Engineered Science
DOI: https://dx.doi.org/10.30919/es8d691

A Computational Fluid Dynamics Study on Patient-Specific Bifurcated Carotid Artery

Abhimanyu H. Hegde,[1,#] Shreyaskumar R. Bhat,[1,#] Rakesh L[1,*] and Prakashini K[2]

Abstract

The carotid artery is one of the main arteries that provide blood to the brain and face. Sclerotic disorders resulting from plaque build-up in the carotid artery can increase the possibility of a stroke in a patient. This study investigates atherogenesis by carrying out a comparative study of the haemodynamic parameters in patient-specific carotid artery using Computational Fluid Dynamics (CFD) methods. The 3-dimensional model of patient-specific arteries was extracted using their Digital Imaging and Communications in Medicine (DICOM) images via Materialise Interactive Medical Image Control System (MIMICS). The processing of arteries was carried out on 3-matic, a meshing software in MIMICS. The artery blocked due to stenosis was reconstructed using an open-source medical software '3-D Slicer', and was later refined using Meshmixer software. Analysis of Systems (ANSYS) Fluent, an engineering simulation software, was used for this analysis. The conclusions have been drawn by monitoring wall shear stress on the artery under two different non-Newtonian viscosity models. A maximum Wall Shear Stress (WSS) of 17 Pa has been observed for the healthy carotid artery whereas the stenosed carotid artery recorded a maximum WSS of 136 Pa. Further analysis is conducted on the topology of the carotid artery based on the concentration of wall shear stress within the artery.

Keywords: Atherosclerosis; Carotid artery; Velocity streamline, Viscosity model, Wall shear stress.
Received: 27 September 2021; Revised: 21 March 2022; Accepted: 02 April 2022.
Article type: Research article.

1. Introduction

The carotid arteries are the major blood vessels in the neck that supply oxygen and nutrients to the head, neck, and face. On either side of the neck, there are two carotid arteries. Within the neck, each carotid artery is split into two parts: the internal carotid artery provides blood to the brain and the external carotid artery delivers blood to the face and neck. Atherosclerosis is a cardiovascular disease in large to medium-sized arteries, which entails complicated connections with the arterial wall and the pulsatile blood supply. It is an inflammatory mechanism characterized by the thickening of the intimate layer of the artery, which triggers plaque formation. Eventually, the growing plaque might restrict the carotid artery, resulting in stenosis and a stroke.[1] Carotid artery disease is caused by plaque build-up in the arteries. A stroke, often known as a "brain attack", can be caused by carotid artery stenosis. As the blood supply to the brain is cut off for more than a few minutes, brain cells begin to die. A stroke can result in long-term brain damage, visual or speech difficulties, paralysis (inability to move), and death.[2,3]

One of the most frequent diagnostic tests for detecting carotid artery disease is carotid ultrasound (commonly known as sonography). It is a painless, risk-free examination that employs sound waves to produce images of the carotid arteries' interiors. This test can determine if plaque has constricted the carotid arteries and the degree of narrowing. Carotid angiography is a form of X-ray. If the ultrasound results are ambiguous or do not provide enough information to the doctor, this test may be used.[4,5] Carotid endarterectomy is performed on individuals whose carotid arteries are 50% or more blocked/stenosed. A cut in the neck to reach the constricted or obstructed carotid artery during the surgery. They will next make an incision in the blocked artery and remove the inner lining of the artery that is restricting blood flow. Finally, the surgeon will use stitching to seal the artery and halt any bleeding. Carotid artery angioplasty is a procedure that widens the carotid arteries and restores blood flow to the brain. A

[1] *Department of Mechanical & Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education (MAHE), Manipal, 576104, Karnataka, India.*
[2] *Department of Radio Diagnosis and Imaging, Kasturba Medical College, Manipal Academy of Higher Education (MAHE), Manipal, 576104, Karnataka, India.*
[#] *These authors contributed to this work equally.*
**E-mail:* rakeshl.pillai@manipal.edu (R. Pillai)

small tube with a deflated balloon is threaded into a blood vessel in the neck to reach the restricted or blocked carotid artery. After the balloon has been placed, it is inflated to press the plaque against the artery wall. To support the inner arterial wall, a stent (a small mesh tube) is inserted into the artery. The stent also helps to keep the artery from contracting or being clogged in the future.[6,7]

Computational Fluid Dynamics (CFD) is often concerned with fluids in motion and how fluid flow behaviour affects processes. Furthermore, the physical properties of fluid movement are generally represented by fundamental mathematical equations, usually in partial differential form, that regulate the operation of interest and is sometimes referred to as governing equations. The American Heart Association defines cardio-vascular diseases as the leading cause of death in the United States.[8] A narrowing of the artery and a decrease in blood flow are common symptoms of this condition. Plaque formation is the narrowing of an artery. Atherosclerotic plaques (hardened arteries) may rupture, causing myocardial infection.

Comparative studies between CFD Models and PC-MRI (Phase-Contrast Magnetic Resonance Imaging) have been done utilizing parameters such as wall shear stress (WSS), oscillatory shear index (OSI), and axial velocity, as well as four distinct viscosity models (Newtonian, Power Law, Carreau-Yasuda, and Casson).[9] The U-tube viscometer method was used to calculate blood viscosity, and the findings were compared to the Carreau-Yasuda model. The Carreau-Yasuda model was found to be the most accurate for measuring whole blood viscosity.[10] To simulate pulsatile flow in CFD, a flow model is developed that uses a grid-free approach called Smoothed Particle Hydrodynamics. It explains the pulsatile flow profile, which is crucial to comprehending blood's behaviour as a Newtonian fluid.[11]

On the coronary artery, CFD was used to determine several haemodynamic parameters such as time-averaged wall shear stress, oscillatory shear index, and relative residence time. Grid independence and time-step independence studies are also used in model verification. The mathematical formulae necessary to calculate the above-mentioned haemodynamic parameters are also discussed in this work.[12,13] These methods and mathematical models can be essential for this study. Gender, body size, neck size, and the sizes of the Common Carotid Arteries (CCA) and Internal Carotid Arteries (ICA) are all significant considerations to consider. Multivariate regression has been used in this domain in studies based on height, weight, age, body mass index (BMI), body surface area, neck circumference, neck length, and blood pressure. Even after accounting for body and neck size, age, and blood pressure, it was shown that women's carotid arteries are smaller.[14,15]

Proof of concept studies for CFD analysis to detect atherosclerotic changes in intracranial aneurysms have been undertaken (in this cardio-vascular problem, a weakening of the wall of a cerebral artery or vein causes a localized dilation or ballooning of the blood vessel).[16] Detailed study was conducted concerning simulation of blood flow in patient-specific arteries, particularly revolving around different categories like viscosity models, flow type, flow parameters and type of solver used.[17]

