Three-Dimensional Numerical Analysis of Pulsatile Blood Flow around Different Plaque Shapes in Human Carotid Artery

Absaar Ul Jabbar, Rana Usman Ali, Khalid Parvez, and Umar H. K. Niazi

Abstract—**The aim of this research is to investigate the effect of plaque shape on blood flow through the carotid artery leading to plaque growth and rupture. For this purpose three plaque shapes were considered; trapezoidal, elliptical and triangular with same base and height measurements, thus imposing same area reduction of 30% in artery. A carotid artery model based on statistical analysis called tuning fork model was constructed. Various Computational Fluid Dynamics (CFD) simulations were performed to analyze the effect of different plaque shapes on blood flow. Comparison of simulation results for the three plaque shapes showed that trapezoidal shape has more effect on blood flow producing highest flow velocities and wall shear stresses. This fact indicates that plaques similar to trapezoidal shape may be more prone to rupture. It was also found that trapezoidal plaques created lowest wall shear stress region downstream of the plaque which may increase the fatty deposits in that area. The study suggests that patients with such plaques should be considered for surgery at an early stage of atherosclerosis to avoid cardiovascular complications.**

Index Terms—**Atherosclerosis, computational fluid dynamics, plaques shape, stroke, wall shear stress.**

I. Introduction

Stroke is a medical emergency that occurs when the blood supply to any part of brain is disrupted, resulting in deprived oxygen supply to brain tissues [1]. Stroke is the second major cause of death worldwide after coronary heart disease [2]. Due to fatty deposits plaques develop in arteries. This slow and progressive build up of plaques on the inner wall of blood vessels due to which artery becomes narrow and loses its flexibility is called Atherosclerosis [1]. These plaques offer resistance to the blood flow thus changing the flow characteristics in the blood vessels. Plaques in carotid artery cause reduced blood supply to brain which may lead to stroke. If the plaques in the carotid artery break down, they may be carried with blood to the brain where they can block smaller blood vessels supplying blood to different parts of brain causing stroke.

Despite dramatic advances made both in diagnostic measures (like Computed Tomography (CT) scan and Magnetic Resonance Imaging (MRI)) and in therapeutic practices for vascular diseases in recent years, on average, one person suffers a stroke every 40 seconds and one dies of a stroke every 3 to 4 minutes [2]. Plaques vary in shape from patient to patient. To help generalize the simulation results Lorenzini et al [3] hypothesized the plaques into three basic geometric shapes. Based on these hypothesized shapes, the current research is aimed to explore which plaque shape in carotid artery is more vulnerable to rupture. Recognizing the features that contribute to this increased vulnerability may help clinicians make early interventions in patients with plaques that are prone to rupture, thus mitigating the stroke chances and remarkably increasing the survival rate and quality of life of such patients.

II. Procedure For Numerical Modeling

A. Carotid Artery Geometry

Carotid artery supplies blood to brain and neck. It is a Y-shaped artery, which can be divided into three parts. First is common carotid artery (CCA) which is bifurcated into two arteries; one internal carotid artery (ICA) which has a sinus and the other one is of smaller diameter called external carotid artery (ECA) [4] as shown in Fig. 1.

B. Geometric Model

For CFD simulations the first step is the construction of geometrical model of the carotid artery. In humans, structure

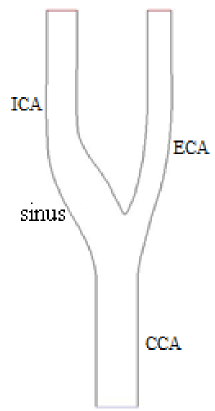

Fig. 1. 2D view of carotid artery model showing common carotid artery, internal carotid artery with sinus and external carotid artery.

of carotid artery varies from person to person so average data based model is used in the study representing features of different carotid specimens [5]. However for analyzing blood flow in carotid artery various models have been used in previous studies including the Y-shaped model in Bharadavj et al [6] and the tuning fork model in Ding et al [5]. In this study the tuning fork model of carotid artery from Ding et al

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[5] was used. This model approximates carotid artery more accurately. It is based on average geometrical data so it represents common feature of all individual geometries observed in this study. For geometric model, points were generated using geometry definition of Bressloff et al [4, 7, 8]. This 2D model geometry was imported to GAMBIT® [9] to construct a 3D model. For the 3D model it was assumed that the artery is circular and some ellipses at the bifurcation were made to ensure the model smoothness.

