Modeling and Simulation of Various kinds of Blockage in Carotid Artery

Kshitij Shakya , Shubhajit Roy Chowdhury
Biomedical Systems Laboratory, MANAS Group
School of Computing and Electrical Engineering, Indian Institute of Technology Mandi,
Mandi, India
Email: d17016@students.iitmandi.ac.in, src@iitmandi.ac.in

Abstract **— This paper focuses on the blood flow in blood vessels and the obstruction faced by it due to plaque which gets accumulated due to deposition of fat and cholesterol on the side walls of the blood vessels. The current research analyses the blood velocity profile and the changes in pressure. The deposition of plaque from initial level to complete blockage of the artery and its consequence on blood flow is also presented in this article. A three dimensional model of a blood vessel along with the deposition of plaque on it has been developed and simulated in Comsol Multiphysics 5.3. This study assumes that the fluid is non-Newtonian, viscous and compressible. Fluid flow is laminar and the arterial wall is elastic. Properties of blood vessel, fat and blood were assigned to the materials of geometry used for simulation. The simulation studies show the hemispherical blockages of carotid artery are really dangerous and may be a cause of concern for imminent ischemic cerebrovascular accident or stroke.**

Keywords- COMSOL Multiphysics; blood vessel; Spherical and hemispherical blockages; carotid arterydisease, computational fluid dynamics.

I. INTRODUCTION

Analysis of flow conditions in the blood vessel is very important to avoid various cardiovascular and cerebrovascular diseases. One of the major arteries, named carotid artery, is often studied for prognosticating imminent cardiovascular and cerebrovascular disorders. The carotid artery disease (CAD) is characterized by the deposition of fat and cholesterol which takes the form of a plaque. It keeps on depositing on the walls of blood vessel until it completely blocks the blood vessel. The severe cases result in heart attacks or even cardiac arrest or cerebral ischemic attack. Early detection of this disease is very important.

Clinical symptoms of carotid artery disease may manifest themselves as stroke or transient ischemic attack [1]. Most cases of carotid artery stenosis are caused by atherosclerotic plaque as part of generalized atherosclerotic disease. Carotid artery stenting (CAS) has been initially used as an alternative treatment option in patients not eligible for surgery [6]. Numerous non-randomized and some randomized studies have assessed the safety and efficacy of CAS in so-called high risk patients. It is hard to reconcile the modest number of patients who are at increased 10-year risk by the Framingham cardio-vascular (CV) risk model with the observation that the lifetime risk of coronary artery disease (CAD) starting at age 40 years is 49% for men and 32% for women [3]. Several studies have shown that plaque presence is associated with systolic blood pressure, use of tobacco, the total to high-density lipoprotein cholesterol ratio, and body-mass index or weight [4]. Carotid plaque is associated with traditional and non-traditional CV risk factors. Several studies have shown that carotid plaque, either alone or combined with other screening tests and information from the patient's history, predicts the presence of cardiac ischemia and angiographic CAD [2].

The current research analyses the various blood flow velocities, lateral minimum and maximum velocity and also the pressure experienced by the arterial wall and the structure of plaque causing obstruction. Our aim is to compare the scenarios between a healthy artery and the artery with disease describing the changes in the blood flow, plaque formation, blood flow velocity and pressure. This computer simulated model is helpful in analysing the possibility of occurrence of CAD and learning the behaviour and consequences of the plaque getting deposited regularly. The model also simulates the formation and growth of the plaque and observes the changes in blood flow which is faster, simpler and safer before doing the treatment.

This paper is organized as follows: Section II focuses on the modeling of the carotid artery, Section III is about results and their discussion and, lastly, Section IV concludes the paper.