CFD simulations were performed on four non-Newtonian models (Carreau, Cross, Quemada and Power-law). Furthermore, wall shear stress and pressure gradient were calculated and compared between the models (Carreau, Cross, Quemada and Power-law).[18] The study focuses to carry out a comparative study of different haemodynamic parameters in patient-specific carotid artery using Computational Fluid Dynamics (CFD) principles. Based on the results obtained, the inference will be drawn regarding atherogenesis. Inference is drawn from two sets of data, (a) patient-specific artery (without plaque) (b) Patient-specific artery (with plaque). The study also monitors wall shear stress values at different flow periods of pulsatile flow at different critical points of the patient-specific artery.[19]

2. Materials and methods

This study has been approved by International Ethics Committee of Kasturba Medical College, Manipal, Karnataka, India. Institutional Ethics Registration No.: ECR/146/Inst/KA/2013/RR-16; Ethics Registration No.: IEC: 922/2018

A three-dimensional (3D) reconstruction of carotid artery model from two-dimensional patient-specific Computed Tomography (CT) images obtained in Digital Imaging and Communications in Medicine (DICOM) format. Image acquisition, segmentation, smoothing, and mesh generation are common steps in reconstructing a 3D arterial geometry. A collection of 2D cross-sectional images is obtained from CT scans, after which segmentation techniques trace lumen borders in each image, and a vessel skeleton is obtained. The study's comprehensive procedures for extracting a three-dimensional model of the carotid artery using Materialise Medical Imaging Software are listed below.

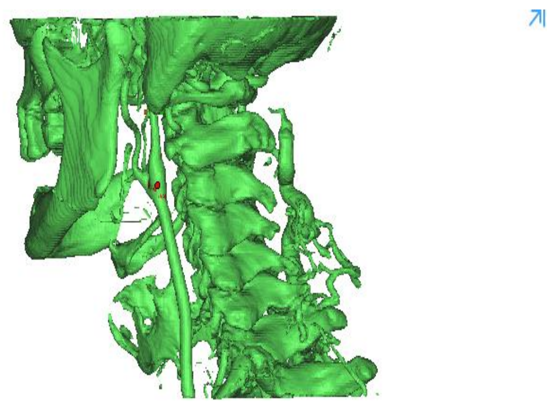

Fig. 1 MIMICS window to visualize carotid artery from the DICOM image (3D) of the patient.

2.1 The methodology adopted in Materialise Interactive Medical Image Control System (MIMICS): Image

visualization & 3-matic: mesh refinement

DICOM images of patient-specific arteries are loaded on to the software. Using Crop & Region Grow tool in segment menu, carotid artery is extracted via a mask & is further processed and enhanced (Fig. 1). This part is then exported to 3-matic for further processing. 3-matic is used to mark inlet & outlet surfaces using the 'Wave Brush Mark' tool which is required to apply boundary conditions in CFD (Fig. 2). Then, the mesh is exported into a STEP (Standard for Exchange of Product model data) file format which can be later imported to ANSYS.

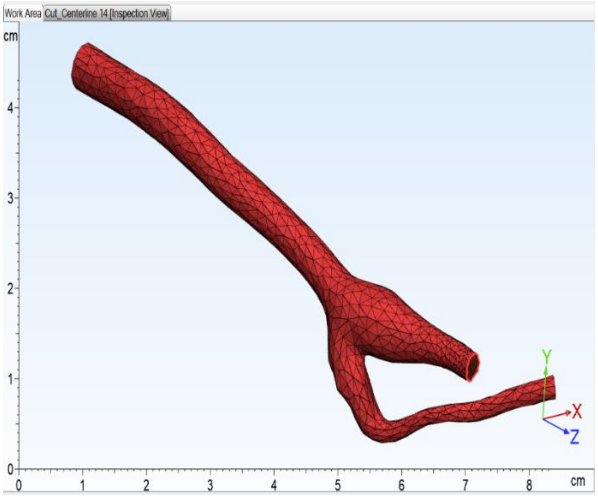

Fig. 2 3-matic work area interface.

2.2 Reconstruction of blocked artery using 3D Slicer

An open-source software '3D Slicer' has been used to reconstruct the blocked artery (carotid artery with stenosis).[23] The general process is largely the same as that of the healthy artery extraction. However, in this case, a new segment or a new mask is created by using a paint tool and marking the carotid artery in individual DICOM images from the axial window (Fig. 3). The Artery file is saved in 'Standard Triangle Language (STL)' format to be used for further processes.

The reconstructed Computer Aided Design (CAD) model developed was imported to ANSYS Fluent for performing CFD simulations on the artery. The parameters for CFD simulation are as follows:

CAD model of the artery is imported to ANSYS Workbench. Body Sizing is applied to the entire domain after mesh generation. Using Second Body Sizing, a sphere of influence is created, the centre of whose coincides with the geometric centre of the body. Systolic pressure for healthy humans is about 120 mm of Hg, and diastolic pressure is about 80 mm of Hg. Thus, Outlet A and Outlet B are set at a static pressure of 100 mm of Hg (13332 Pa). Simulation is conducted for a flow time of up to 0.5 s using a transient model with a time phase of 0.01 s and a total of 50-time steps. A total of 200 iterations per time step are set. Solutions are saved for every 0.1 s of flow time to record wall shear stress data at that time. A user defined function (UDF) is used to simulate the pulsatile flow of blood at the inlet. During a systolic phase, flow velocity at the inlet changes in a sinusoidal pattern.[20] The human blood is considered as a non-Newtonian fluid and its viscosity is determined by the components, flow parameters, and the relationship between their fluctuations (ratio between shear stress and shear rate). Two related viscosity models under laminar flow are used in the simulations carried in the present study.

