

Blood Flow Modeling

Subjects: **Others**

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Blood flow modeling consists of using computational techniques to investigate the blood flow behavior in a rapid and accurate fashion. This has become an area of extensive research due to the prevalence of cardiovascular diseases, responsible for a critical number of deaths every year worldwide, most of which are associated with atherosclerosis, a disease that causes unusual hemodynamic conditions in arteries. In the present review, the application of computational simulations by using different physiological conditions of blood flow, several rheological models, and boundary conditions, were discussed.

atherosclerosis

coronary arteries

hemodynamics

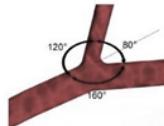
numerical methods

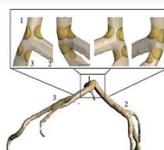
1. Introduction

Despite the progress done in experimental studies and blood flow measurement techniques, there are still some challenges associated with them^[1]. For instance, in vitro wall shear stress (WSS) measurements are extremely difficult to perform and the velocity measurements have high associated errors. These, combined with other complications of directly measuring quantities of interest, have motivated the use of computer simulations to predict them in silico^[2].

The earliest numerical detailed studies solving the flow problem in constricted tubes were conducted by Lee and Fung (1970)^[3]. After that, other studies in this field conducted by Caro et al., (1971)^[4], Glagov et al., (1989)^[5], and Ku et al., (1985)^[6] are important references in this area and should be highlighted. Ever since, CFD approaches have been progressively adopted by most researchers as the preferred technique for numerical modeling of hemodynamics. Owing to the continued growth of computational power, these have become an increasingly reliable tool for measuring biomechanical factors vital for clinical decision-making and surgical planning. However, the proper selection of the flow boundary conditions has to be done, otherwise, the findings can be considered uncertain, weak, and unrealistic^[7]. In this regard, the different geometries, boundary conditions, and flow characteristics applied by some researchers in the last ten years are summarized in [Table 1](#).

Table 1. Numerical studies of hemodynamics and the respective assumptions for numerical simulations.

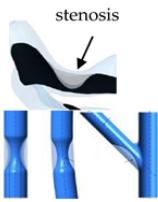
Geometry	Schematic Representation	Modeling Approaches	Fluid	Boundary Conditions	Wall	Inlet	Outlet	Authors
Idealized		Laminar	Non-Newtonian (Carreau-Yasuda)	Rigid	Time-dependent velocity profile	Zero gauge pressure		Kashyap et al., (2020) [8]
Idealized		Laminar	Newtonian	Rigid	Time-dependent mass flow profile	Zero surface tension		Biglarian et al., (2019) [9]
Idealized		Laminar	Non-Newtonian (Cross model)	Rigid and Flexible	Constant inlet velocity	Constant pressure outlet (10 kPa)		Mulani et al., (2015) [10]
Idealized		Laminar	Newtonian	Rigid and Flexible	Time-dependent flowrate profile	Time-dependent pressure profile		Wu et al., (2015) [11]
Idealized		Laminar	Newtonian	Rigid	Constant inlet velocity (fully developed parabolic profile)	Constant pressure outlet (13 kPa)		Kenjereš et al., (2019) [12]
Idealized		Laminar	Newtonian	Rigid	Constant inlet velocity	Zero gauge pressure		Carvalho et al., (2020) [13]
Idealized		k-ω turbulent model	Non-Newtonian (Carreau model)	Rigid	Spiral boundary condition with a parabolic velocity profile	Zero gauge pressure		Kabir et al., (2018) [14]
Idealized		k-ω turbulent model (SST)	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile	Zero gauge pressure		Carvalho et al., (2020) [15]
Idealized		k-ω turbulent model (SST)	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile	Zero gauge pressure		Carvalho et al., (2020) [16] [17]