II. MODELING OF CAROTID ARTERY

In the current work Comsol Multiphysics® has been used to model the geometry of the artery and do the desired simulations. A cylindrical shaped structure of 6 mm radius and 50 mm length has been taken to model the artery. To design two different types of blockages, a sphere with 3 mm radius was embedded on the upper wall of the artery and, in the second case, two hemispherical chords like structure were embedded on the upper and lower wall of the artery. For simulation of the blood flow inside the artery, it was assumed to have a3D laminar flow. For studying the effect of blood flow on the walls of the carotid artery, solid mechanics accompanied by a stationary study solver have been used. The material for the blood has been assumed to

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be non-Newtonian, viscous, and compressible and the artery walls have been assumed to be elastic. The blood flow is governed by the continuity equation and Navier-Stokes equation.

The model contains three domains, one forms the cylinder containing the walls of the artery, the second forms the space where blood flows and the third is for the fat or cholesterol structure forming the plaque.

TABLE I. MATERIAL PROPERTIES USED FOR SIMULATION

Properties	Blood	Artery	Fat deposit
Density (Kg/m^3)	1060	1.06e3	1050
Dynamic Viscosity(Pa.s)	0.005	-	-
Young's modulas (MPa)	-	2	20
Poisson's ratio	-	0.49	0.11

The flow under laminar flow physics was modelled for blood as a non-Newtonian fluid with no slip boundary condition. Two boundaries for inlet and outlet flow have been selected with inlet velocity of 0.15m/s and outlet pressure of 0 atm.

Two types of cholesterol deposits are modelled against the artery wall: one is sphere shaped and the other is hemispherical type whose parameters used for simulations are shown in Table I. A 3D shape of a cylindrical blood vessel is shown in Figure 1 with cross section and longitudinal view.

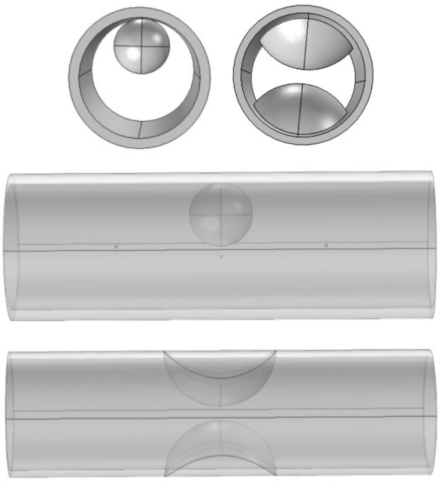

Figure 1. Cross section and longitudinal view of two different types of blockage

The outer cylinder in the above images can be viewed as blood vessel, the spherical and two hemispherical geometries as the fat deposit and the space inside the cylinder as the channel for blood flow. The initial radius or sphere and hemispheres were 3 mm and 5 mm, respectively and this was incremented to increase the range of blockage.

The thickness of the artery has been taken as 1 mm with 8 mm radius and 60 mm length. The inlet blood flow velocity has been taken as 0.15 m/s throughout the simulation. A parametric sweep has been applied to the radius of the sphere and hemisphere to model the variations in fat deposit and hence finding the changes in the blood flow and pressure.

A finite element mesh has been created for the described geometry with free tetrahedral and fluid dynamics physics for the blood flow channel and free tetrahedral and general physics for the remaining geometry with the number of vertex elements being 29, the number of edge elements being 572, the number of boundary elements being 7042 and number of elements being 49038.

III. RESULTS AND DISCUSSION

The artery with no blockage is modeled first and its velocity profile is shown in Figure 2. The artery with the spherical blockage is modeled next and shown in Figure 3. In Figure 3, the initial blockage sphere of 3 mm radius has been shown. Figure 4 depicts spherical blockage of artery of 6 mm radius.

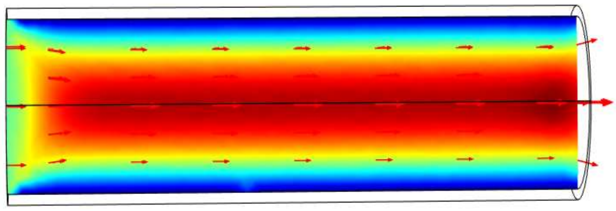

Figure 2. Artery with no blockage

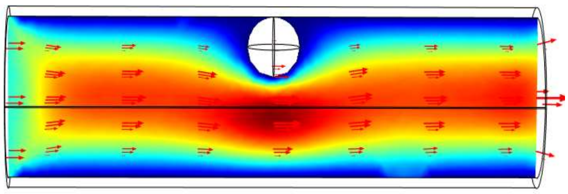

Figure 3. Spherical blockage of 3mm radius

In Figures 2, 3 and 4, the velocity of blood at different points is indicated by the colour code with red having the highest value and blue having the lowest.

