Proceedings of 8th International Conference on Mechanical Engineering and Renewable Energy 2025
10-12 December, 2025, Chattogram, BANGLADESH

SciEn Conference Series: Engineering Vol. 4, 2026, pp 413-417 https://doi.org/10.38032/scse.2026.4.185

Numerical Investigation of Blood Flow in Arteries with Different Stenosis Geometries

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ABSTRACT

Arterial stenosis causes a dramatic change in the hemodynamic characteristics of an artery, including the pressure drop distribution along with velocity fields and wall shear stress (WSS), which are important indicators for the development of disease and its potential treatment. A comparative numerical study is reported here of blood flow in semicircular and trapezoidal stenosis domains for different degrees of 25%, 50% and 75% degree of blockage. The hemodynamic conditions were then investigated in CFD simulations at an average Reynolds number of 132.5. The findings show that stenosis severity and geometry have significant impact on the Post Stenotic flow disturbances, WSS distribution and velocity streamlines. Trapezoidal stenoses resulted in sharper velocity gradients and higher localized WSS than those of the semicircular stenoses, which indicated a more hazardous condition against arterial wall damage and rupture. Degree of stenosis correspondingly increased hemodynamic disturbances in all situations, with 75% blockage having the most severe flow disturbance. The clinical relevance of stenosis geometry for diagnostic work-up and therapeutic strategies is underlined by these findings. The results provide a valuable insight to vascular biomechanics and contribute to the formulation of geometry-dependent approaches for more accurate diagnosis and therapy in cardiovascular diseases.

Keywords: Hemodynamics, Computational fluid dynamics, Stenosis, Wall share stress(WSS), Biomedical simulation.

1. Introduction

Cardiovascular diseases hold on to the main reason for death worldwide taking accounts for approximately 17.9 million deaths per year, where coronary artery disease (CAD) is one of the most significant manifestation [1] .Arterial stenosis, the narrowing of the blood vessel caused by the formation of atherosclerotic plaques made of lipids, calcium and cholesterol dramatically changes the hemodynamic environment [2], [3]. These changes show up as variations in wall shear stress (WSS), pressure drop, and velocity distribution parameters that are closely linked to the development and rupture of plaque. Therefore, it is essential for both clinical practice and biological research to analyze blood flow dynamics in stenosed arteries [4]. Numerous computational and experimental investigations of the flow properties of stenosed arteries have been carried out in recent decades. Important insights into turbulence formation and pressure recovery downstream of stenosis were obtained using experimental methods, such as those used by Ahmed and Giddens and Young and Tsai [4], [5]. Similar to in-vivo or in-vitro investigations, numerical methods using computational fluid dynamics (CFD) have grown more popular due to the ability they have to capture elaborate flow behavior at a lower cost and complexity [6]–[8]. Despite these advancements, the majority of earlier research used idealized geometries and mainly looked at axisymmetric or cosine-shaped stenoses [4], [5]. Though, clinical proof shows that stenoses often showed irregular geometries, like trapezoidal and semicircular shapes, which have been numerously ignored currently in existence investigation [9]–[11]. Because plaque morphology performs a critical role in identifying peak WSS lengths of separation, recirculation zones, ignoring non-circular geometries which can result in leak of disease progression understanding. For example Lee and Liu [5] showed that under pulsatile flow there is a noteworthy difference in pressure drop characteristics, where Chou and Liu [9] reported that deviations in WSS were further amplified by non-Newtonian blood characteristics. Additionally, arterial conformance of the wall, as marked by Sarkar et al.[10] adds complexity which was not frequently included in simplified rigid-wall models. In this way, the research comprehensive comparison of realistic shapes is still an unresolved topic of study. In order to fill the gap of previous research this study performed comparative numerical study of blood flow through trapezoidal and semicircular stenosis geometries with 25%, 50%, and 75% severities. CFD simulation was performed in ANSYS fluent applying physiologically appropriate Reynolds numbers to solve the Navier-Stokes equations. The study focuses on an analysis of WSS and velocity profile to demonstrate geometry specific hemodynamic changes. The objectives of this work are: A comparative study of numerical evaluation of the trapezoidal stenosis and semicircular geometries with varied severity. Evaluation of WSS and velocity profile in order to determine the effect of turbulence intensity and geometry on recirculation. Finding hemodynamic changes brought on by geometry that may have clinical consequences for early diagnosis and therapy planning. Through connecting biomedical applications with numerical base engineering modeling this study participates in a greater comprehension of the morphology of stenosis and how it affects hemodynamics. It is expected that the result of this study will help understand hemodynamic changes in non circular stenosis and assist in developing more precise patient specific models for treatment and cardiovascular diseases.

