Effect of flow velocity and pressure on carotid artery due to deposition of different shapes of plaque

Raman Yadav¹, Sharda Vashisth², Ranjit Varma³ and Kaushal Kumar⁴

¹Department of EECE, K.R. Mangalam University, Gurgaon, Haryana, India
²Department of EECE, The North Cap University, Gurgaon, Haryana, India
³Director, Delhi Technical Campus, Greater Noida, Uttar Pradesh, India
⁴Department of ME, K.R. Mangalam University, Gurgaon, Haryana, India
raman.y.90@gmail.com

Abstract: Atherosclerosis is the disease progressed because of the deposition of stenosis at the interior walls of arteries which results in reducing the size and causing blockage in the carotid artery leading to brain attack or stroke. Two-dimensional model of carotid artery is designed and analyzed by Computational Fluid Dynamics (CFD). Designing of general analytical model of artery followed by meshing of geometry, application of boundary conditions and analysis is done with ANSYS Fluent 16.2. The objective of this research is to analyze the consequence of flow velocity and pressure on the arteries having blockage to assess the diseases related to carotid artery. This paper provides analytical analysis of flow velocity and pressure on the artery due to deposition of different shapes of plaque. We consider plaque shape1, plaque shape2, cosine plaque and irregular plaque shapes. Hemodynamic variables like velocity and pressure differ with commute mostly in the shape of geometry. It’s found that velocity is maximal at the constraint as compared to pre- and post-stenotic areas which shows that the artery having more stenosis area has maximum pressure and velocity on the wall of the artery.

Keywords: Atherosclerosis, Computational Fluid Dynamics (CFD), Contour, Stenosis, Bifurcation

1. Introduction
Atherosclerosis is the cardinal source of death and consequential impairment in the developed countries [1]. It is accountable for fatality and morbidity universally which is resulted because of debilitation of the immune system [2]. Cerebrovascular diseases are associated with the flow of blood in arteries. Atherosclerosis is the one of the vital arterial disease which is originated due to accumulation of plaque in arteries due to the accumulation of fat, cholesterol, carbohydrates, fibrous tissue and low-density lipoproteins [3, 4]. It is frequently referred to hardening of the arteries. Bifurcation and division of arteries are the most preferred sites for the progression of atherosclerosis. With the progression of the ailment, these plaques enlarge and lead to the impairment of flow velocity in the artery [5]. The symptom of atherosclerotic cerebrovascular disease is brain attacks or strokes. The Fluid dynamics of carotid artery gives us better understanding of flow of blood though artery and commencement and growth of atherosclerotic ailment [11, 19].

The role of the Carotid artery is to impart blood and other nutrients to the brain, face and neck of the human body. Here we have carotid artery, on both side of our neck. Each carotid artery can be divided into two division viz. internal carotid artery (ICA) and external carotid artery (ECA) [6, 17]. Internal carotid artery has larger diameter as compared to the external carotid artery as revealed in Figure 1. The purpose of the ICA is
to impart blood to the brain and that of the ECA is to impart blood to the face, scalp and neck.

Laser Doppler anemometry has been widely used as an experimental technique for the visualization and quantification of blood flow through arteries. B-mode ultrasound is another technique for the detection of early atherosclerosis which begins with intima-media thickening. Direct visualization of both artery wall and lumen is possible with it. This information contributes to significant function for the diagnosis and assessment of atherosclerotic ailment.

Computational Fluid Dynamics (CFD) [12] representation is used effectively for prediction of flow pattern within the artery, and for checking the initiation and progression of plaque in the arterial wall [8, 9, 15]. CFD, applied to 2-D arterial geometries having different plaque shapes, provide precious simulation of complex geometry. Computational methods are easy to simulate and gives result more accurate and cost effective [7, 10].

The shape and size of plaque are variable for patients [13, 14]. In this study, four different shapes of the stenosis are assumed, and its velocity and pressure contour are determined. The consequence of the stenosis shapes on the flow of blood throughout carotid artery is analyzed. The consequence of different shapes of plaques on the flow pattern and pressure of the artery at the bifurcation is also determined.

2. Methodology

2D idealize geometry of carotid artery is created by means of CFD Fluent for the simulation of blood flow. After that the geometry is meshed by inherent mesh tool in workbench. For meshing the geometries, tetrahedral elements are used. The anatomical geometrical representation of idealized carotid artery used in this study is shown in Fig. 2. Then boundary conditions are applied at inlet and outlets of the artery. The boundary condition functional for transient flow examination is inlet velocity according to the user defined function and the pressure for the stenosis artery at mutual outlet surface is 0 Pa. Carreau-Yasuda model is employed for the Non-Newtonian type of flow and for the Newtonian flow power law model is adopted.

![Anatomical model of healthy carotid artery](image)

**Figure 1.** Anatomical model of healthy carotid artery

2.1. Software used

ANSYS Fluent® is economically accessible CFD software delivers unprecedented productivity, enabling simulation and highly reliable. It has capability to solve steady and transient simulations. It is communicating in programming language C which has wide variety to make it more versatile and flexible. On ANSYS workbench platform geometrical representation is designed, meshed and then relevant boundary conditions are decided. After identifying boundaries User Defined Functions (UDF) communicated in C are adjoined to the fluent, thus increases its adaptability. Variety of functions can be implemented using Fluent. Here finite volume discretization method is used to convert
Partial differential equation of conservation of mass and momentum into non-linear algebraic equations.