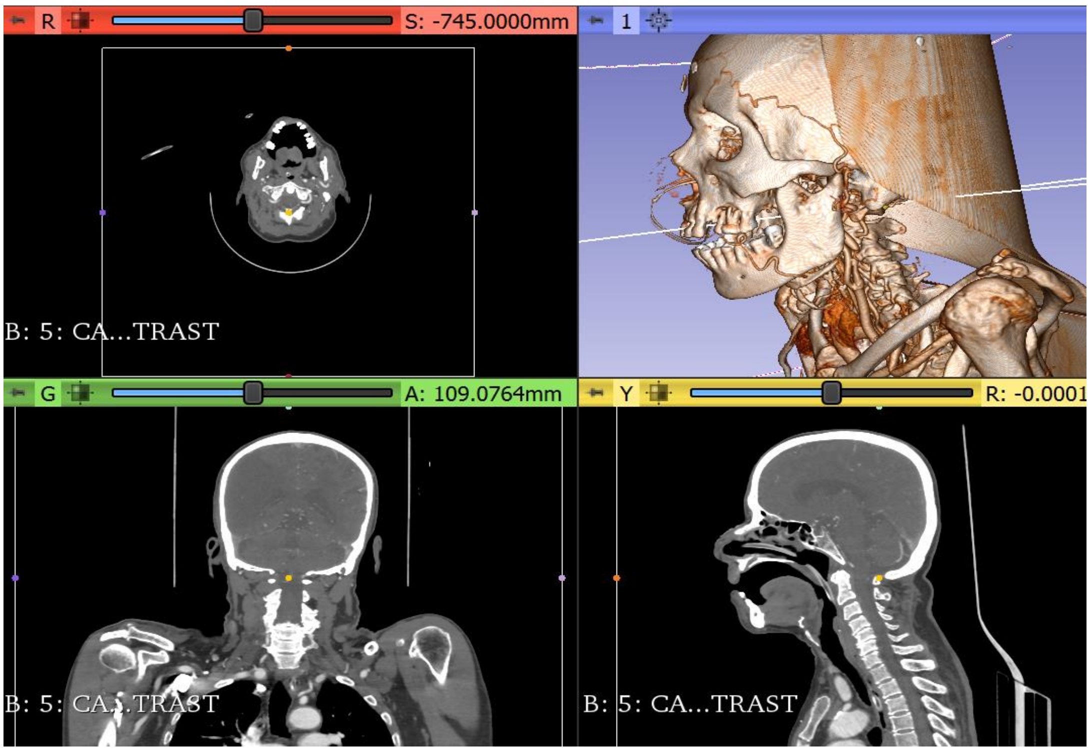

Fig. 3 3D Slicer interface for extraction of stenosed carotid artery.

2.3 Carreau and Casson viscosity models

The Carreau viscosity model is helpful to understand the flow behaviour of fluids in the high shear rate area; it is a form of non-Newtonian fluid whose viscosity is dependent on shear rate. Carreau provided rheological equations derived from molecular network theories for the first time.[21,22]

$$\mu_{eff}(\dot{\gamma}) = \mu_{inf} + (\mu_0 - \mu_{inf})(1 + (\lambda\dot{\gamma})^2)^{\frac{n-1}{2}} \quad (1)$$

where, λ = relaxation time (s), n = power index, μ_0 = viscosity at 0 shear rate (Pa·s), μ_{inf} = viscosity at ∞ shear rate (Pa·s).

Table 1. Material Constants for blood under Carreau and Casson models.

Carreau		Casson	
Constant	Value	Constant	Value
λ	3.313	n	0.4
n	0.3568	μ_0	0.00145 kg/m-s
μ_0	0.056 kg/(m·s)		
μ_{inf}	0.0035 kg/(m·s)		

Non-Newtonian fluid behaviour is described using Casson fluid model. Casson fluid is a shear-thinning liquid with an infinite viscosity at zero rates of shear, yield stress below which no flow occurs, and a zero viscosity at an infinite rate of shear, as well as other properties (Table 1). If the fluid is subjected to shear stress less than the yield stress, it acts like a solid, but if the shear stress is more than the yield stress, it begins to move.[21,22]

3. Results and discussion

3.1 Boundary conditions and solution method

We will analyze flow field and wall shear stress (WSS) developed at the bifurcation point in the post-processing phase. The simulation is conducted for a flow time of up to 0.5 s using a transient model with a time phase of 0.01 s and a total of 50 time steps. A total of 200 iterations per time step is set. Coupled vs. SIMPLE – For steady-state flows, the linked algorithm (coupled) produces a long-lasting and effective single-phase implementation that outperforms segregated solution methods. The density-based and pressure-based segregated algorithms, both of which employ SIMPLE type p-v coupling, are replaced by this pressure-based coupled method. The Coupled method is recommended when mesh quality is poor or longer time-steps are used for transient flows.[24,25]

3.2 Grid and time independency

The model has to be checked for consistency in results regarding the number of mesh elements and the length of time-step used. For this reason, we run a Grid and Time-step independency study on geometry.

Grid Independence Study – The model is tested at different levels of mesh refinement. As observed in the tabulated data, the wall shear stress and deformation results have a negligible deviation. (Table 2)

Time Independence Study - The model was initially run with a time-step of 0.01 s at 50 iterations per time-step. As the time period for sinusoidal flow is 0.5 s, appropriate combinations of time-steps and iterations/time-steps are chosen, and the simulations are performed. As observed in the tabulated data, wall shear stress and deformation results have a negligible deviation (Table 3).

3.3 Patient-specific artery

We proceed with realistic outlook by incorporating patient-specific case; Healthy left carotid artery & Stenosed left carotid artery. Ethical permission has been obtained from IEC (International Ethics Committee) of Kasturba Medical College, Manipal, India. Healthy artery is obtained from male patient of 70 years of age, and stenosed artery is obtained from

Table 2. Grid Independence Study on CAD model of ideal carotid artery.

Mesh	Time-step; Iterations per Time-step	Nodes in the Mesh	Elements in the Mesh	WSS at Bifurcation (Pa)		Deformation (mm)	
				Carreau	Casson	Carreau	Casson
M1	0.01 s; 50	161159	376093	4.3636	3.2757	0.97045	0.96969
M2	0.01 s; 50	316535	786912	4.6616	3.5834	0.97041	0.96965
M3	0.01 s; 50	736794	2061601	4.7894	3.6233	0.97038	0.96971
Standard Deviation				0.1784	0.1553	0.00003	0.00002

Table 3. Time Independence Study on CAD model of ideal carotid artery.

Version	Timestep	Iterations per Timestep	WSS at Bifurcation (Pa)		Deformation (mm)	
			Carreau	Casson	Carreau	Casson
V1	0.05	10	4.7532	3.6047	0.97045	0.96973
V2	0.01	50	4.6616	3.5834	0.97046	0.97046
V3	0.005	100	4.6363	3.5669	0.97046	0.96972
Standard Deviation			0.0502	0.0155	4.714E-06	0.00035

another male patient of 78 years of age. A comparison between the two viscosity models will be made parallel as we proceed through the analysis.

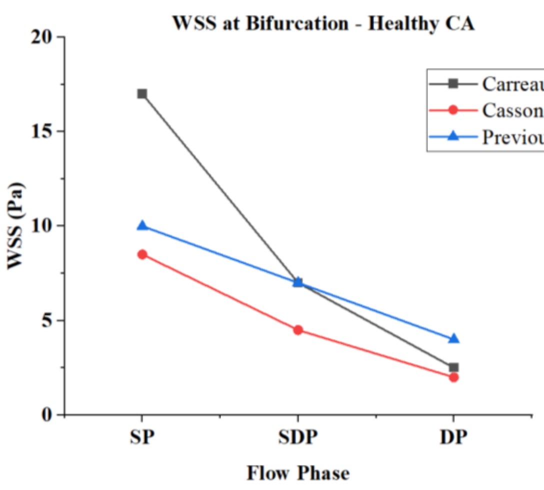

Fig. 4 Wall Shear Stress at Bifurcation.

