Emirates Journal for Engineering Research

Volume 29 | Issue 2 Article 3

5-5-2024

PRESENCE OF ATHEROMATOUS PLAQUES AND THEIRS EFFECTS ON THE BLOOD FLOW

belhocine mostefa Bm
Department of mechanic, Faculty of technology, University Batna 2, Algeria, mostefabelhocine@gmail.com

amrani hichem AH
Higher National School of Renewable Energy, Environment & Sustainable Development, Algeria, hichem.amrani@hns-re2sd.dz

fedaoui kamel dr
Higher National School of Renewable Energies, Environment & Sustainable Development, k.fedaoui@hns-re2sd.dz

mazouz Hammoudi Mh
LRP laboratory, University Batna 2, Algeria, h.mazouz@univ-batna2.dz

PRESENCE OF ATHEROMATOUS PLAQUES AND THEIRS EFFECTS ON THE BLOOD FLOW

Mostefa Belhocine [1], Hichem Amrani [2], Kamel Fedaoui*[2], Hammoudi Mazouz [1, 3]

[1] Department of mechanic, Faculty of technology, University Batna 2, Algeria, mostefabelhocine@gmail.com
[2] HNS-RE2SD, Batna, Algeria, hichem.amrani@hns-re2sd.dz
[3] LRP laboratory, University Batna 2, Algeria, h.mazouz@univ-batna2.dz
* Corresponding author, e-mail: k.fedaoui@ hns-re2sd.dz

Abstract

The paper utilizes a finite element method to study both the blood flow and atheromatous plaques. Specifically, the COMSOL finite element package is employed to achieve a fluid model. COMSOL is a powerful finite element tool commonly used in various research and industrial domains to study multiphysics problems. The focus of the investigation is on the geometric aspects of the atheromatous plaques. The study considers different forms and arrangements of stenosis, taking into account the irregularities formed by various shapes of the plaques and the resulting flow patterns. The key findings of the research suggest that the pressure and velocity of blood flow in the artery are dependent on the presence, position, number, and shape of the atheromatous plaques. This information is crucial for understanding the impact of these plaques on blood flow dynamics and may have implications for the diagnosis and treatment of arterial conditions.

Keywords

Vascular biomechanics, Fluid, repetition stenosis form, blood flow

1 Introduction

According to medical survey data, stroke is among the leading reasons of death worldwide. Ischemic strokes account for approximately 85 percent of all strokes in adults. A significant proportion of ischemic strokes are induced by a jam in an artery responsible for providing blood to the brain, resulting in a reduction in blood transportation (ischemia) [18].

The rupture of atherosclerotic plaques is the major cause of cardiovascular thrombosis events such as stroke and ischemic attacks [1]. The length of the internal artery can range from 5 to 10 mm [2, 3]. Mechanical analysis depends on the precise determination of the range of lengths in which the vulnerability model is developed. The properties of vulnerable plaque are well defined in numerous pathological investigations [4-7]. Plaques are distinguished by a large lipid pool surrounded by a thin fibrous cap. These atherosclerotic lesions can rupture at any time causing an acute thrombotic reaction.

Owing to the geometrical complexity of atherosclerotic plaques beside their material constitution diversity, biomechanical investigations by means of finite element (FE) methods are employed to examine the stresses and strains distribution on the wall and plaque under physiological loading [8-10]. Up to now, the majority of investigations were founded on 2D lesion cross-sections geometries with the lowest luminal area acquired from histological analysis [11-15], or ex-vivo intravascular ultrasound (IVUS) images, and lately, in-vivo IVUS images.

The use of finite elements investigation in the last 5 years by Chao Liu et al. in the investigation of the effect of carotid bifurcation stenosis degree on pulsatility characteristics [22-26]. Azim Azahari et al propose a 3D Model of Generalized Power Law Blood Flow in a Stenosed Bifurcated Artery. Norliza Mohd Zain et al use a numerical Analysis of Blood Flow Behaviour in a Constricted Porous Bifurcated Artery under the Influence of Magnetic Field. Shin-Seok et al propose a clinical investigation and Analysis of atherosclerotic plaque distribution in the carotid artery[27-30]..

The purposes of this study were as follows: (i) to examine the model predictability of plaque fracture location mechanism via a mechanical analysis in vivo, and (ii) to demonstrate how the plaque morphology affects mechanical response by employing finite element (FE) methods to examine the blood transportation system parameters in terms of pressure and velocity values for stenosis [19-21].

2 Healthy artery and Atherosclerosis

The oxygen-rich blood is conducting to the body's tissues through the heart by means of arteries, which are the blood vessels. Thus, every artery is a three-layered muscular tube covered by smooth tissue, figure 1 shows an example:

- The intima is the central layer, which is covered by a smooth tissue named endothelium;
- The media, a layer of muscle that allows arteries to withstand the strong pressures generated by the heart;
- The adventitia, a tissue that connects arteries to surrounding tissues.