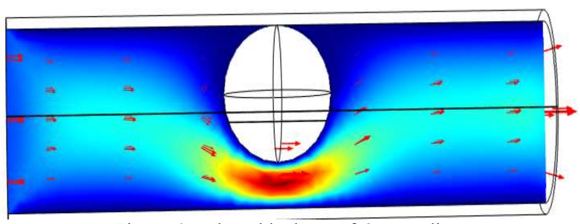

Figure 4. Sphere blockage of 6mm radius

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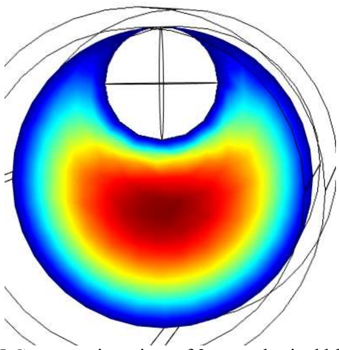

Figure 5.Cross section view of 3mm spherical blockage

The pressure experienced by the blockage in both cases above are shown in Figures 6 and 7 below.

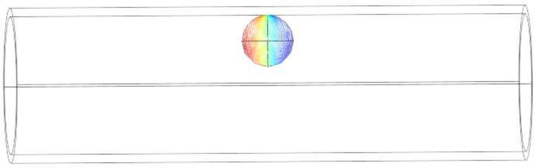

Figure 6. Pressure experienced by blockage due 3mm to blood flow

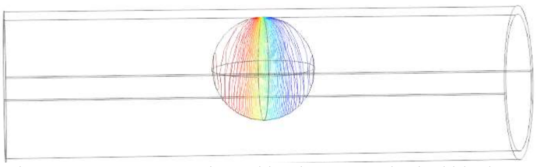

Figure 7. Pressure experienced by the 6mm spherical blockage

Figures 6 and 7 show the pressure distribution on the spherical blockage and the colour pattern shows that the smaller sphere experiences less pressure than the bigger one having 9.35 Pa and 427.5 Pa, respectively.

Next, simulations are repeated for the hemispherical blockage. The radii of the blockages have also been varied to study the velocity profile of the blood. The initial radius has been taken as 5 mm and the final 9 mm. Figure 8 depicts velocity profiles of the carotid artery with hemispherical blockages of radius 5 mm. Figure 9 shows the velocity profile of carotid artery with hemispherical blockages of radius 9mm. Figures 10 and 11 show the blood pressure profiles of carotid artery with hemispherical blockages radius 5 mm and 9 mm, respectively.

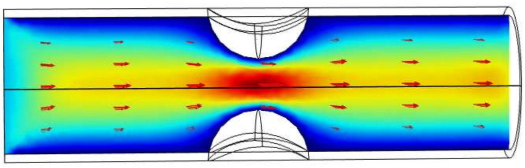

Figure 8.Artery with two hemispherical blockages with big gap

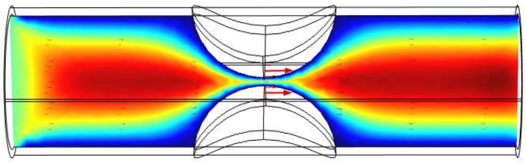

Figure 9. Artery with two hemispherical blockages with narrow gap

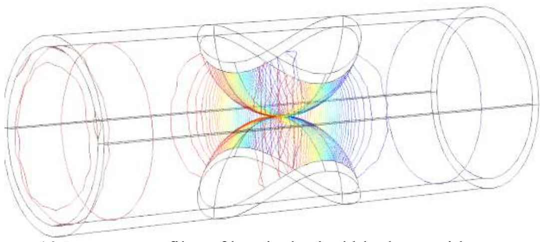

Figure 10.Pressure profiles of hemispherical blockage with narrow gap

In the previous paragraph, we have seen blood flow through the carotid artery under various conditions. Starting from the point where there is no blockage, we see that the velocity is uniform throughout the artery. In the midway, it is highest and at the walls it is lowest. This profile signifies a healthy artery.