3.3.1 Patient-specific artery – healthy

Wall shear stress - As per the above data and a graphical representation, the Carreau model shows a substantial deviation in WSS at higher flow velocity than the Casson model (Figs. 4 and 5). The results show that the Carreau model is much more sensitive to higher shear rates than the Casson model (Table 4).

Velocity streamlines in the healthy arteries are monitored at different flow phases under both viscosity models. It is seen that higher velocity magnitudes are achieved at the systolic phase. The bifurcation in the artery creates blood flow separation and causes flow recirculation at the carotid bulb. The immediate change in diameter of the artery at the ICA decreases flow velocity (Figs. 6(a) and 7(a)). At the dystolic phase, flow is much more laminar, owing to reduced velocity (Figs. 6(b) and 7(b)). Flow velocity is higher at ICA than the ECA due to the geometry of the artery. It is to be noted that flow behaviour at different flow phases is similar in both viscosity models, in the healthy specimen.

The velocity streamlines at different flow phases are compared with their corresponding wall shear stress contour plots. The shear stress values are low at the neck of the ICA, where the magnitude of velocity was low, and flow recirculation was predominant. Similarly, the point of bifurcation and upper region of the ICA bulb showed higher values of shear stress, where velocity gradients were more drastic. Consistently, maximum wall shear stress was observed at the systolic phase, whereas shear stress is considerably low in the base of bifurcation (end of Common Carotid Artery [CCA]) the dystolic phase.

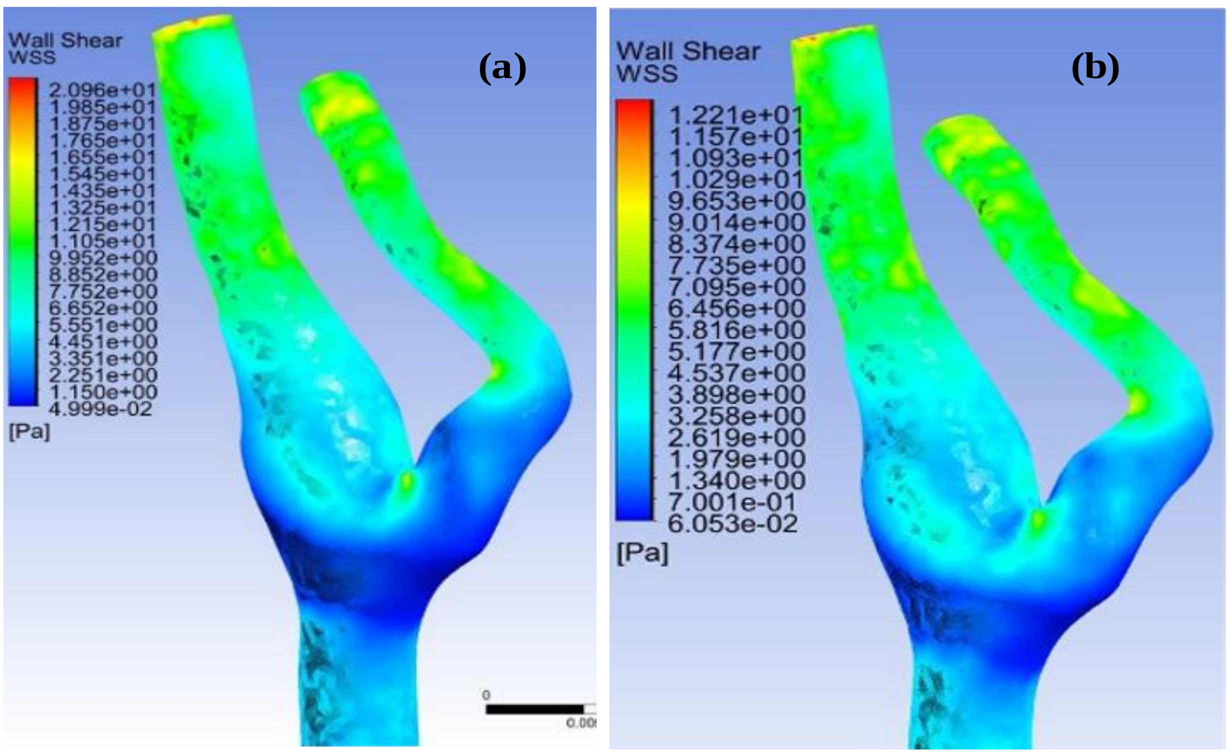

Fig. 5 Distribution of WSS at Systolic Phase, under (a) Carreau model and (b) Casson model.

Table 4. WSS in healthy carotid artery.

	WSS at Bifurcation (Pa)		WSS at ICA (Pa)		WSS at ECA (Pa)		Velocity and Time
Phase	Carreau	Casson	Carreau	Casson	Carreau	Casson	
Systolic Pressure (SP)	17.1636	8.4883	12.9055	8.0547	15. 3929	9.7997	v = 0.5 m/s at 0.1s
Dystolic Pressure (DP)	1.8575	1.3644	1.8144	1.3553	1.4778	1.0220	v = 0.1 m/s at 0.5s

SP = Systolic Phase, DP = Dystolic Phase, ICA = Internal Carotid Artery, ECA = External Carotid Artery.