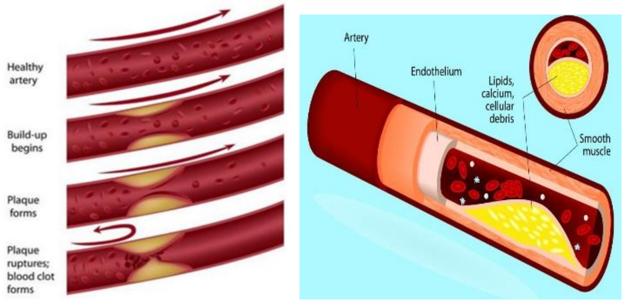


Fig. 1. Stage of Healthy artery and Atherosclerosis: (a) Stage of Healthy artery and Atherosclerosis and (b) 3D representation [5].

3 Numerical modeling

It is considered that the blood has a Newtonian behavior and that the flow is stationary. The most widely used mathematical model for modeling flow phenomena is based on the resolution of Navier-Stokes partial differential equations (PDE) [23]. The arterial wall is assumed to be rigid and non-slip. It is supposed that blood is compressible. As a result, the following Navier-Stokes equations can characterize a steady laminar blood flow:

$$\frac{\partial V}{\partial t} + (V.\nabla)\mathrm{V} = -\frac{1}{\rho}\nabla p + v\nabla^2 V + f \quad (1)$$

$$\nabla.\mathrm{v} = 0 \quad (2)$$

Where V is the blood flow velocity vector, p denotes pressure, ρ represents blood density, v denote the kinematic viscosity and f refers to the body force term per unit of mass[25].

3.1 Boundary conditions

Inlets, outlets, and walls are the boundaries of the computational domain. Inlets are defined with velocity value or expression. In all the studies of the blood flow, the very common boundary condition used is pressure on the outlets. The vessel walls are assumed to be rigid in this model, with no-slip boundary conditions.

In real situation with pulsatile nature of blood flow, see Fig 2, the velocity profile was defined at the aorta entrance. This velocity varies as a function of time according to [20].

In all the computation, a moderate input speed V = 0.6 m/s is considered, with the condition of non-slip at the interface to ensure the velocity of the vessel wall equal to the velocity of the surrounding fluid, and finally a pressure of 15900 Pa at the downstream that corresponds to normal blood pressure. The Blood density is set to 1057 kg/m3, [16]. This framework is utilized for every element of the plaque, as shown in Figure 3.

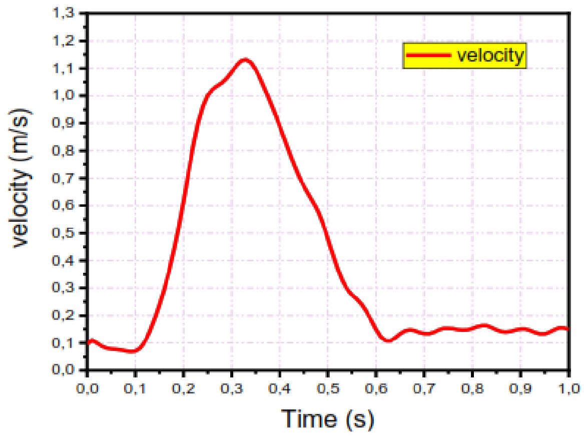


Fig.2 Illustration of the boundary conditions applied to the aorta: (a) profile of the transverse velocity at the entry of the ascending aorta, (according to [23]) and (b) boundary conditions at inlet and outlet.

3.2 Geometrical model

The model of the axisymmetric plaque consists of a lipid core inside and healthy wall, as depicted in Fig 3. The inside diameter of a healthy arterial lumen is about 3 mm radius and its length is 20 mm. These dimensions correspond to the average values of the internal artery [3], which is modeled as the radius of the vessel. The length of the plate is between 5 and 10 mm.

In patients with stenosis radius intensity higher than 70%, this value refers to a significantly larger plate [5, 3] of successive strokes. Nevertheless, it is commonly assumed that stenosis radius severity alone is insufficient to describe plaque weakness, and it has been demonstrated that several ruptured plaques are just relatively stenosis [1].