Moving to the spherical blockage artery, we see that the velocity just beneath the sphere increases and then decreases. The artery with bigger sphere blockage in Figure 4 can be clearly seen to have decreased its velocity by the density of red color. Looking at the pressure profile of the fat content, it shows the increased pressure in the direction of flow and decreased on the other side.

The comparison between the healthy artery, the spherical blockage artery and two hemispherical blockage artery is done below on the basis of pressure experienced at the side walls and velocity. For this, a point is marked on the side wall of the artery to measure pressure for every increment in the blockage. For measuring velocity, a point at the bottom of the artery has been marked. Figure 13 shows the velocity measured for different radii of the spherical blockage. Table 2 shows the velocity of blood flow against changing different radii of the sphere.

TABLE II. VELOCITY MEASURED FOR SPHERICAL BLOCKAGE

Radius of sphere (mm)	Velocity of blood(m/s)
3	0.182
3.5	0.256
4	0.393
4.5	0.802
5	1.521
5.5	3.868

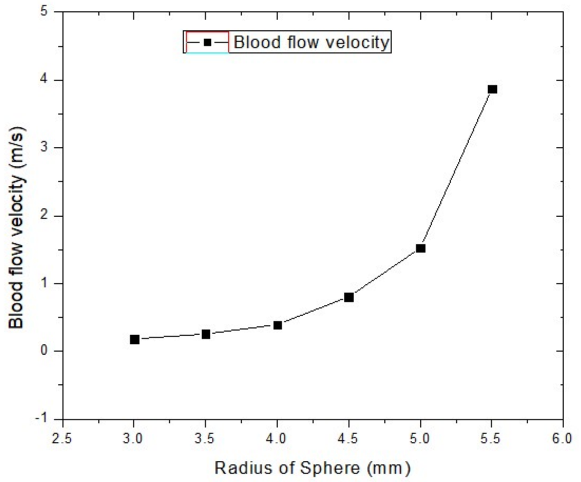

Figure 11.Velocity changes for spherical blockage

Figure 12 depicts the velocity measured at different radii of two hemispherical blockages. Table 3 depicts the velocity of blood flow in the artery for different radii of hemisphere in hemispherical blockage.

TABLE III. VELOCITY MEASUREMENT FOR HEMISPHERICAL BLOCKAGES

Radius of hemisphere(mm)	Velocity of blood(m/s)
4	0.35
5	0.39
6	0.47
7	0.57
8	0.63
9	0

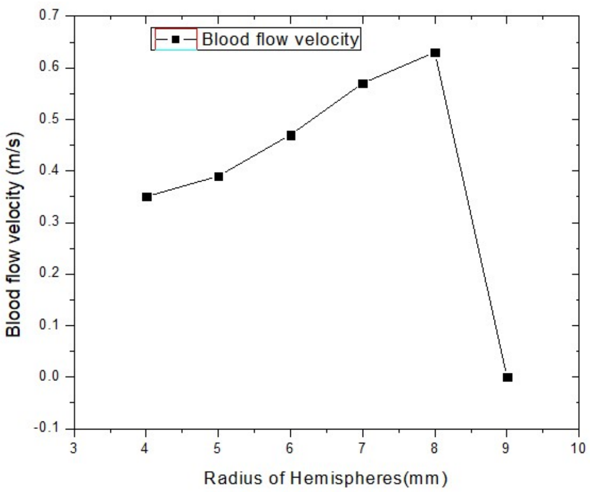

Figure 12.Velocity changes for hemispherical blockage

The graph is plotted next to visualize the above table values and shows one peculiar thing, after raising, this graph suddenly drops to zero. It is due to the fact that here both the hemispheres have touched each other and at that point blood doesn't flow anymore but from the side ways. This sets up a perfect condition for ischemic cerebrovascular accident or stroke. Table 4 shows the pressure experienced by the artery wall due to spherical blockage. Given below is the table for pressure on side walls against radius of sphere (Table 4).

