Computational Fluid Dynamics Analysis of Blood Rheology

Guilherme S. Souza, Enzo D. Giustina, Marcus V. Carvalho, and Raquel J. Lobosco

Abstract Computational fluid dynamics can be an auxiliary tool for the diagnostic and treatment of cardiovascular diseases. Thrombosis and atherosclerosis are pathologies that affect the delivery of blood to the neck and head. One of the most affected by these pathologies is the carotid sinus. The objective of this paper is to improve the accuracy of blood flow simulations, in order to avoid using in vivo experiments on developments of new technologies and treatments. To reproduce flow characteristics, the numerical model used is based on the average dimensions of many angiograms. The geometry and the correct rheological model are crucial to the fidelity of the physical phenomenon. The blood as a non-Newtonian fluid was modeled with the Casson and Carreau-Yasuda Model. Using the open-source software OpenFOAM for the numerical simulations integrating the rheoTool facilities, non-Newtonian models and Newtonian assumptions were compared.

Keywords Blood · Rheology · OpenFOAM · Artery

1 Introduction

The study of blood behavior is a fundamental field of biotechnology development. According to clinical observations, bifurcation regions and curvatures are more sensitive to pathological alterations. The carotid sinus (a region in the carotid artery where

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a bifurcation occurs) is most affected by arteriosclerosis lesions [1]. Therefore, the hemodynamic study is important for a better understanding of arteriosclerosis and its relation with the blood flow [2]. In addition, it is important to mention that in vivo precise measures of some parameters are extremely difficult, such as shear rate. Consequently, numerical simulations turn in a great ally in the development of new technologies devices and research development in the area [2].

There is no consensus in which the rheological model better represents the blood viscosity due to its complex rheology. The most used fluid models are the power law, Casson, and Carreau-Yasuda [3]. Some researchers argue that the Newtonian behavior hypothesis is a good assumption [1, 4] for large arteries and the non-Newtonian behavior is more important for capillaries and small vessels. Since the shear stress in the vessel walls has great relation with atherosclerosis, it would also be relevant to investigate non-Newtonian behaviors in large arteries [2]. However, none of those models considers its viscoelasticity.

In order to improve the computational fluid dynamics, CFD, simulations of blood flow, this study reproduced some cases implemented by Carvalho [5] and integrated different boundary conditions in the rheoFoam tool, an external solver for simulating complex fluids at OpenFOAM package. This package allows a viscoelastic treatment for non-Newtonian fluids.

2 Methodology

2.1 Mesh

The similarity between the geometry model and the real artery is a crucial parameter. In this work, the geometry is based on the model used by Bharadvaj [6], Ku et al. [7], Gijsen et al. [8], which was developed by fifty-seven angiograms of twenty-two adults and thirty-five children, which such data, used in this research, come from to the studies referenced.

The flow characteristics were analyzed in the internal carotid in the regions depicted in Fig. 1; the planes S1 to S5 are divided by horizontal and vertical sections; A-A and B-B, respectively, note that the diameter of the vessel increases until its maximum value in S1, where it starts to decrease afterward.

2.2 Boundary Conditions

Two different values of inlet velocity were implemented. At first, we have used a steady velocity of 0.09 m/s with a parabolic radial distribution, just like M. V. P. Carvalho, in order to be able to compare the data from the rheoTool solver with previous results.

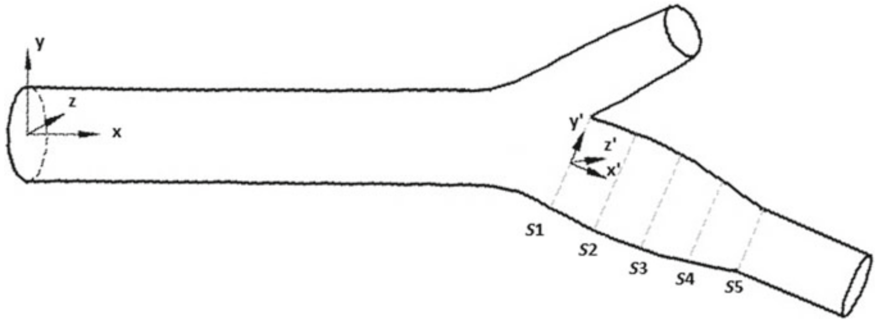


Fig. 1 Geometry used at Gijsen et al. [8]