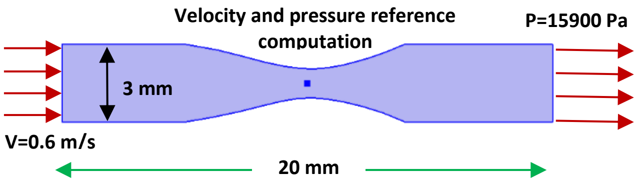


Fig.3 Schematics of the 2D plaque geometric model

Because thromboembolic occurrences are caused by fibrous cap rupture, fibrous cap thickness is an essential geometrical characteristic for plaque weakness. For the sake of simplification, a thin fibrous cap is regarded to sit the investigation in a scenario of vulnerable plaque; the fibrous cap thickness is uniform along the stenosis. Comsol is used to model the plaque as a basic stenosis with various shapes [17]. The stenosis is symmetric upstream and downstream. Table 1 shows how various shapes are fined by various values.

Table 1 Assessment of discharge coefficient, air core diameter and spray cone angle**.**

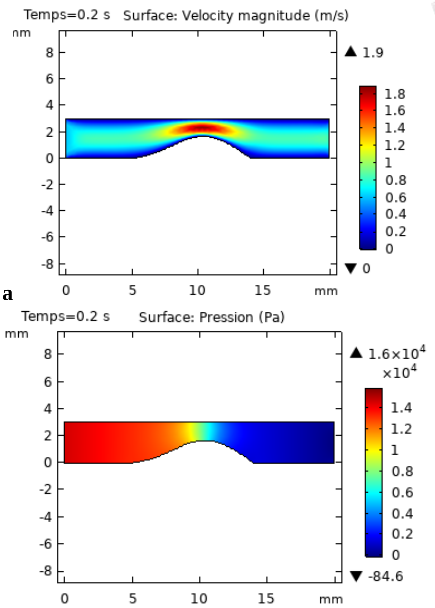
Model	Scenario I Single stenosis	Scenario II double stenosis	Scenario III Symmetric Single stenosis	Scenario IV Symmetric double stenosis
Triangular form				
Semicircular form				
Hyperbolic Form				

4. Results and discussions

In this section, the results obtained from the study of the influence of the form on the speed of flow of the blood and the arterial pressure will be presented.

4.1 Effect of stenosis form (case I)

The first case of plaque in this investigation is about the presence of single simple plaque. The chosen geometry were listed in table 1. For the case I, the numerical computation shows that the maximum blood velocity and pressure were observed with the triangular stenosis form. Circular and hyperbolic form presents a low pressure and velocity, see figures 4 and 5.

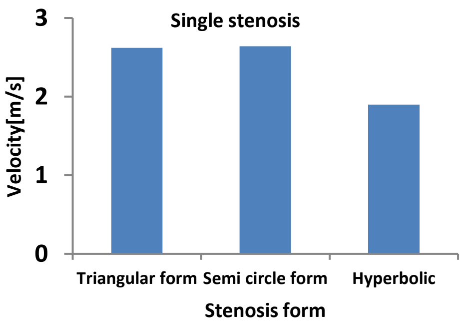


a b

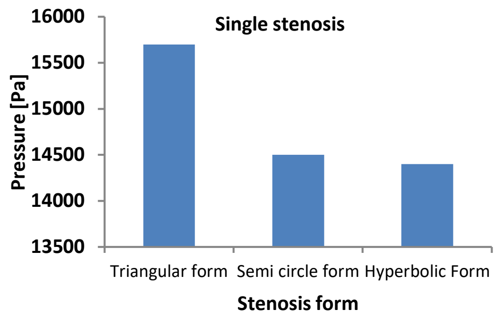
Fig.4 a) Blood velocity for stenosis single form b) pressure value for stenosis single form

4.1.1 Effect of stenosis repetition form (case II)

The blood flow in the artery in the case of stenosis repetition form as shows in figures 6, the value of pressure is different in the cases study. The pressure diagram shows that the maximum value is in the triangular form. The low velocity and pressure were detected in the case of circular and hyperbolic one.

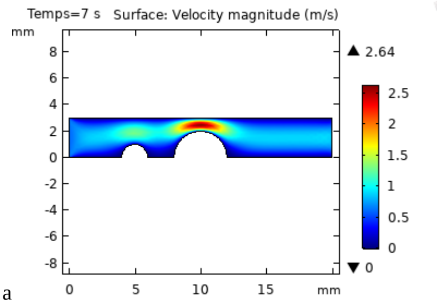


a

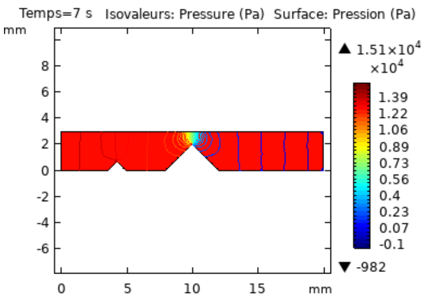


b

Fig.5 a) Blood velocity for stenosis single form b) pressure value for stenosis single form