Geometry	Schematic Representation	Modeling Approaches	Fluid	Wall	Boundary Conditions	Inlet	Outlet	Authors
Idealized		N.A ¹	Newtonian	Flexible	Time-dependent velocity profile	Time-dependent pressure profile		Jahromi et al., (2019) [18]
Idealized		Laminar	Newtonian	Rigid	Time-dependent velocity profile	Flow partition implied in Murray's law		Doutel et al., (2018) [19]
Patient-specific		Laminar	Non-Newtonian (Generalized power-law model) and Newtonian	Rigid	Time-dependent flow rate profile	Time-dependent pressure profile		Chaichana et al., (2012) [20]
Patient-specific		Laminar	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile	Time-dependent pressure profile		Liu et al., (2015) [21]
Patient-specific		Laminar	Newtonian	Rigid and Flexible	Time-dependent pressure profile	Parabolic velocity profile		Siogkas et al., (2014) [22]
Patient-specific		N.A	Newtonian	Rigid	Time-dependent pressure profile	Constant pressure outlet (9.85 kPa)		Zhao et al., (2019) [23]
Patient-specific		Laminar	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile	Flow partition implied in Murray's law		Pandey et al., (2020) [24]
Patient-specific		Laminar	Non-Newtonian (Carreau model)	Rigid	Various time-dependent velocity profiles	Flow partition implied in Murray's law		Rizzini et al., (2020) [7]

Geometry	Schematic Representation	Modeling Approaches	Fluid	Boundary Conditions	Authors	
			Wall	Inlet	Outlet	
Patient-specific		N.A	Non-Newtonian (Power-law model)	Rigid	Time-dependent velocity profile Pressure outlet (N.A)	Zhang et al., (2020) [25]
Patient-specific		k-ω turbulent model (SST)	Non-Newtonian (Bird-Carreau model)	Rigid	Time-dependent velocity profile Constant pressure outlet (10 kPa)	Kamangar et al., (2019) [26]
Patient-specific		Laminar	Newtonian	Rigid	Time-dependent flow rate profile Two-Element Windkessel Model	Lo et al., (2019) [27]
Patient-specific and Idealized		Laminar	Newtonian and Non-Newtonian (Carreau model)	Rigid	Constant inlet velocity and Time-dependent velocity profile N.A	Doutel et al., (2019) [28]
Patient-specific and Idealized		k-ω turbulent model (SST)	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile Outflow condition	Mahalingam et al., (2016) [29]
Patient-specific and Idealized		N.A	Non-Newtonian (Carreau model)	Rigid	Time-dependent velocity profile Constant pressure outlet (10 kPa)	Rabbi et al., (2020) [30]

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models
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requiring much computational time and without the need to collect the medical images, which is highly time-consuming. In this regard, a promising study was proposed by Doutel et al., (2018) wherein artificial, but realistic stenosis can be generated.

It was also noted that, although the modelling of blood as a Newtonian fluid is a good approximation for large vessels with high shear rates, the assumption of non-Newtonian behavior of blood flow has been increasingly used

Geometry	Schematic Representation	Modeling Approaches	Fluid	Boundary Conditions	Authors	
			Wall	Inlet	Outlet	
Patient-specific and Idealized		Laminar	Newtonian	Rigid	Constant inlet mass flow and Time-dependent flow rate Zero gauge pressure	Malota et al., (2018) [31]

profiles more adequate to study the blood flow behavior in coronary arteries.

Despite the great efforts that have been made so far, the blood has been mainly modeled as a single phase fluid. [8][12][15][24][13][10][11][16][20][26][7][9][12][14][17][18][21][22][23][25][27][28][29][30][31]

However, blood is a mixture of plasma, red blood cells, white blood cells, and platelets. Therefore, the consideration of multiphase models is of great importance when modeling atherosclerotic lesions. Although some studies have already applied these models, the research is still in the beginning. Moreover, it should be also noted that the use of these models is a promising option for studying nanoparticle-mediated targeted drug delivery treatment of atherosclerosis. In this context, a promising study was conducted by Zhang et al., (2020). The authors used an Eulerian-Lagrangian approach coupled with FSI to investigate the impact of plaque morphology on magnetic nanoparticles targeting under the action of an external field.

Due to the continuous improvements acquired in computational methods, in the following years more amazing and complex hemodynamic studies will be performed. The work of Zhao et al. (2019) should be highlighted since their numerical approach has a great potential to achieve more realistic simulations. They have simulated 4D hemodynamic profiles of time-resolved blood flow. The results proved that these simulations can provide extensive information about blood flow, both qualitatively and quantitatively that may be advantageous for future investigations of clinical diagnosis and treatment of atherosclerosis.

To conclude, although computational methods have been extensively used for atherosclerosis investigations in recent years, they are expected to become more popular and more effective to simulate the blood flow in the cardiovascular system, and consequently, they will promote medical innovation at an affordable cost. However, to this end, active collaborations between engineers and medical staff are needed to assure the successful application of this technique in atherosclerosis treatment.

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