TABLE IV. PRESSURE ON ARTERY WALL DUE TO SPHERICAL BLOCKAGE

Radius of sphere(mm)	Pressure(Pa)
3	3.58
3.5	3.90
4	4.39
4.5	5.10
5	6.36
5.5	8.71
6	13.09

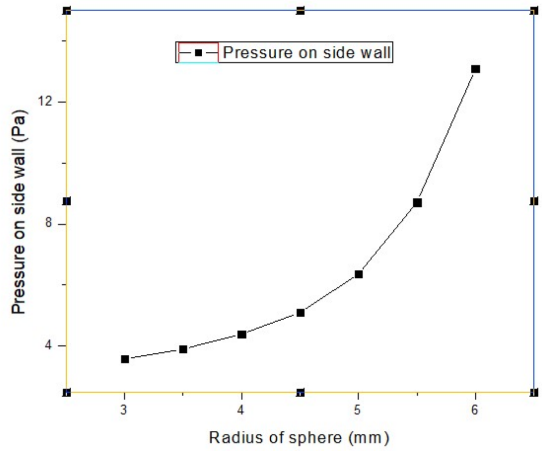

Figure 13. Pressure on artery wall due to spherical blockage

Figure 13 shows the variation of pressure on the arterial wall due to spherical blockage. The graph indicates an exponential rise of the pressure on the side walls. Table 5 shows the pressure experienced by the artery wall due to hemispherical blockage.

TABLE V. PRESSURE ON ARTERY WALL DUE TO HEMISPHERICAL BLOCKAGE

Radius of sphere(mm)	Pressure(Pa)
4	3.74
5	4.04
6	4.82
7	7.29
8	17.59
9	96.91

Figure 14 shows the variation of pressure on the atrial wall due to the hemispherical blockage. Again, we find an exponential increase of pressure on the side wall of the artery. This graph shows an abrupt reading when the radius of hemispheres reaches 9 mm. This is the point where both hemispheres almost touch each other, as shown in Figure 9. The side wall pressure of the healthy artery is found to be 3.13 Pa.

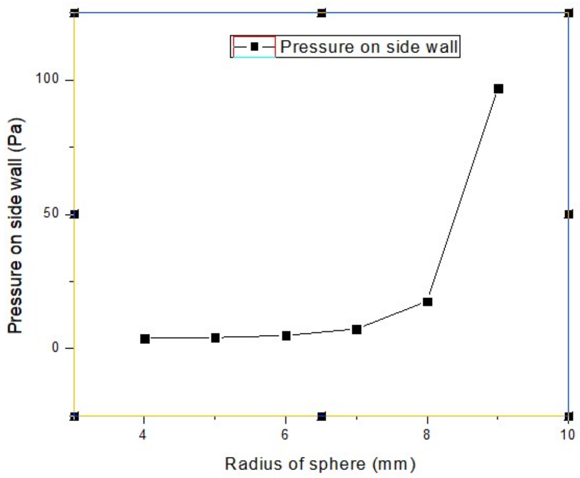

Figure 14. Pressure experienced by artery wall due to hemispherical blockage

IV. CONCLUSION

In this paper, the blood flow in the blood vessels with different shapes and sizes of blockages in the carotid artery has been studies. The velocity and pressure of blood have been studied in each case. While comparing the two types of blockages, we see that one with spherical blockage rises exponentially and the other one shows an abrupt rise when the fat covers most of the cross section of the artery. Clearly, this gives us the intuitive idea that the hemispherical blockage from both walls is very dangerous. Also, another point that can be learned is that when the blockage is small there is not much pressure on the walls, but since it increases exponentially it should be detected at early stage, because as it keeps on accumulating it can be proved fatal and might even lead to burst of the artery.

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