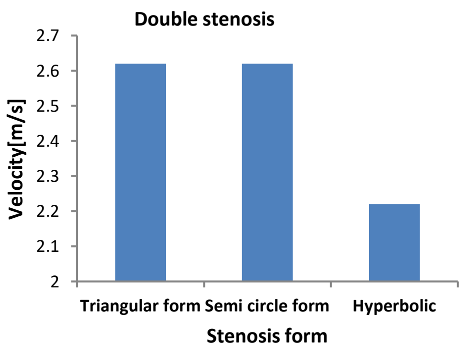


a

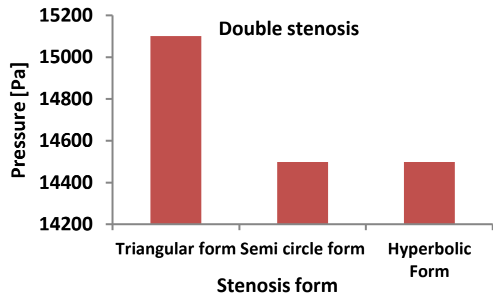


b

Fig. 6 a) Blood velocity for stenosis repetition form, b) pressure value for stenosis repetition form



a

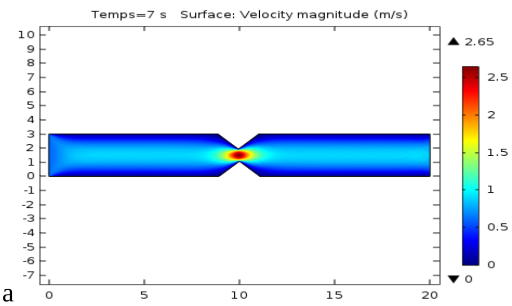


b

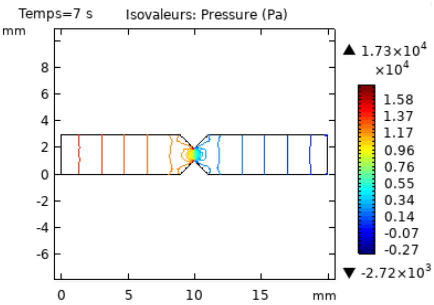
Fig. 7 a) Blood velocity for all cases of stenosis repetition form, b) pressure value for all cases of stenosis repetition form.

4.1.2 Effect of stenosis symmetric form (case III)

For the third case (stenosis symmetric form), the maximum pressure value is located in the symmetry triangular form. We note that the flow velocity takes a maximum value in the same location in symmetry triangular single form.

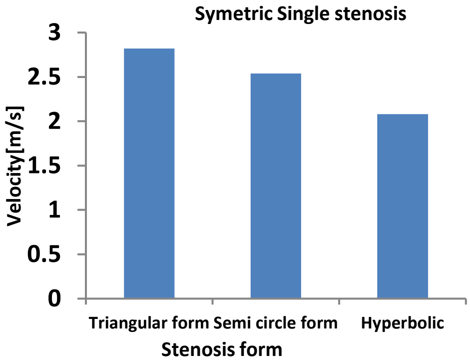


a

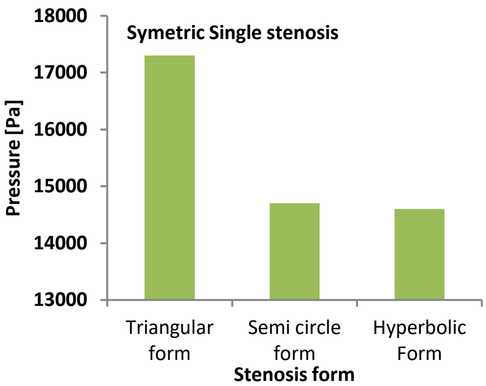


b

Fig. 8 a) Blood velocity for stenosis symmetric form, b) pressure value for stenosis symmetric form



a

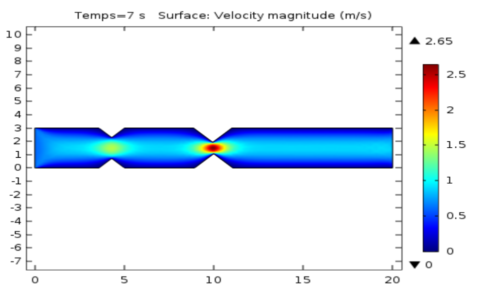


b

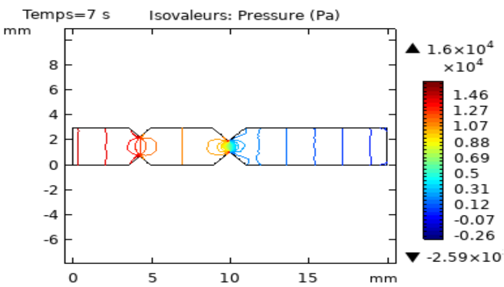
Fig.9. a) Blood velocity for stenosis symmetric form, b) pressure value for stenosis symmetric form

4.1.3 Effect of stenosis symmetric and repetition form (case IV)

The pressure and the flow velocity values stay in the maximum level in the triangular symmetry form and repeated form for the last study case.