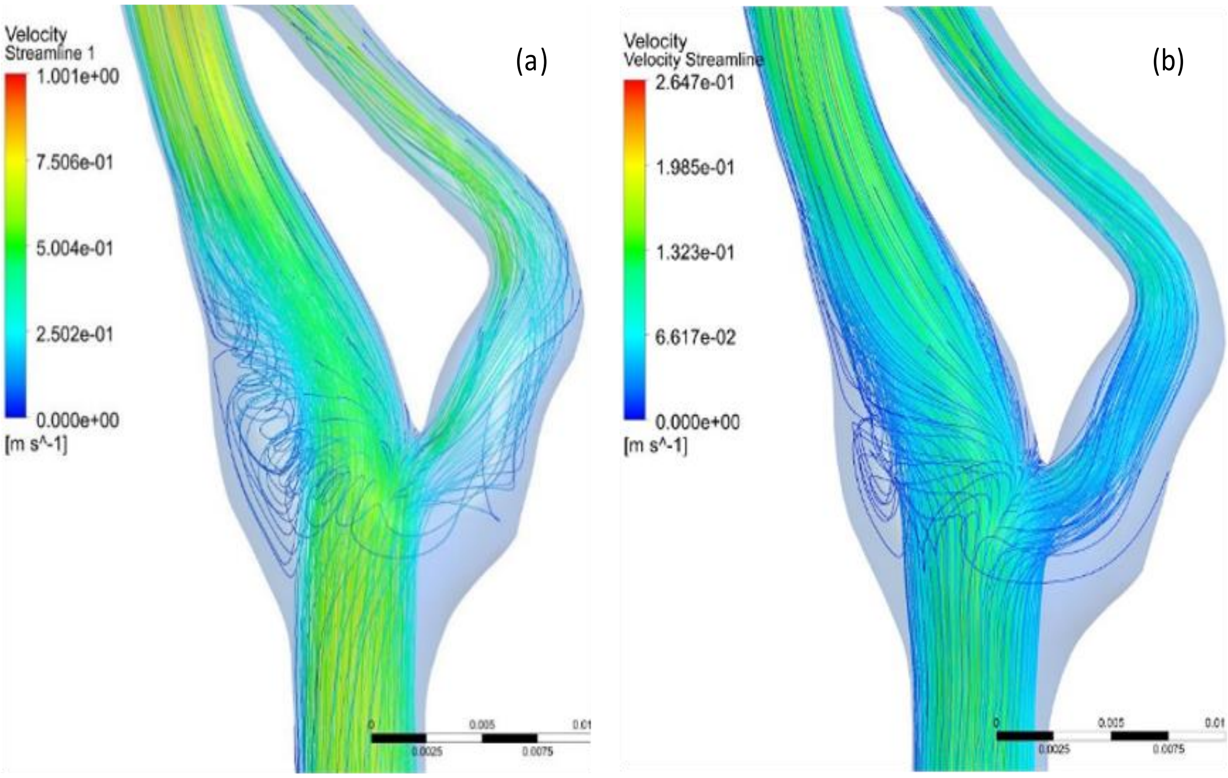

Fig. 6 Velocity Streamline in Carreau model at (a) Systolic phase and (b) Dystolic phase.

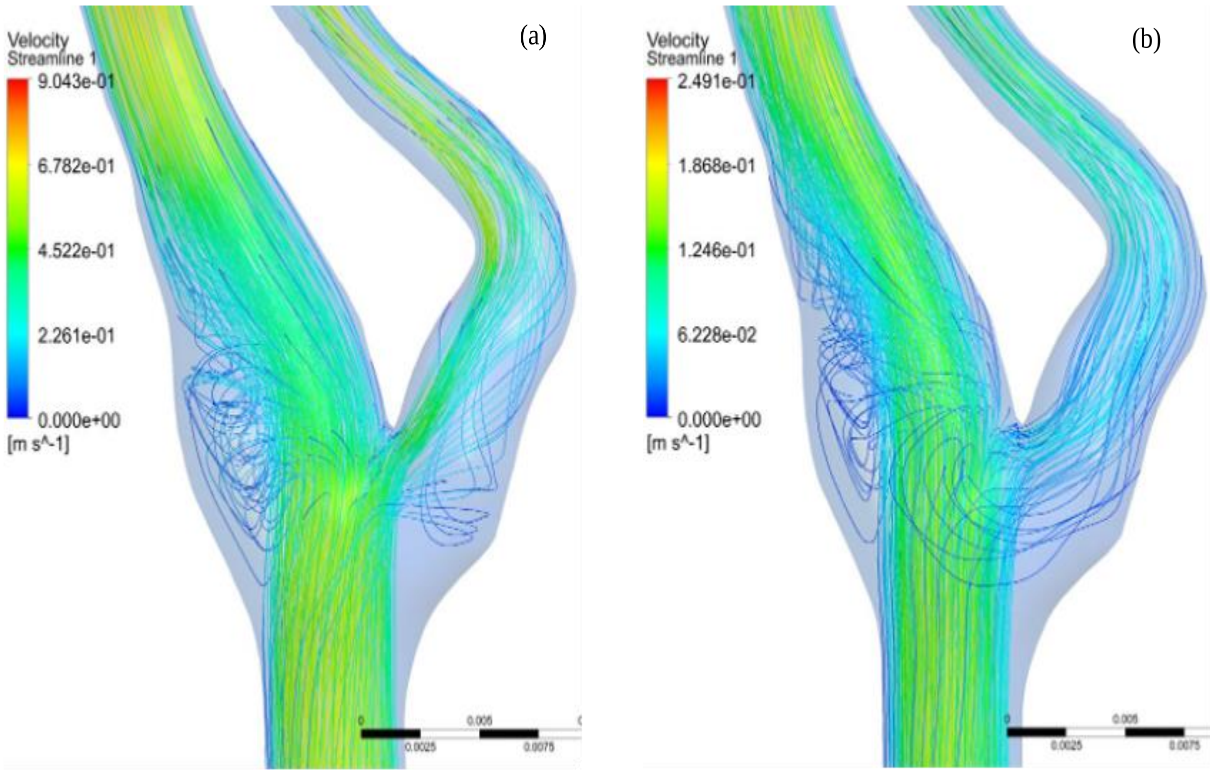

Fig. 7 Velocity Streamline in Casson model at (a) Systolic phase and (b) Dystolic phase.

3.3.2 Patient-specific artery – unhealthy

Similar analysis techniques are employed for unhealthy arteries. The patient is a 78-year-old male with a constriction in the internal carotid artery (ICA).

By comparing the diameter of ICA and diameter at the constriction, it is found that the artery exhibits 77.08% stenosis. The table below has the detailed tabulation of wall shear stress data for the two viscosity models at three key points, namely – the point of bifurcation, ICA, and ECA. (Table 5).

Table 5. WSS in stenosed carotid artery.

	WSS at Bifurcation (Pa)		WSS at ICA (Pa)		WSS at ECA (Pa)		Velocity and Time
Phase	Carreau	Casson	Carreau	Casson	Carreau	Casson	
SP	102.8610	61.0223	135.7820	83.7057	88.7288	50.4766	v = 0.5 m/s @ 0.1s
DP	11.5695	7.5084	12.7454	7.1481	10.3979	7.0900	v = 0.1 m/s @ 0.5s

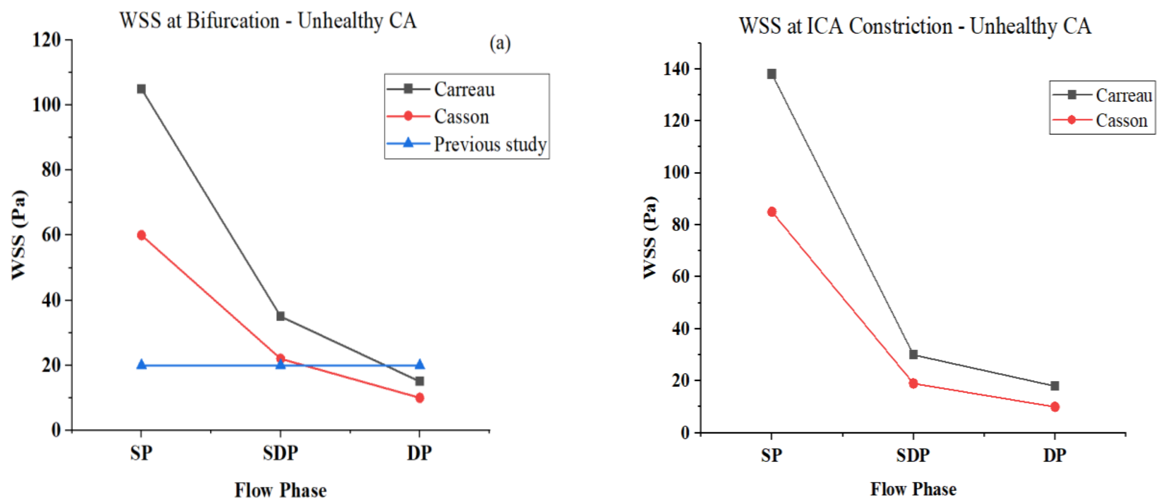

Fig. 8 WSS at (a) Bifurcation and (b) ICA Constriction.