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2. Research Methodology

Using a numerical simulation approach based on CFD, the study will investigate the hemodynamics of stenosis in semicircular and trapezoidal geometries. To solve the Navier-Stokes equations, which govern fluid dynamics, suitable numerical methods were employed, such as finite element methods (FEM) or finite volume approaches (FVM). The study of methodology is presented the initialization of the simulation process involves the problem definition: which encompasses physical model, governing equations and objectives. Geometry is built, pre-processed and then the mesh generation discretizes the domain to allow for accurate computation. Boundary conditions, fluid properties and an appropriate turbulence model have been used to set up the case. Settings and initialization of solver parameters are set to keep the simulation numerically stable. Residuals and physical parameters are used to monitor the convergence. Post-processing and visualization are conducted to analyze the velocity, pressure, and other flow properties after calculation. Key data are analysed and results discussed and compared with available theoretical or experimental information. At last, all the proposed procedures and conclusions are reported for validation and further reference.

2.1 Problem Definition

Arterial stenosis, result of atherosclerotic plaque deposition, which appears as a significant risk factor for cardiovascular health. Stenosis changes the hemodynamic environment by disrupting velocity distribution, raising wall shear stress (WSS) and increasing pressure drop. These factors are directly associated with plaque formation and rupture, which causes cardiovascular disorders like stroke and myocardial infarction [5, 6]. To further understand the impact of stenosis geometry in these alterations, this work uses computational fluid dynamics (CFD) to explore semicircular and trapezoidal stenosis models with varied degrees of severity (25%, 50%, and 75%).

2.2 Numerical Assumption

In order to simplify the computational domain while keeping physiological relevance, these assumptions had to be made : 1. Blood flow is incompressible having steady flow and viscous fluid. 2. Assume the artery is axisymmetric and two-dimensional. 3. To save complexity in modeling, the artery wall is assumed to be stiff rather than elastic.

2.3 Physical Modeling

A human artery can be visualized as a rigid tube. In this particular case, a two-dimensional rigid tube with a single sequential blockage is used to treat stenosis arteries. Blood doesn't count as a Newtonian fluid. Thus, blood is classified as a non-Newtonian fluid. The flow of blood is described as constant and laminar. The shape of stenosis is regarded as semicircular. Figure 2.1 depicts the physical structure of a human artery with a semicircular-shaped stenosis, where L=125 mm, D = 2.5 mm = 2R. And 'a' is constant.Here, d = radius of semicircular stenosis, d/D = percentage of the stenosis severity, R = radius of non-stenotic blood vessel ,L = Blood vessel length .

Case 1: d/D =25%

Case 2: d/D =50%

Case 3: d/D =75%

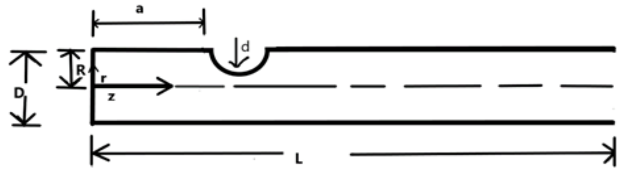

Fig 2.1:Artery geometry with a single semicircular stenosis.

In another case the shape of stenosis regarded as trapezoidal Figure 2.2 depicts the physical structure of a human artery with a trapezoidal shaped stenosis where L=125 mm, D=2.5 mm = 2R. And 'a' is constant.Here, s = depth of stenosis,s/D = percentage of the stenosis severity , R = radius of non-stenotic blood vessel, L = length of blood vessel

Case 1: s/D =25%

Case 2: s/D =50%

Case 3: s/D =75%

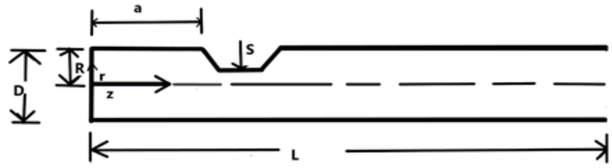

Fig 2.2: Artery geometry with a single trapezoidal stenosis.