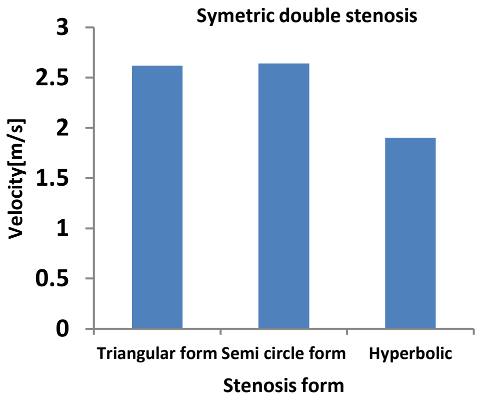


a

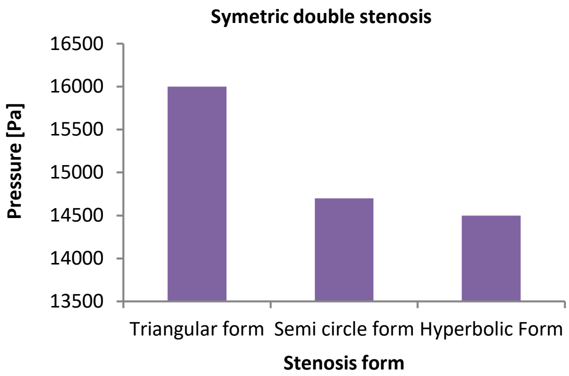


b

Fig.10 a) Blood velocity for stenosis symmetric and repetition form b) pressure value for stenosis symmetric and repetition form



a



b

Fig.11 a) Blood velocity for all the cases of stenosis symmetric and repetition form b) pressure value for all the cases of stenosis symmetric and repetition form

For the interpretation of the results, we present the findings of the simulation of the blood flow in the artery subjected to different obstacles inside, showing the most important physical parameters like pressure and the flow velocity.

For pressure, we note that the maximum pressure is found in the case of the triangular form with an increase when one repeats the hyperbolic form and it is due to the orientation of the obstacle, which plays a role of obstacle with respect to the axis of blood flow. In the velocity computation, the triangular and circular form presents the maximum values.

To properly interpret the effect of different forms of stenosis on the velocity and pressure of the blood flow, curves were drawn for the different cases along the blood flow, as shown in the following figures:

In Figure 11; case of circular stenosis, the flow velocity varies according to a sinusoidal function of a maximum value of 2m / s an average distance of x = 10mm, on the other hand for the other cases are close values. The figure 12 of the pressure shows that the curves are descending with a maximum value of 17000 Pa at the start of the flow.

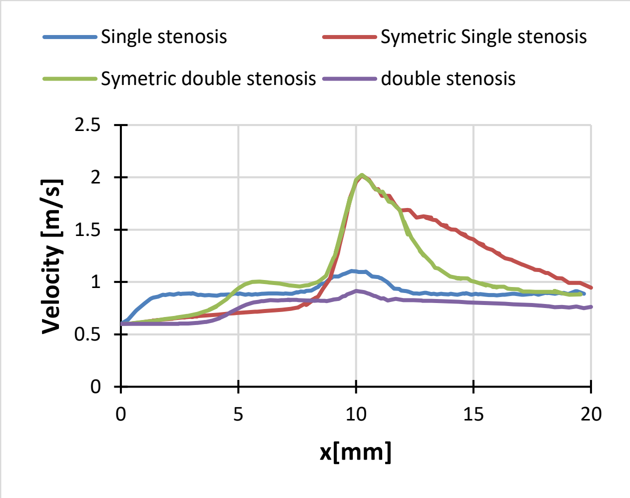


Fig.11 Distribution of velocity in circular form of stenosis arteries for all the cases

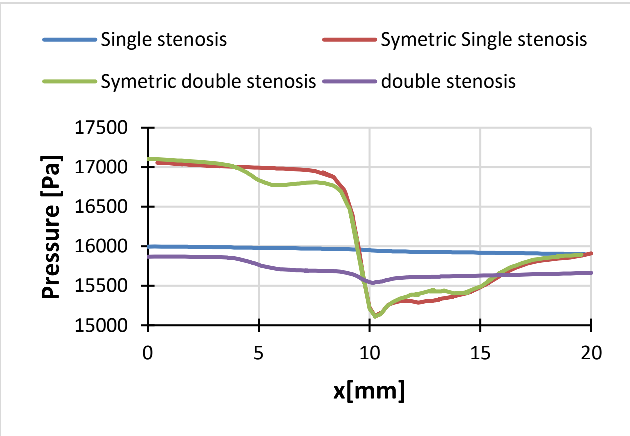


Fig.12 Distribution of pressure in circular form of stenosis arteries for all the cases

In figure 13, the case of hyperbolic stenosis; the maximum value of the velocity always in the simple shorthand case, and values almost constant for the other cases. However, in the figure 14 of the pressure, the maximum values for all cases are decreased with a maximum value in the double stenosis case; on the other hand, the value of the double symmetry stenosis case is almost zero.