C. Plaques Geometry

The geometry of plaques was adopted from study of Lorenzini et al [3] which includes three shapes i.e. Trapezoidal, elliptical and triangular. The location of the plaque was adopted from the fact that the low shear stress zone is favorite for plaque buildup [10], [11], [12]. Our 3D results for normal artery show that the outer wall of the carotid sinus produces a low shear stress zone so it was selected as the location for plaque shape analysis. This atherosclerosis modeling is based upon three constraints:

1) All plaques have same dimensions for base and height. (same base & height)[3].
2) All plaques cause equal flow area reduction of 30% in artery.
3) All plaques are at same location in carotid artery, i.e. at outer wall of sinus as shown in Fig. 2.

D. Grid

The meshing of all carotid artery models was carried out in GAMBIT® [9], a preprocessor of Fluent® [13]. Due to complex geometry of the carotid artery, unstructured mesh was used in this study.

A symmetry condition was also applied in order to save computational resources. Triangular elements were used to mesh faces. T-Grid Scheme was used to mesh the artery; in this scheme tetrahedral volume elements are constructed due to which mesh becomes aligned with curved wall of artery [14]. Meshing of healthy model is shown in Fig. 3. Meshing of three other models with plaques is shown in Fig. 4. Mesh size was nearly equal in all cases.

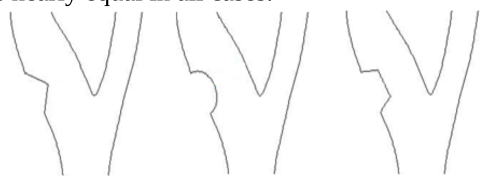

Fig. 2. Different plaque shapes at the outer wall of sinus.

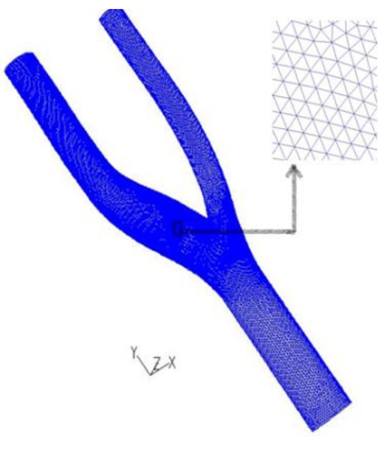

Fig. 3. Mesh of 3D healthy carotid artery model.

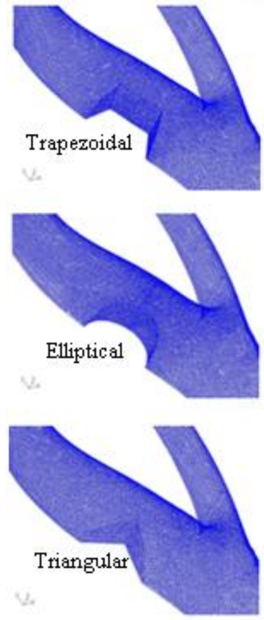

Fig. 4. Meshes of three carotid artery models with plaques.

E. Computational Method

In 2D analysis unsteady velocity at the inlet is considered and the approximated curve [5] is shown in Fig. 5. A user defined function was interpreted in Fluent for unsteady velocity at the inlet. The flow was assumed to be incompressible, laminar, Newtonian and transient in case of 2D and steady in case of 3D analysis. Blood is non-Newtonian fluid having different constituents, but can be

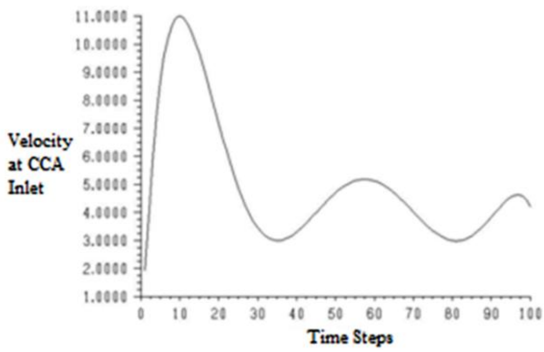

Fig. 5. Pulse velocity used as boundary condition at inlet of CCA

approximated as Newtonian fluid for larger arteries [15]. Steady simulations in case of 3D model were run for the maximum value of velocity.

The density of blood is taken 1060 kg/m^3 and viscosity is set to 0.0027 kg/m-s [16]. Details of boundary conditions for 2D and 3D case are given in Table I.

