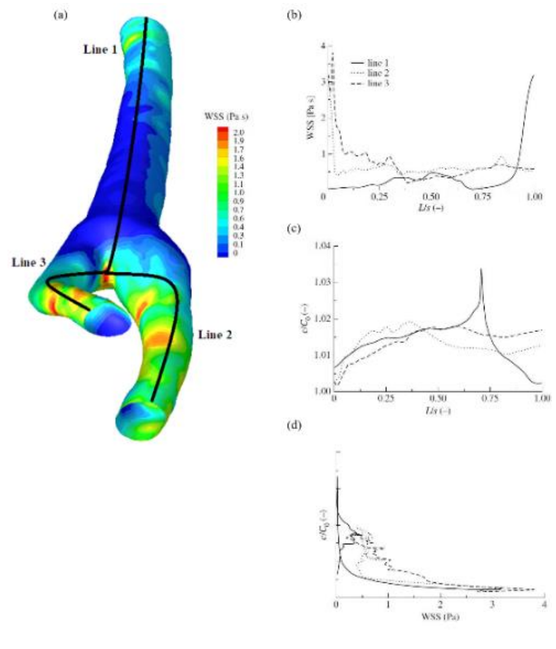

Fig. 5. Contours of the WSS at the lumen–endothelium interface and selected polylines (a). The profiles along the lines shown above: WSS (b), LDL concentration (c/C_0) (c). The LDL concentration versus WSS along the same lines (d).

section as well as in the areas close to the recirculation area.

5- The total volume of the vortex region and its elongation estimated by the non-Newtonian models is overall less than by the Newtonian model. Among the two non-Newtonian models, the GPL also predicts the volume of the vortex region larger than the modified Casson model.

6- In conclusion, the shear shining non-Newtonian nature of blood has little effect on LDL and oxygen transport in most regions of the carotid, but in the atherogenic-prone areas where luminal surface LDL concentration is high, its effect is apparent.

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