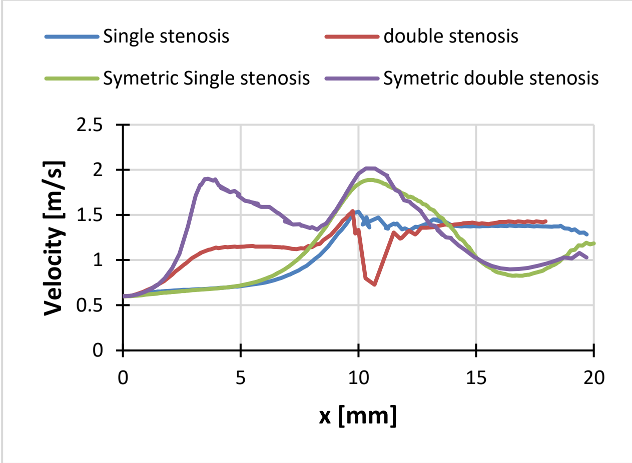


Fig.13 Distribution of Pressure in hyperbolic from of stenosis arteries for all the cases

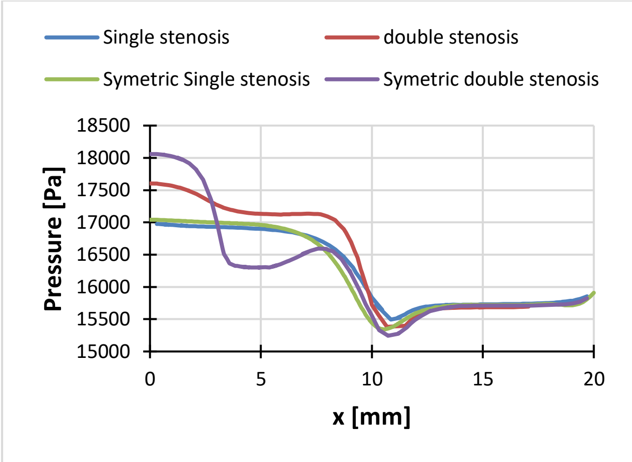


Fig.14 Distribution of velocity Distribution in hyperbolic form of stenosis arteries for all the cases

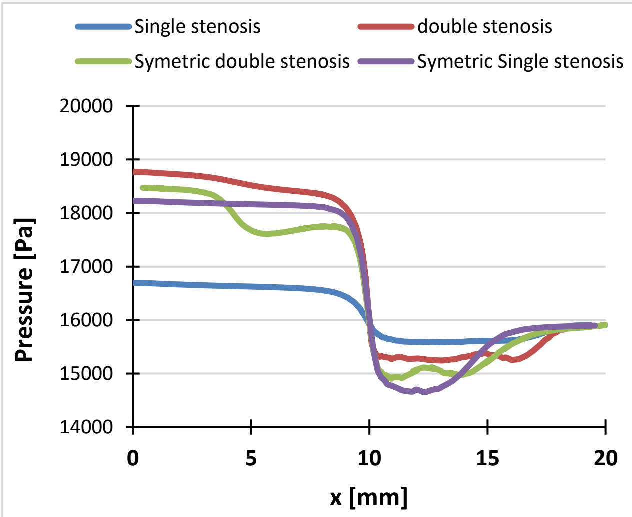


Fig.15 Distribution of velocity in triangular form of stenosis arteries for all the cases

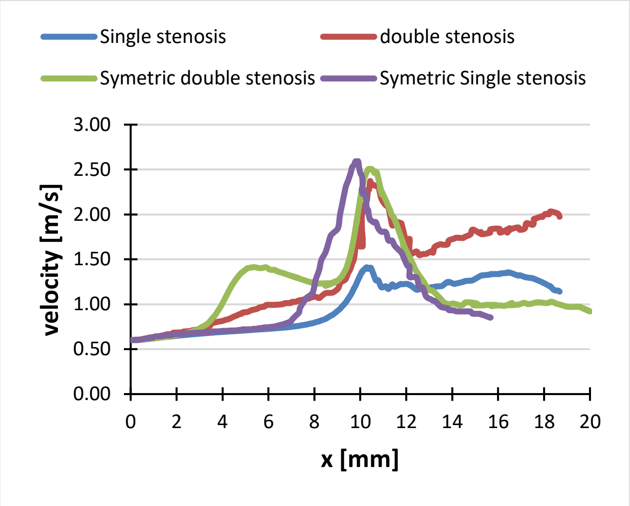


Fig.16 Distribution of velocity in triangular form of stenosis arteries for all the cases

In Figure 15 with the cases of triangular stenosis, the maximum value of the velocity appeared in the cases of single stenosis and double symmetry stenosis. However, in the figure 16 of the pressure, the double stenosis case takes the initiative with a value of 18500 Pa and increase of very important value for double symmetry stenosis.