The second condition was based on the work of Wiwatanapataphee et al. [9] to reproduce this flow velocity variation on time. The periodical velocity disturbance was used in this study to mimic the influence of the heart pulsation characteristics on the flow. The Fourier transform was used to get the velocity function used in the simulations.

The speed is assumed to be directly proportional to the flow rate, when the section's area is constant (Fig. 2).

The normalized function of the sign shown in Fig. 7 was implemented as an oscillatory regime in blood flow. The interval from 0 to 0.45 s is the diastole and 0.45 to 0.8 s the systole. The sign function multiplied for the maximum velocity in the common carotid results in the approximated velocity function that was used as the boundary conditions.

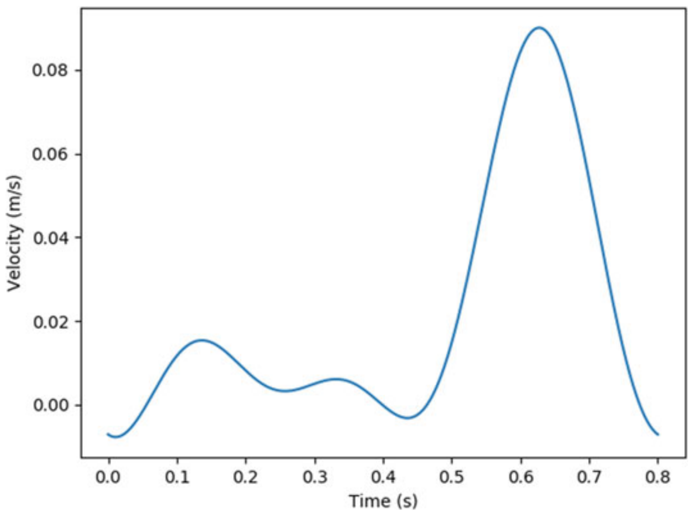


Fig. 2 Speed profile with 0.089 m/s [10] as maximum speed

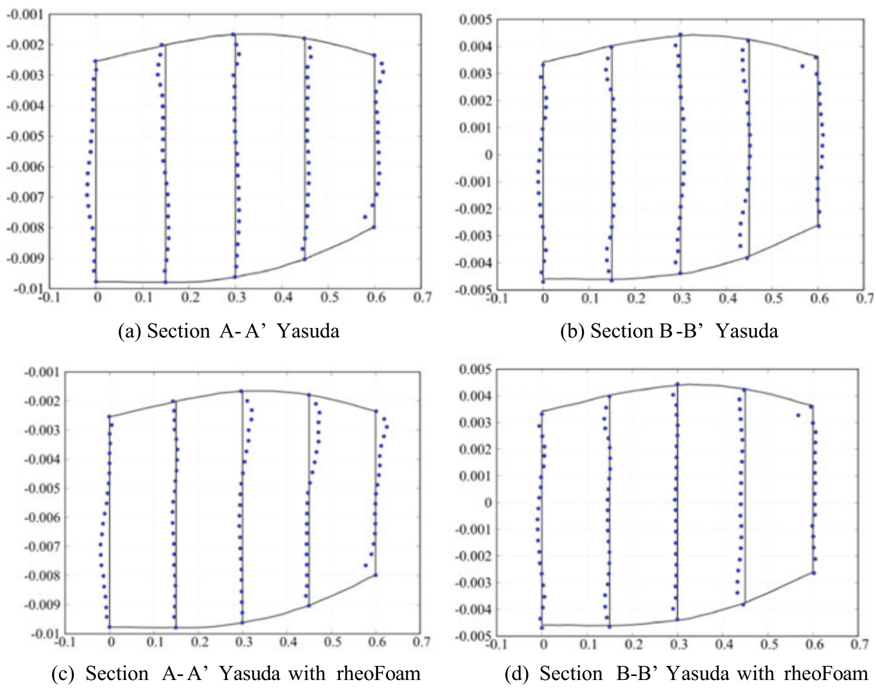
The velocity distribution has a parabolic profile and the pressure on the inlet, and the outlets are constant. In the outlet, the atmospheric pressure resembles the experiments made by Ku et al. [7]. For all the simulations, it was considered a stress-free condition at both exits and a no-slip condition in the vessel walls.

