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Influence of fluid rheology on blood flow hemodynamics in patient-specific arterial networks of varied complexity – in silico studies

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ABSTRACT: Results obtained with CFD (computational fluid dynamics) tools rely on assumptions used during a pre-processing stage. One of such assumptions is a mathematical description of a fluid rheology. Up to this date there is no clear answer to several aspects, mainly connected with a question whether blood can be simplified to a Newtonian fluid during CFD analyses. Different research groups present contradictory results, so the question remains unanswered. Therefore, the objective of this research was to perform stationary and pulsatile blood flow simulations using 8 different rheological models in geometries of varied complexity. A qualitative comparison of shear- and viscosity-related parameters did not show any meaningful discrepancies, but a quantitative analysis shown significant differences, especially in magnitudes of wall shear stress (WSS) and its gradient (WSSG). For large arteries blood should be modelled as a non-Newtonian fluid, whereas for cerebral vasculature assuming blood as a simple Newtonian fluid can be treated as a valid simplification.

KEY WORDS: blood rheology, CFD, non-Newtonian blood flows, arterial systems

1. Introduction and research objective

Physical properties of blood depend on numerous patient-specific factors such as age, sex, hydration, diet, etc. In general, blood is a non-Newtonian fluid (its viscosity varies when subjected to external stresses) that is characterized by a shear-thinning behaviour. It means that viscosity decreases with an increasing shear rate. This can be observed when blood velocity is high or when vessel cross section is relatively small. The shear-thinning phenomenon occurs at higher shear rates since erythrocytes and other blood cells start to deform under applied stresses. Otherwise, they form aggregates which increase attractive forces between them, leading to a higher viscosity. The non-Newtonian properties of blood are significant for lower values of shear rates –after exceeding 100 s^{-1} threshold, blood can be treated as a simple Newtonian fluid of constant viscosity [1, 2]. Similarly as for any experimental investigation of the living tissue, researchers have obtained different results of the blood shear-thinning behaviour. Therefore, over the course of last decades, dozens of rheological blood models have emerged in literature. Unfortunately, they do not mimic the real behaviour of blood in whole shear range, thus, there is no golden standard to model the complicated properties of blood.

Concerning an influence of fluid rheology on the numerical data, different research groups present contradictory results. For instance, Johnston et al. [2, 3] investigated flow through coronary arteries and proved that Newtonian blood model is a reliable assumption for approximately 70% of the cardiac cycle and for mid-range to high shear rates during stationary simulations. Similar conclusions were drawn by Boyd et al. [4] who analysed stenosed and unstenosed carotid arteries – one can neglect the non-Newtonian properties of blood. However, Razavi et al. [5] shown that each rheological model of blood results in varied magnitudes of wall shear stress (WSS) and these differences are non-negligible. Karimi et al. [6] examined pulsatile flows in an aorta model and proved that blood rheology affects the flow solution, while Newtonian assumption tends to underestimate WSS values. Contrary, Caballero and Lain [7], who compared cycle-averaged results for several blood models, claimed that hardly any differences in WSS and global I_G parameter could be observed. This indicated that non-Newtonian model is not of great significance for pulsatile flow.

Therefore, the main objective of this research was to perform stationary and pulsatile blood flow simulations reliant on 8 different blood models in patient-specific geometries of varied complexity to assess an influence of the chosen blood model on the numerical data. This could help in answering two unsolved hypotheses whether blood can be simplified to a Newtonian fluid for large arteries and for small vessels characterized by high blood flux or during cycle-averaged and stationary investigations.

2. Methodology: numerical domain

Geometries were reconstructed basing on biomedical imaging data deriving from angiographic examinations with Computed Tomography (angio-CT). Semi-automatic image segmentation procedures, 3D models extraction and their preparation for CFD purposes were covered in a software named AMR, *Anatomical Model Reconstructor*, developed by one of the authors. The following patient-specific models were generated: common carotid artery (CCA) bifurcation, entire aorta with major branches and complicated system of intracranial arteries (CoW). AMR program allows for an automatic generation of volumetric meshes by importing prepared STL files and specific macro files into ANSYS ICEM package. Similarly, an entire pre-processing stage can be performed in AMR software, so there is no complex user interaction with any ANSYS modules. Developed program allows the user to choose 8 most well-known rheological blood models that are widely used for the numerical analyses. These include Newtonian (NEWT), Casson (CAS), Carreau (CAR), Cross (CRO), K -L, Power Law (PL), modified Power Law (MPL) and Quemada (QUE). Therefore, all of them were investigated during this research – see Fig. 1.