We can deduce from all the computation results that the stenosis form is one of principal causes of the artery failure. The presence of the stenosis in the artery increase the blood pressure and velocity. After the stenosis, the blood pressure and velocity decrease to normal values. This augmentation can cause the failure of the artery wall especially when the artery material behavior change.

Conclusions

Atheromatous plaques take on different morphological form and lengths that may have a various degree of weakness. It has been shown in this numerical investigation that the pressure exerted by the blood on the artery is independent of the plaque shape and the increased risk caused by the form of stenosis.

From the results of this study, we note an important remark that the increase of pressure near the plaque is the most provocation parameter of artery damage. The pressure in the artery with a given form is a degree of visible severity can increase if the stenosis is repeated or if it contains several obstacles. In vitro experiments on animal models are nowadays being conducted to determine the prevalence of various plaque forms and morphologies. In addition, the work consists in determining how certain geometric characteristics of the stenosis can be obtained in vivo to the clinician by medical imaging.

References

[1] Rosamond W, Flegal K, Friday G, Furie K, Go A, Greenlund K, Haase N, Ho M, Howard V, Kissela B et al., 2007. Heartdisease and stroke statistics – 2007 update. A report from the American heart association statistics committee and stroke statistics subcommittee. Circulation. 115:69–171.

[2] Tang D, Woodard PK, Zeng J, Huang X, Yang C, Ferguson M, Yuan C, Canton G, Teng Z. 2010. 3D critical plaque wall stress is a better predictor of carotid plaque fracture sites than flow shear stress: an in vivo MRI-based 3D FSI study.JBiomech Eng. 132:031007-1-9

[3] Douglas AF, Christopher S, Amankulor N, Din R, PoullisM,Amin-Hanjani S, Ghogawala Z. 2011. Extracranial carotid plaque length and parent vessel diameter significantly affect baseline ipsilateral intracranial blood flow. Neurosurgery. 69(4):767–773.

[4] Kerwin WS, Oikawa M, Yuan C, Jarvik GP, Hatsukami TS: MR imaging of adventitial vasa vasorum in carotid atherosclerosis. Magnetic Resonance in Medicine 2008, 59:507-514.

[5] Kolodgie FD, Gold HK, Burke AP, Fowler DR, Kruth HS, Weber DK, Farb A, Guerrero LJ, Hayase M, Kutys R: Intraplaque hemorrhage and progression of coronary atheroma. New England Journal of Medicine 2003, 349:2316-2325.

[6] https://www.healthnavigator.org.nz/health-a-z/a/atherosclerosis/

[7] Virmani R, Kolodgie FD, Burke AP, Farb A, Schwartz SM: Lessons from sudden coronary death a comprehensive morphological classification scheme for atherosclerotic lesions. Arteriosclerosis, thrombosis, and vascular biology 2000, 20:1262-1275.

[8] Stroud JS, Berger SA, Saloner D. 2000. Influence of the stenosis morphology on flow through severely stenotic vessels: implication for plaque rupture. J Biomech. 33:443–455.

[9] Belzacq T, Avril S, Leriche E, Delache A. 2011. Modelling of fluid–structure interactions in stenosed arteries: effect of plaque deformability. Comput Methods Biomech Biomed Eng. 13(S1):25–26.

[10] Fung YC. 1996. Biomechanics, circulation. 2nd ed. New York, NY: Springer-Verlag.

[11] Formaggia L, Quarteroni A, Veneziani A. 2009. Cardiovascular mathematics, modelling and simulation of the circulatory system. Vol. 1. S pringer
Naghavi M, Libby P, Falk E, Casscells SW, Litovsky S, Rumberger J, Badimon JJ, Stefanadis C, Moreno PR, Pasterkamp G: From vulnerable plaque to vulnerable patient: a call for new definitions and risk assessment strategies: Part II. Circulation (Baltimore) 2003, 108 :1772-1778.

[12] Sadat U, Teng Z, Young VE, Zhu C, Tang TY, Graves MJ, Gillard JH: Impact of plaque haemorrhage and its age on structural stresses in atherosclerotic plaques of patients with carotid artery disease: an MRimaging-based finite element simulation study. The International Journal of Cardiovascular Imaging 2011, 27:397-402.