III. Results and Discussion

A. 2D Results

Simulations were performed on FLUENT® [13]. Pulse velocity was calculated at the same site for all three plaques shapes models and the healthy case. Comparison of these pulse velocities for different cases revealed that the trapezoidal and triangular plaques produce the highest velocities, which leads to the abrupt flow changes. Fig. 6 shows a cross comparison of average flow velocities across different plaques and healthy model.

TABLE I: BOUNDARY CONDITIONS

BC	2D	3D
Wall	Rigid Wall with no slip	Rigid Wall with no slip
Inlet	Unsteady Velocity Inlet	Steady Velocity Inlet
Outlet	Outflow	Outflow with 70:30 ratio[7]
Symmetry	-----	Applied

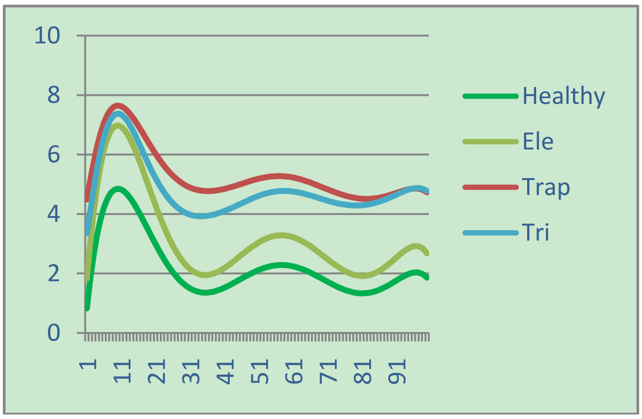

Fig. 6. Comparison of flow velocities measured in 2D case with time step of 0.008 seconds and velocity in meter/second of pulse on horizontal & vertical axis respectively

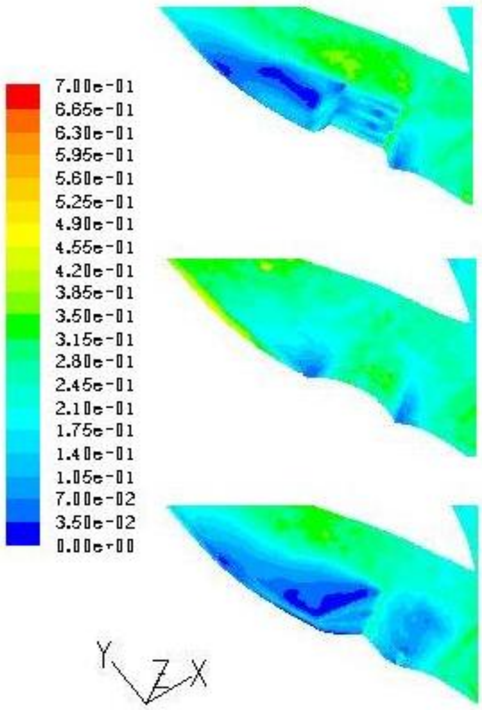

Fig. 7. Contours of wall shear stress (pascal) across different plaque shapes are shown low shear stress zones at downstream of trapezoidal and triangular plaques are prominent.

B. 3D Results

Wall Shear Stress (WSS) is the tangential force per unit area exerted by a moving fluid on solid boundary [17]. In 3D transient analysis it was observed that variation of wall shear stress followed velocity pulse variation and maximum WSS corresponded to maximum velocity. So a steady analysis was performed at maximum velocity of pulse on fine meshes to save computational time.

Contours of wall shear stress for a 3D steady state case are shown in the Fig. 7. Previous studies show that one of the main factors involved in plaque buildup is low wall shear stress and on the other hand plaque rupture can be due to high shear stress as it causes high flow changes in the vessel [10]. The maximum value of wall shear stress was found on trapezoidal plaque while maximum average wall shear stress was found on elliptical plaque because it causes a continuous change in velocity across its surface.

A complete comparison of wall shear stress for different plaque shapes is shown in Fig. 8.

Trapezoidal plaque not only caused a highest wall shear stress but also developed lowest wall shear stress zone. So plaques similar in shape to the trapezoidal plaque may result in more downstream fatty deposit on artery wall. Triangular plaque appears to be the second most severe plaque.