3 Results

A comparison of the relative error between the computational and experimental results can be seen graphically in Fig. 3. Each section cut represents the sections S1, S2, S3, S4, and S5. The relative error values, like the one shown in Fig. 3 for the Yasuda model, are measured in Table 1.

Figure 4 shows a comparison in the velocity profile, and the dots are the experimental results.

Table 1 presents the statistic comparison. The mean deviation of Yasuda's rheological model using rheoTool package from the experimental result was 0.007365 while it was 0.0082734 m/s, reproducing the simulations of Carvalho and Lobosco [5]. The standard deviation in the same case was 0.004945 on rheoFoam while it was 0.005604. Those results mean that using the rheoTool package, the precision and accuracy were improved.



(a) Section A-A' Yasuda

(b) Section B-B' Yasuda

(c) Section A-A' Yasuda with rheoFoam

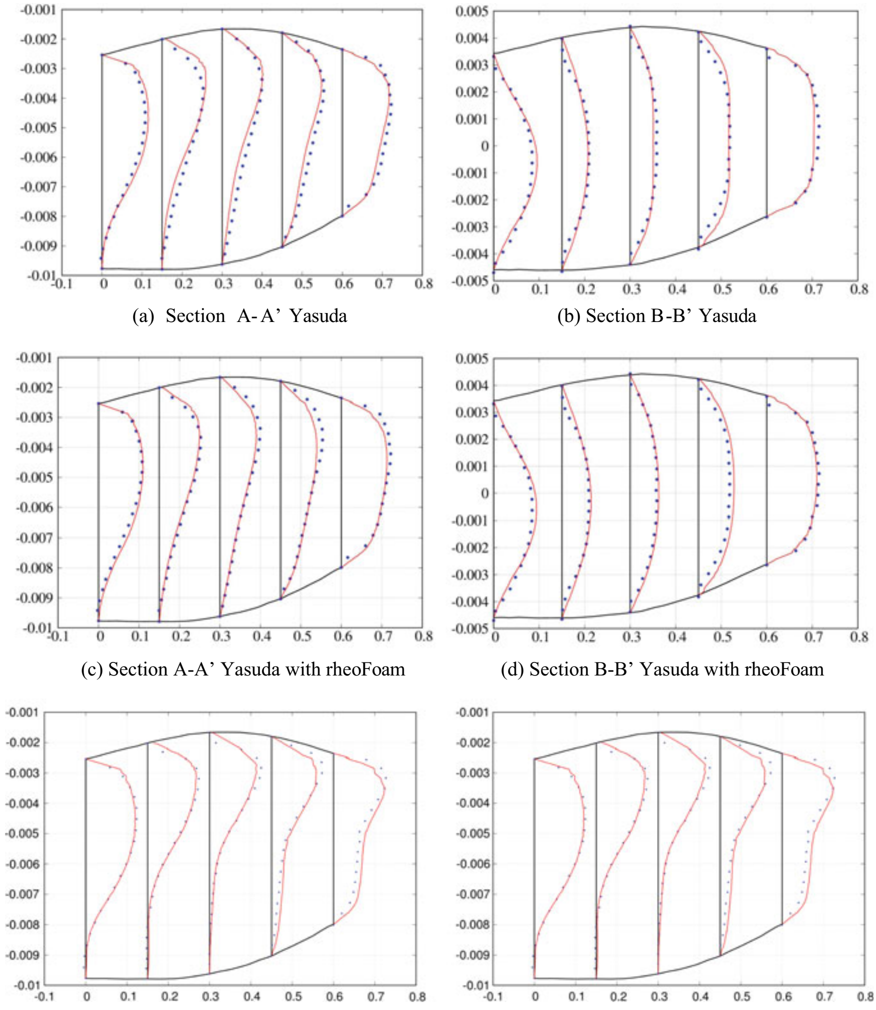