Wall shear stress – The stenosed artery has significantly high shear stress values, especially at ICA constriction (Fig. 8), as compared to WSS at bifurcation (Fig. 8). It is yet again evident that the Carreau model shows a considerable deviation in wall shear stress at higher velocity magnitudes than the Casson model. The results show that the Carreau model is much more sensitive to higher shear rates than the Casson model. (Fig. 9)

Velocity streamlines - The velocity streamlines in the unhealthy arteries are monitored at different flow phases under both viscosity models. It is seen that higher velocity magnitudes are achieved at the Systolic phase. Owing to the narrow geometry at ICA, flow magnitude is higher at the constriction. Because of the narrow pathway for blood to flow, recirculation is more predominant in the base of the ICA in all flow phases (Figs. 10 and 11).

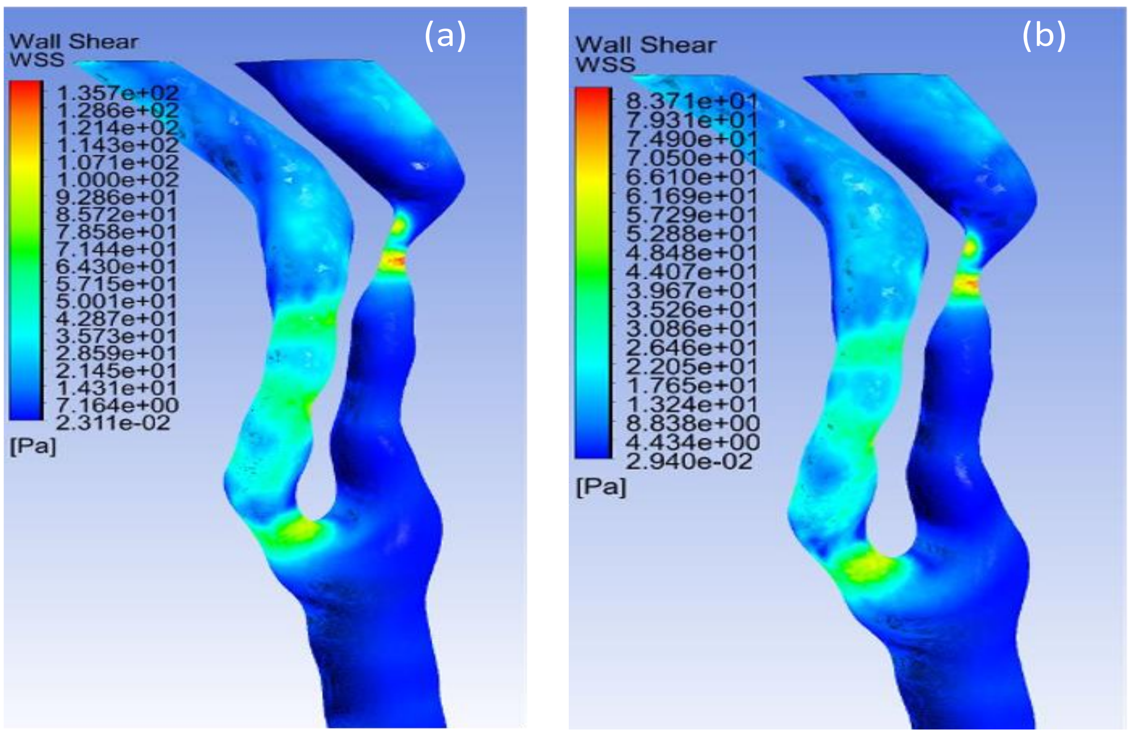

Fig. 9 WSS at Systolic Phase under (a) Carreau Viscosity model, (b) Casson Viscosity model.

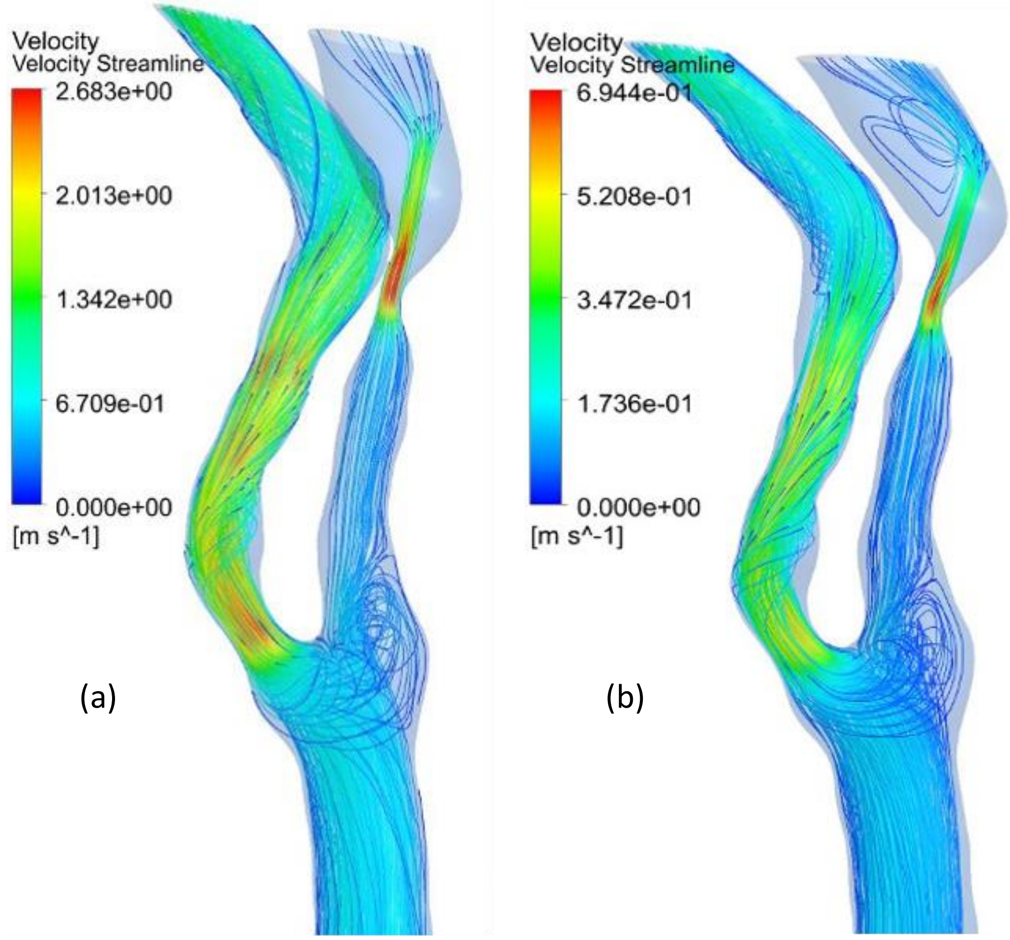

Fig. 10 Velocity streamline in Carreau Model at (a) Systolic phase and (b) Dystolic phase.