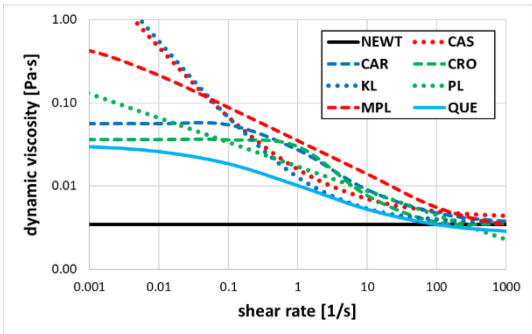

Fig. 1. Dynamic viscosity as a function of shear rate

The most optimal meshes were chosen for each geometry type after mesh independence tests. The flow was assumed as an isothermal and adiabatic one, while blood was modelled as an incompressible fluid of constant density equal to 1045 kg/m^3. The turbulence model was set as k-ω SST and each stationary simulation was treated as completed when it either reached convergence criteria (10^{-6}) or exceeded 500 iterations. For transient simulations, at least 5 full cardiac cycles were simulated to ensure that there is no influence of initial conditions on the obtained results. Magnitudes of inlet and outlet boundary conditions derived from clinical case studies as well as from literature. A Prandtl velocity profile was set at the inlet cross section in the aorta case study, while for all the other ones parabolic profiles were used.

3. CFD results analysis

A qualitative comparison of shear- and viscosity-related parameters did not show any meaningful differences – distribution of almost all investigated parameters was very similar in each analysed case study – see Fig. 2. This suggested there is a very slight influence of the fluid rheology on the numerical data. The only difference could be observed for the local non-Newtonian importance factor, I_L, for the aorta geometry.

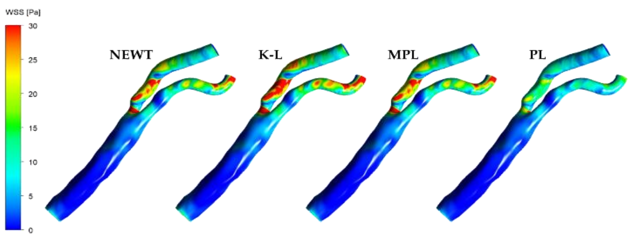

Fig. 2. WSS distribution for CCA bifurcation (4 chosen rheological blood models)

After a thorough quantitative analysis of WSS, WSS spatial gradient (WSSG), non-Newtonian effect factor (NNEF), oscillatory shear index (OSI) as well as I_G parameter, it turned out oppositely. Significant differences in magnitudes of the chosen hemodynamic indicators were obtained, mainly for CCA and aorta case studies. For instance, differences of WSS exceeded dozens of pascals for the entire aorta case study – see Tab. 1.

Table 1. Values of WSS at the model walls

	WSS [Pa]							
	NEWT	CAR	CAS	CRO	KL	MPL	PL	QUE
aorta	**129.53**	**132.35** (2%)	**143.96** (11%)	**130.56** (1%)	**159.42** (23%)	**130.38** (1%)	**70.13** (-46%)	**120.90** (-7%)
CCA	**42.97**	**43.94** (2%)	**48.96** (14%)	**42.99** (0%)	**54.89** (28%)	**42.49** (-1%)	**22.72** (-47%)	**39.33** (-9%)
CoW	**24.22**	**24.75** (2%)	**27.96** (15%)	**24.20** (0%)	**31.63** (31%)	**23.75** (-2%)	**12.83** (-47%)	**21.82** (-10%)

For both geometries of large arteries I_G parameter exceeded a threshold value of 0.15 in almost every investigated time-step, whereas for cerebral vasculature it was always below it, even during diastole. Blood distribution across numerical domain was not affected by fluid rheology – maximal differences were negligible.

4. Conclusions

Performed in silico analyses of fluid rheology influence on CFD results lead to the following conclusions:

1) Complexity of the arterial system affects an intensity of rheology influence on flow hemodynamics.
2) In large arteries such as entire aorta or CCA bifurcation, blood should be treated as a non-Newtonian fluid, especially when shear-related parameters are meant to be analysed.
3) For cerebral vasculature (small arteries with high blood flux), treating blood as a Newtonian fluid is a valid simplification.

Summing up, to prevent from an oversimplification of the CFD analysis, it is advisable to model blood as a non-Newtonian shear-thinning fluid, notwithstanding geometry complexity and simulation type, especially that it does not prolong simulation time.

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