(d) Section B-B' Yasuda with rheoFoam

Fig. 3 Graphics comparing the deviation of simulation from the experiment on each section on computational simulation and the experimental result

Table 1 Statistic comparison of the differences in computational results and experimental

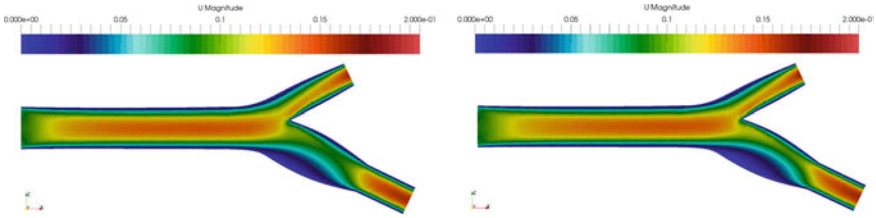
Rheologic model	Solver	Mean	Standard deviation
Yasuda	Non-NewtonianIcoFoam	−0.008273	0.005604
	rheoFoam	−0.007365	0.004945
	[a]rheoFoam	0.011122	0.017199
Newtonian	Non-NewtonianIcoFoam	−0.004181	0.006717

[a]The oscillatory regime was used on simulation, but the experimental was a steady flow



(a) Section A-A' Yasuda
(b) Section B-B' Yasuda
(c) Section A-A' Yasuda with rheoFoam
(d) Section B-B' Yasuda with rheoFoam
(e) Section A-A' Newtonian
(f) Section B-B' Newtonian

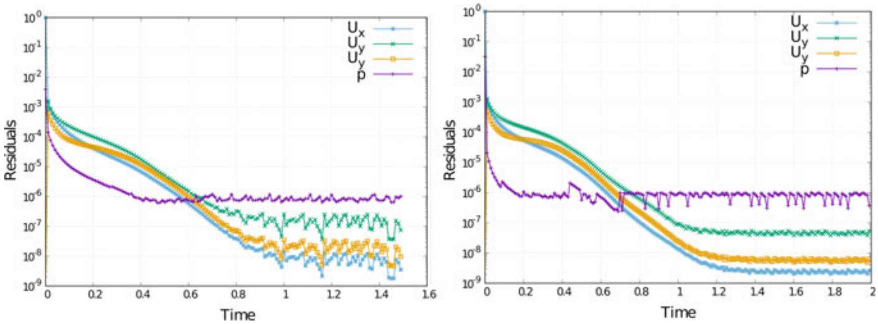
Fig. 4 Graphics comparing the velocity on each section on computational simulation and the experimental results