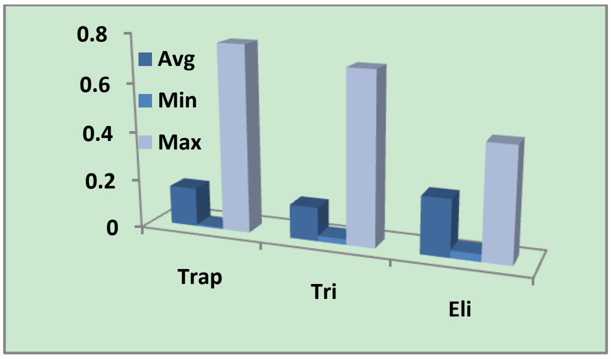

Fig. 8. Comparison of wall shear stresses with respect to shape of the plaque showing that trapezoidal plaque not only constitutes maximum WSS but also the minimum one.

IV. CONCLUSION

A detailed comparison of effect of different plaque shapes on blood flow through human carotid artery was done. Significant differences in flow velocities and wall shear stresses for different plaque shapes were observed. This shows that it may be important to consider the shapes of the plaque in the carotid artery in addition to artery area reduction for prediction of cardiovascular complications. This may require enhancing the image processing methods in order to determine plaque shapes. Further CFD studies are required to see the effect of varying blood properties (such as density, lipid content, pressure and velocity) on blood flow and plaque buildup. This can be developed into a predictive tool for clinicians to assess the probable speed of plaque development in their patients. These blood properties can be managed by lifestyle changes and drug administration, thus guiding the clinician to better manage high risk patients.

REFERENCES

[1] Medical Dictionary.
[2] American Heart Association. [Online]. Available: http://www.americanheart.org.
[3] L. Giulio and E. Casalena, “CFD analysis of pulsatile blood flow in an atherosclerotic human artery with eccentric plaques,” *Journal of Biomechanics*, 2008
[4] Anatomy Book.
[5] Z. Ding, K. Wang, J. Li, and X. Cong, “Flow field and oscillatory shear stress in a tuning-fork-shaped model of the average human carotid bifurcation,” *Journal of Biomechanics*, 2001
[6] B. K. Bharadvaj, R. F. Mabon, and D. P. Giddens, “Steady flow in a model of the human carotid bifurcation. Part I—Flow visualization,” *Journal of Biomechanics*, 1982.

[7] N. W. Bressloff, J. Banks, and K. V. Bhaskar, “Parametric geometry definition and analysis of the human carotid artery bifurcation,” *ASME Mechanical Engineering Congress, Anaheim, CA*, 2004.

[8] N. W. Bressloff, “Parametric geometry exploration of the human carotid artery bifurcation,” *Journal of Biomechanics*, 2006.

[9] *GAMBIT, Geometry and Mesh Generation Software Package*, Ver. 2.3.16, Fluent Inc, Lebnon, NH, 2006

[10] H. Frank, S. Dolf, D. C. Rini, P. H. Berend, R. E. Poelmann, P. C. Evans, and K. Rob, “Effect of shear stress on vascular inflammation and plaque development,” *Current Opinion in Lipidology*, vol. 18, Issue 5, October 2007.

[11] D. N. Ku, D. P. Giddens, C. K. Zarins, and S. Glagov, “Pulsatile flow and atherosclerosis in the human carotid bifurcation: Positive correlation between plaque location and low and oscillating shear stress,” *Arteriosclerosis*, 1985.

[12] C. K. Zarins, D. P. Giddens, B. K. Bharadvaj, V. S. Sottiurai, R. F. Mabon, and S. Glagov, “Quantitative correlation of plaque localization with flow velocity profiles and wall shear stress,” *Circulation Research.* 1983.

[13] *Fluent, Computational Fluid Dynamics Software Package*, Ver. 6.2.16, Fluent Inc, Lebnon, NH,2006

[14] *GAMBIT, Geometry and Mesh Generation Software Package User Guide*, Ver. 2.3.16, Fluent Inc, Lebnon,NH, 2006

[15] Y. B. Fan, W. T. Jiang, Y. W. Zou, J. C. Li, J. Chen, and X. Y. Deng, “Numerical simulation of pulsatile non-Newtonian flow in the carotid artery bifurcation,” *Acta Mechanica Sinica*, 2009.

[16] Z. H. Sun, B. Mwipatayi, T. Chaichana, and C. Ng “Hemodynamic effect of calcifed plaque on blood flow in carotid artery disease: A preliminary study,” *ICBBE* 2009

[17] D. Katritsis, L. Kaiktsis, A. Chaniotis, J. Pantos, E. P. Efstathopoulos, and V. Marmarelis, “Wall shear stress: Theoretical consideration and methods of measurements,” *Progress in Cardiovascular Diseases*, vol. 49, no. 5, pp 307-329, March/April 2007.