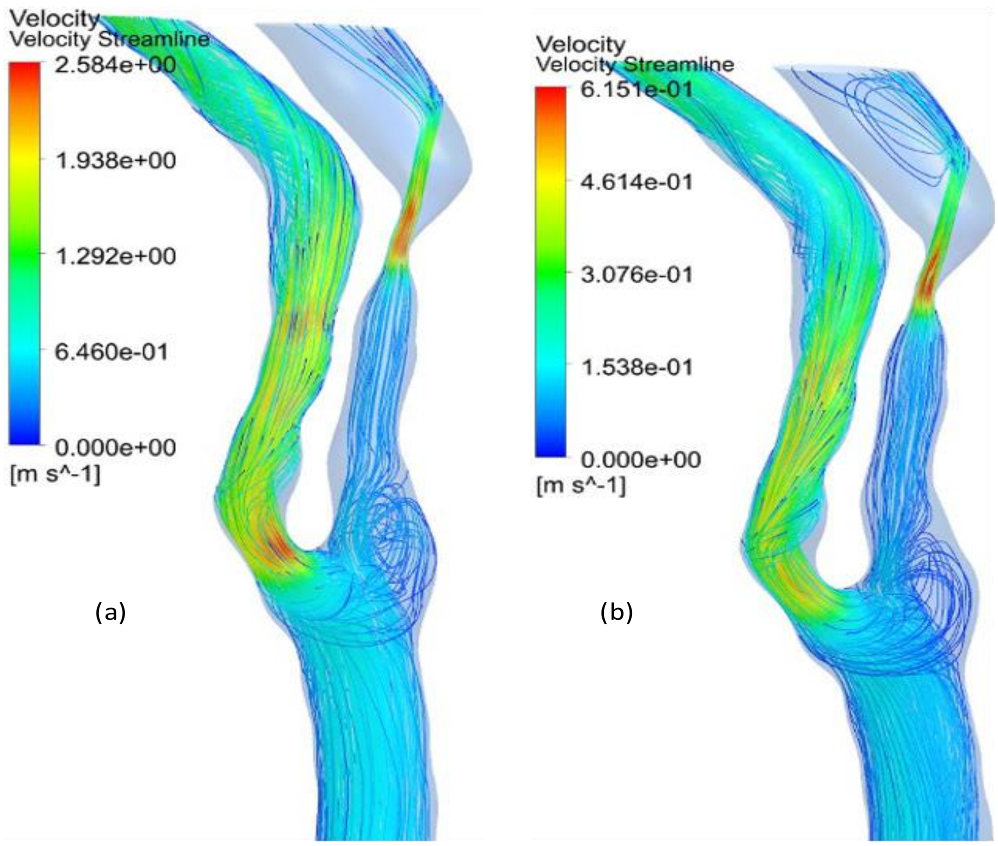

Fig. 11 Velocity Streamline in Casson model at (a) Systolic phase and (b) Dystolic phase.

The WSS values have been compared with a paper exploring similar parameters.[26] The viscosity model used was Carreau-Yasuda model exhibiting a maximum wall shear stress of 10 Pa (Fig. 4). In case of the stenosed artery, the maximum wall shear stress recorded was 20 Pa in the other paper.[26] There is a significant difference in the values as the percentage of stenosis is much higher in the carotid artery in this study. (Fig. 8(a))

This study conducted a transient analysis of the impact of pulsatile flow on the wall shear stress and the flow circulation under the two laminar flow viscosity models, Carreau and Casson viscosity. A comparative study of the patient-specific artery of both healthy and stenosed geometry was conducted. After visualization and extraction, the models were refined in the medical software MIMICS, 3D Slicer, and 3-matic. ANSYS Fluent is used for engineering simulation and post-processing.

As observed in the comparative study of the two sets of patient-specific arteries, the haemodynamic parameters, wall shear stress, in particular, is governed by mainly the geometry of the artery and type of blood flow. It is observed that WSS values were of larger magnitude in places of flow separation and over regions of maximum velocity gradients. Correspondingly, areas of flow recirculation (at the carotid bulb, in case of healthy CA; at the base of the ICA in case of Stenosed CA) are prone to particle accumulation and, as a result, plaque formation over due course of time.

Both the viscosity models similarly predicted the behaviour, except at higher velocities (Systolic phase). The Carreau Model showed higher sensitivity at such flow periods than the values generated using the Casson Model.

4. Conclusions

The primary conclusions that can be drawn from this study are: WSS is governed by mainly the topology of the artery and the type of blood flow (pulsatile; viscosity model). Maximum WSS was observed at places where there is a flow separation and high-velocity gradients. Due to low wall shear stress at the areas of flow recirculation, such regions are prone to particle accumulation, which, over time, leads to the formation of plaque and ultimately blockage of the artery. As per the results from the CFD simulation, the Carreau model showed higher sensitivity towards WSS than the Casson model, at higher flow velocities (Systolic Phase).

Acknowledgements

We gratefully acknowledge the help done by the Dept. of Radio Diagnosis and Imaging, KMC, Manipal Academy of Higher Education (MAHE), Manipal, Udupi, Karnataka, India for supplying the necessary CT data of patients for this study, and to Manipal Institute of Technology, Manipal Academy of Higher Education (MAHE), Manipal for their extended support. We also acknowledge all those who have directly or indirectly helped us in this regard.

Conflict of Interest

The authors declare no conflict of interest.

Supporting information

Not applicable.

References

[1] B. Forgo, E. Medda, A. Hernyes, L. Szalontai, D. Laszlo Tarnoki and A. Domonkos Tarnoki, *Twin Res. Hum. Genet.*, 2018, **21**, 333-346.

[2] MayoClinic.org, https://www.mayoclinic.org/diseases-conditions/carotid-artery-disease/symptoms-causes/syc-20360519.

[3] C. Radiology, *in Vascular Ultrasound. (Cremorne Radiology)*, 2022.

[4] E. Hitchner, W. Zhou, *Int. J. Angiol.*, 2015, **24**, 185-188.

[5] P. E. Gates, A. Gurung, L. Mazzaro, K. Aizawa, S. Elyas, W. D. Strain, A. C. Shore, R. Shandas, *Ultrasound Med. Biol.*, 2018, **44**, 1392-1401.