(a) Speed profile on Yasuda's model using rheoFoam

(b) Speed profile on Yasuda's model using standard solver

Fig. 5 Illustration of velocity magnitude



(a) Yasuda residues with rheoFoam

(b) Yasuda residues

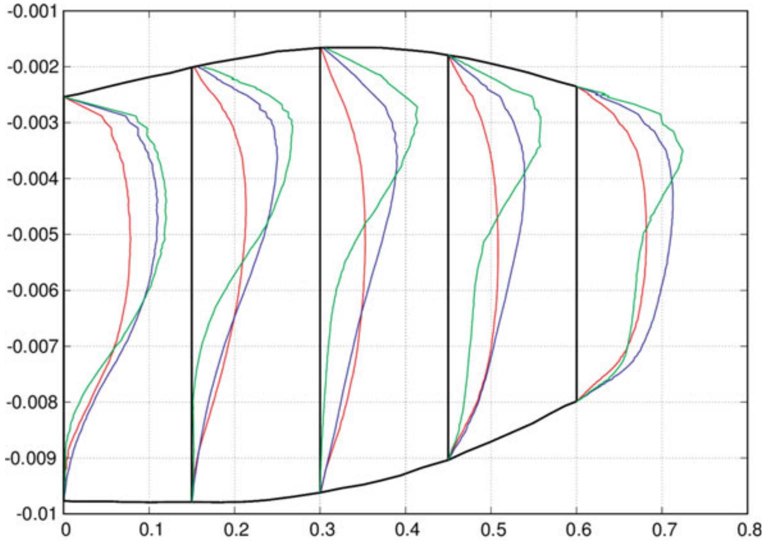
Fig. 6 Graphics of residues of pressure (purple) and the velocity components x (blue), y (green) and z (yellow) on a logarithm scale

An illustration of the numerical velocity profile can be seen in Fig. 5 while Fig. 6 shows the computational numerical residues.

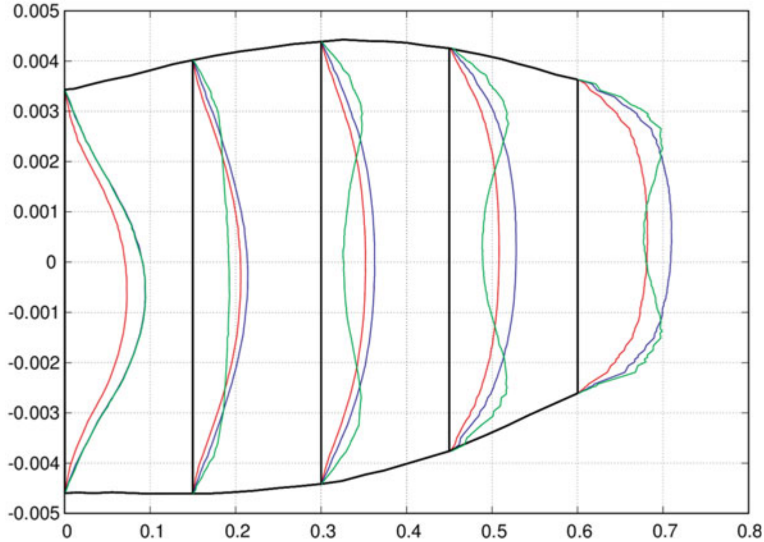
The results which are shown in Fig. 5 allow a comparison between the oscillatory velocity profile and the steady-state flow. Both models, the Newtonian and non-Newtonian can be compared in the graph.

Figure 7 compares the velocity profiles obtained from simulations with different fluid dynamic models applied. As can be seen, Newtonian and non-Newtonian steady-state hypotheses present substantial differences, and these results agree with the results stated at [2, 7], which non-Newtonian approaches are preferable.

Comparing the steady-state and oscillatory velocity profiles for non-Newtonian models, it can be seen that the oscillatory condition has a more uniform profile. This difference would be due to the periodic disturbance of the velocity in oscillatory conditions, which do not allow the velocity to achieve the fully developed velocity magnitude in the steady-state condition.



(a) Section A-A’ velocity profile



(b) Section B-B’ velocity profile

Fig. 7 Graphics of velocity profile adopting the Newtonian model (green), Yasuda’s model (blue), both on steady flow and Yasuda’s model (red) simulating the heart beating on systoles

4 Conclusion

The oscillatory boundary condition highly impacts the results of the simulation, showing that steady flow models may be inadequate. The rheoFoam improves the accuracy of the simulation. The results shown in this paper are not definitive, because of some simplification in the vessel wall conditions and unconsidered viscoelastic characteristics; therefore, the result contributes to the progress of the numerical research of complex fluids in arteries.

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