2.2. Governing Equations
The Navier- Stokes (1) and (2) represent the continuous fluid flow through artery. It consists of three equations; Continuity equation, Momentum equation and Energy equation which are obtained by applying conservation of fluid flow.

\[ \nabla \cdot \mathbf{u} = 0 \]
\[ \rho \frac{\partial \mathbf{u}}{\partial t} = -\nabla P + \mu \nabla^2 \mathbf{u} \]  

(1)
(2)

Where \( \rho \) be the density, \( \mathbf{u} \) be the velocity vector, \( P \) be the pressure, \( \mu \) be the coefficient of viscosity and \( t \) be the time.

2.3. Non-Newtonian Equations
For Non-Newtonian and Carreau model complex rheological behaviour of blood is approximated, here apparent viscosity is expressed as the function of shear rate [18] the governing equation is:

\[ \mu = \mu_\infty + (\mu_\infty - \mu_0)[1 + (\gamma \lambda)^2]^{n-\frac{1}{2}} \]  

(3)

Parameters used for Carreau Non-Newtonian model are; time constant, \( \lambda = 3.313s \); power law index, \( n = 0.3568 \); resting viscosity, \( \mu_0 = 0.56P \); infinite strain viscosity, \( \mu_\infty = 0.0345 \text{ P} \); density of blood, \( \rho = 1060 \text{ kg/m}^3 \) [16]

3. Result
3.1. 2D idealized Carotid artery
The 2D geometry of carotid artery is created and meshed using ANSYS followed by calculations and further analysis. Fig. 2 shows the representation of healthy carotid artery along with its dimensions.

Blood flow refers to the movement of blood through the arteries. Flow of blood is inversely proportional to the area of the artery. Velocity of blood flow reduces as cross-sectional area increases. Velocity increases if the plaque is deposited in the artery which results in decrease of cross-sectional area of the artery. Pressure on the arterial wall may be defined as the measure of force that blood exerts on the wall of the artery as it moves blood through artery. Pressure and velocity of flow through artery is affected due to the deposition of the plaque in it. The stenosis shape results in varying the velocity and pressure of the blood on the wall. Velocity and pressure measurement of the blood flow through the artery due to presence of the stenosis are very important parameters to measure the severity of blockage which may lead to fatal situation if not diagnosed accurately.
3.2. Velocity Contour
Shapes of the plaque vary from person to person. Fig. 3 shows the velocity contour of healthy artery. In our study we use different types of plaque shapes categorized as plaque shape 1, plaque shape 2, cosine plaque and irregular plaque as shown in Figures 4-7. Therefore, the velocity and pressure contour are calculated for all artery having different shapes of plaque.

From the results we can observe that velocity does not vary much before the blockage and remains nearly same in the proximal region. From the contours it is observed that velocity near the wall of the artery is nearly zero and the maximum velocity occurs at the region having maximum stenosis. The artery having maximum restriction results in increasing the flow velocity and the region having less percentage of restriction results in reducing flow velocity. This indicates that with increase in restriction, there is more possibility of deposition of plaque in arterial wall.

Figures 4-7 represent the velocity contours for different stenosis shapes taken in our study. It is noted that velocity contour of plaque shape 2 have maximum blood velocity at the stenotic region followed by plaque shape 1, irregular shape, cosine shape and healthy artery. Therefore, from the velocity contour figures it is revealed that the physiological effect of shape of stenosis is more in plaque shape 2. Area for fluid passage is also less in this case which in turn increases the chance of atherosclerosis and results in stroke. Velocity contour of the arteries exhibits how the different shapes of the stenosis influence the flow of blood through it. We have observed that the buildup of stenosis in the artery bring about blockage and the consequential reduction in region give rise to the flow of velocity of blood through it.

Figure 3. Flow velocity for healthy plaque
Figure 4. Flow velocity for plaque #1

Figure 5. Flow velocity for plaque #2

Figure 6. Flow velocity for Cosine plaque

Figure 7. Flow velocity for Irregular plaque
3.3. Pressure Contour

Figures 8-11 shows the pressure contour of the artery having stenosis. Stenotic arteries in our study are arteries having plaque shape 1, plaque shape 2, cosine plaque and irregular plaque as discussed above. Pressure contour is calculated for all artery having different shapes of plaque. Through it we can measure the force exerted by the blood on the artery wall. As the percentage of restriction increases, the pressure on the artery also increases. Subsequently we can perceive that the maximal pressure takes place at the region having maximum stenosis. The artery having maximum restriction results in increasing the pressure through the artery whereas the region having less percentage of restriction results in reducing pressure through it. Maximum pressure through the artery was found at the mid of the stenosis and in the post stenotic region there is decrease in the pressure. Figs. 8-11 represent the pressure contours for different stenosis shapes taken in this study.

![Figure 8. Pressure contour for Plaque #1](image1)

![Figure 9. Pressure contour for Plaque #2](image2)

![Figure 10. Pressure contour for Cosine Plaque](image3)
From figures it is noted that pressure contour of plaque shape 2 have maximum pressure at the stenotic region followed by plaque shape 1, irregular shape and cosine shape. Therefore, from the pressure contour figures it is revealed that the physiological effect of shape of stenosis is more in case of plaque shape 2. It is observed that the accumulation of stenosis in the artery leads to blockage and the considerable reduction in area bring about increase in the pressure of the blood through it.

4. Conclusion

The conclusion of this work can be outlined as observed: As stenosis in the artery increases, blood flow through it also increases. In this work, different shapes of stenosis are considered which shows that there is significant consequence of the shape of stenosis on the blood flow characteristics. Plaque shape 2 has maximum flow velocity followed by plaque shape 1, irregular and cosine plaque. Pressure through the artery in the presence of the plaque is also a diagnostic parameter which is also calculated for different plaque shapes and the pressure through the artery having plaque shape 2 is maximum then other arteries. From this we conclude that the artery having plaque shape 2 has maximum severity level and is more prone to rupture as compared to other plaque shapes.

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