[6] MayoClinic.org, https://www.mayoclinic.org/tests-procedures/carotid-endarterectomy/about/pac-20393379.

[7] I. Bytyçi, R. Shenouda, P. Wester, M. Y. Henein, *Arteriosclerosis, Thrombosis, and Vascular Biology*, 2021, **41**, e224-e237.

[8] D. Tang, C. Yang, S. Kobayashi, J. Zheng, R. P. Vito, *Ann. Biomed. Eng.*, 2003, **31**, 1182-1193.

[9] H. Gharahi, B. A. Zambrano, D. C. Zhu, J. K. DeMarco, S. Baek, *Int. J. Adv. Eng. Sci. Appl. Math.*, 2016, **8**, 46-60.

[10] Y. Pratumwal, W. Limtrakarn, S. Muengtaweepongsa, P. Phakdeesan, S. Duangburong, P. Eiamaram, and K. Intharakham, *Songklanakarin, J. Sci. Technol.*, 2017, **39**, 625-631.

[11] M. Sinnott, P. Cleary, M. Prakash, *An investigation of pulsatile blood flow in a bifurcation artery using a grid-free method*, 2006.

[12] A. Buradi, A. Mahalingam, *Advances in Mechanical Engineering, Select Procedings of ICRIDME*, 2020, 107-118.

[13] Z. Ding, K. Wang, J. Li, X. Cong, *J. Biomech.*, 2001, **34**, 1555-1562.

[14] J. Krejza, M. Arkuszewski, S. E. Kasner, J. Weigele, A. Ustymowicz, R. W. Hurst, B. L. Cucchiara, S. R. Messe, *Stroke*, 2006, **37**, 1103-1105.

[15] R. Faturechi, A. Hashemi, N. Abolfathi, A. Solouk, A. Seifalian, *Vascular*, 2019, **27**, 636-647.

[16] S. I. Sugiyama, H. Endo, K. Niizuma, T. Endo, K. Funamoto, M. Ohta and T. Tominaga, *Comput. Math. Methods Med.*, 2016, **2016**, 2386031.

[17] D. Lopes, H. Puga, J. Teixeira, R. Lima, *J. Biomech.*, 2020, **111**, 110019.

[18] J. B. Mendieta, D. Fontanarosa, J. Wang, P. K. Paritala, T. McGahan, T. Lloyd & Z. Li, *Biomech. Model. Mechanobiol.*, 2020, **19**, 1477-1490.

[19] D. Martin, A. Zaman, J. Hacker, D. Mendelow, D. Birchall, *Brit. J. Radiol.*, 2009, **82**, S33-S38.

[20] S. Gupta, Skill-Lync Inc, https://skill-lync.com/student-projects/3d-bifurcating-artery.

[21] S. Kim, Y.I. Cho, W.N. Hogenauer, K.R. Kensey, *J. Non-Newton. Fluid Mech.*, 2002, **103**, 205-219.

[22] M. Khan, H. Sardar, M. M. Gulzar, A. S. Alshomrani, *Results Phys.*, 2018, **8**, 926-932.

[23] A. Fedorov, R. Beichel, J. Kalpathy-Cramer, J. Finet, J. C. Fillion-Robin, S. Pujol, C. Bauer, D. Jennings, F. Fennessy, M. Sonka, J. Buatti, S. Aylward, J. V. Miller, S. Pieper, R. Kikinis, *Magn. Reson. Imaging*, 2012, **30**, 1323-1341.

[24] D. Lopes, H. Puga, J. C. Teixeira, S. F. Teixeira, *Int. J. Mech. Sci.*, 2019, **160**, 209-218.

[25] N. Kumar, A. Khader, R. Pai, S. Khan, *Int. J. Eng. Sci. Technol.*, 2020, **154**, 103341.

[26] H. Gharahi, B. A. Zambrano, D. C. Zhu, J. K. DeMarco, S. Baek, *Int. J. Adv. Eng. Sci. Appl. Math.*, 2016, **8**, 40-60.

Author Information

Abhimanyu H. Hegde *has been born and brought up in Mumbai, India. He completed his undergraduate studies in Mechanical Engineering from Manipal Institute of Technology, Manipal, India with a specialization in Machine Design. He has worked as a Production Engineer in VITECH Equipments Pvt. Ltd., India, working on manufacturing of Heat Exchangers, Crystallizers and multi-stock Deodorizers. Outside of his academic field of interests,*

Shreyaskumar R. Bhat *is currently pursuing his graduate degree in Industrial Engineering from Northeastern University, Boston. Formerly, a Mechanical Engineering graduate from Manipal Institute of Technology, Shreyaskumar's interest lies in research and application of Optimization math-models and Engineering simulations to solve multidisciplinary problems. As a graduate senator for the student government at Northeastern university, he has been an advocate for increased participation of aspiring engineers in the field of healthcare product and service sector.*

Mr. Rakesh L *is working as Asst.Professor(Senior) in the department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education (MAHE) since 2007.He has done his B.E(Mechanical Engg) from Kumaraguru College of Technology, Tamilnadu and M.Tech(Industrial Engg) from National Institute of Technology, Trichy, Tamilnadu and currently he is pursuing his doctoral Program at National Institute of Technology, Surathkal Karnataka. He has attended and participated in various conferences and workshops.His areas of interests include Fluid Mechanics, Computational fluid dynamics, Hemodynamics, Experimental fluid mechanics.He has more than a decade experience in teaching subjects like Fluid Mechanics, Engineering Graphics and Thermodynamics. Currently he is committed towards his research titled "Experimental investigation of hemodynamics of patient - specific bifurcated human carotid artery".*

Dr. Prakashini Koteshwar*, is professor in the department of Radiology, KMC, Manipal, MAHE, Udupi, Karnataka, serving at Kasturba Medical college since 2006. Pursued MD degree in Radiodiagnosis and Imaging from prestigious university, Manipal Academy of Higher Education. Since then she is serving at her alma mater at different cadre and since 2014 she is positioned as professor. Presently since last 3 years she is heading the department of Radiology at Kasturba medical college. During her tenure she initiated different academic programmes and recently commenced Interventional Division which is going to provide all high end semi invasive non-surgical options of treatment, to various emergency and non-emergency conditions. Her area of interest is neuroimaging, cardiovascular imaging and Interventional Radiology. She has completed Level I accreditation in CT and MRI reporting of cardiac imaging. She has been working with AI based algorithm applications in brain tumours and computational flow dynamics in carotid, renal arteries and presently on 'effect of peristalsis on ureteric flow'. She has several publications to her credit both in national and international reputed journals on clinical, radiological and AI aspects. She has been guiding several research and PhD projects of MD radiology, MSc medical imaging students and also engineering graduates. She is an auditor of NABH and ISO accreditation. Also looking at the documents related to MCI recognition for MBBS and MD radiology. Working with grant projects of DST/SERB and industry collaborations too.*

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.