[13] Jacques O, Gérard F, François T, Gilles R, and Olivier D, 2005, A three-dimensional finite element analysis of stress distribution in a coronary atherosclerotic plaque: In-vivo prediction of plaque rupture location, Biomechanics Applied to Computer Assisted Surgery, 225-.

[14] Uchida S. 1956. The pulsating viscous flow superposed on thesteady laminar motion of incompressible fluid in a circular pipe. J Appl Math Phys. 7(5):403–422.

[15] Avril S, Huntley JM, Cusack R. 2009. In vivo measurements of blood viscosity and wall stiffness in the carotid using PC-MRI. Eur J Comput Mech. 18:9–20

[16] Formaggia L, Quarteroni A, Veneziani A. 2009. Cardiovascular mathematics, modelling and simulation of the circulatory system. Vol. 1. Springer.

[17] Logiciel De Modélisation COMSOL Multiphysics

[18] Esam A. Alnussairy and Ahmed Bakheet , MHD Micropolar Blood Flow Model through a Multiple Stenosed Artery. 1

Department of Mathematics, College of Computer Science and Mathematics, Wasit University, Iraq. Department of Mathematics, College of Science, University Iraq.

[19] H. Yao, K. C. Ang, J. H. Ye o and E. K. W. Sim, Journal of Computation al modelling of blood flow through curved stenosis arteries. Cardiovascular Dynamics Laboratory, School of Mechanical & Production Engineering, Nanyang Technological University, Singapore ³ National University Hospital, Singapore. Medical Engineering & Technology, Volume 24, Number 4, (July/ August 2000), pages 163–168

[20] Ashkan Javadzadegan,Andy S. C. Yong, Michael Chang, Austin C. C. Ng, John Yiannikas, Martin K. C. Ng, Masud Behnia, and Leonard Kritharides. Flow recirculation zone length and shear rate are differentially affected by stenosis severity in human coronary arteries

[21] Afroza Akter, and Salma Parvin. Numerical Analysis of a Blood Flow Model for Arterial Stenosis in Presence of External Magnetic Field - Department of Mathematics, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh. Cite as: AIP Conference Proceedings 2121, 100001 (2019); https://doi.org/10.1063/1.5115932 Published Online: 18 July 2019

[22] Mathematical Modeling of Blood Flow With the Suspension of Nanoparticles Through a Tapered Artery With a Blood Clot Sapna Ratan Shah* and Rohit Kumar.Bio-Mathematical Lab-34, School of Computational and Integrative Sciences, Jawaharlal Nehru University, New Delhi, India https://www.frontiersin.org/articles/10.3389/fnano.2020.596475/full

[23] Mukesh Roy, Basant Singh Sikarwar*, Mohit Bhandwal and Priya Ranjan .Modelling of Blood Flow in Stenosed Arteries 7th International Conference on Advances in Computing & Communications, ICACC-2017, 22- 24 August 2017, Cochin, India .ScienceDirect,Procedia Computer Science 115 (2017) 821–830

[24] Pinyo Owasit1,3 and Somchai Sriyab2,3* Owasit and Sriyab Mathematical modeling of non-Newtonian fluid in arterial blood flow through various stenosis, Advances in Difference Equations (2021) 2021:340 https://doi.org/10.1186/s13662-021-03492-9

[25] Azim Azahari, Zuhaila Ismail∗ and Normazni Abdullah, 3D Model of Generalized Power Law Blood Flow in a Stenosed Bifurcated Artery, MATEMATIKA, 2018, Volume 34, Number 1, 87–102

[26] Norliza Mohd Zain, Zuhaila Ismail, Peter Johnston , Numerical Analysis of Blood Flow Behaviour in a Constricted Porous Bifurcated Artery under the Influence of Magnetic Field, CFD Letters 15, Issue 1 (2023) 39-58

[27] Shin-Seok Yang MD, Shin-Young Woo HD, Dong-Ik Kim MD, Analysis of atherosclerotic plaque distribution in the carotid artery, Clin Cardiol. 2022;45:1272–1276.

[28] Yanyan Cheng, Hongxing Liu, Zhen Tian, Meng Zhang, Youjun Liu and Qun Nan, Comparison of ablation characteristics of three different radiofrequency applicators in renal sympathetic denervation, international journal of hyperthermia 2021, vol. 38, no. 1, 1251–1262

[29] T. Probst, K. Richter, A. Hundertmark, Utilizing COMSOL® in a workflow to assess stroke risks in a large set of patients carotid arteries, comsol conf 2023

[30] Chao Liu, Gao Wu, Jianxin Xu, Qingtai Xiao and Hua Wang, Numerical investigation of the effect of carotid bifurcation stenosis degree on pulsatility characteristics, Front. Physiol. 14:1169198.