2.4 Governing Equations

The flow of fluids is analyzed using the continuity equation and the Navier-Stokes equation (NSE). Use Conservation of Mass:

$$\partial\rho/\partial t + \partial(\rho u)/\partial x + \partial(\rho v)/\partial y = 0 \quad (1)$$

Conservation of Momentum:

$$\partial(\rho u)/\partial t + \partial(\rho u^2)/\partial x + \partial(\rho uv)/\partial y = \partial\tau xx/\partial x + \partial\tau xy/\partial y \text{ and } \partial(\rho v)/\partial t + \partial(\rho v^2)/\partial x + \partial(\rho uv)/\partial y = \partial\tau xy/\partial x + \partial\tau yy/\partial y. \quad (2)$$

Equations of Motion and Continuity (for Non-Newtonian Fluid):

$$\rho(\partial v/\partial t + v\cdot\nabla v) = -\nabla p + \nabla\cdot T;\ \nabla\cdot v = 0 \quad (3)$$

Carreau–Yasuda Viscosity Model:

$$\mu c = \mu\infty + (\mu 0 - \mu\infty)\,[1 + (\lambda^a \cdot \gamma^a)]\text{^}((nc - 1)/a) \quad (4)$$

where , $\mu 0$(low shear rate limit) = 0.056 Pa·s,$\mu\infty$(high shear rate limit) = 0.00345 Pa·s,λ = 3.313 s,nc = 0.3568,a = 2; Inlet Boundary Condition: $Vz = (1/A)\ [\ \bar{Q} + P\cdot\sin(2\pi t/T)\ ]$;Vr = 0;At the outlet: $\partial Vr/\partial z = \partial Vz/\partial z = 0$. At the centerline of the tube, axial symmetry condition. At the wall, no-slip flow:Vr = Vz = 0.Where A is the area of the tube, $\bar{Q}$ is the mean flow rate, P is the pulsating amplitude, t is time, and T is the time period of the pulsatile flow.

2.5 Boundary Conditions

Suitable boundary conditions were applied to model blood flow in stenosis arteries. This experiment included rigid walls with no-slip boundary constraints. The input included an approximation of heart rates identified in velocity profiles. An arterial network model was used to calculate the velocity profile of a single artery. Each outlet had zero-pressure outlet boundary conditions.

2.6 Present Numerical Study's Validity

In the current study, computations and results were compared to guarantee their reliability. As a preliminary step in interpreting the results, the numerical simulations must be validated against several analytical and experimental approaches that were equivalent to unsteady laminar flows in a confined tube. The conditions at the boundaries were comparable to those reported by Hasan and Das (2008) [12], as were the time average of wall shear stress.

2.7 Wall Shear Stress and Streamlines for Re-132.5

Because the flow in this investigation was pulsatile, a time-sensitive flow field was more appropriate for biomedical purposes. Reynolds' number was expected to be about 132.5. Smaller arteries, such as arterioles and capillaries that are smaller may have a lower Reynolds number, generally less than 100, suggesting higher laminar flow.The streamlines would depict the flow field in great detail. Wall shear stress as Re-132.5 is calculated using the amount of severity of stenosis referred to as 25%, 50%, and 75%.

2.8 Meshing

Meshing is an important step in CFD since it affects simulation reliability and solution convergence. ANSYS offers a dedicated module within ANSYS Mechanical for effective mesh production.

2.9 Code Validation

We understand that mesh creation has a significant impact on numerical outcomes. As a result, a grid sensitivity test will be done to determine the optimal number of elements for discretizing the computing domain. Meshes of various sizes and numbers were tested. Many computations had to be performed with fixed blood artery lengths so that the results were independent.

There were a few parameters that we considered in ANSYS to examine the hemodynamic parameters of various stenosis severity those are presented below. Meshing parameters:

For all cases, the physics preference was CFD, solver Fluent, element order Linear, inflation algorithm Pre, and solution scheme PISO. The element size was fixed at 1×10^-5 m with a growth rate of 1.2 . Semi-circular stenosis: 25% (33,617 nodes, 64,616 elements, first layer height 0.057 mm, 6 layers), 50% (33,134 nodes, 63,626 elements, 0.0652 mm, 4 layers), 75% (32,762 nodes, 62,839 elements, 0.067 mm, 4 layers) . Trapezoidal stenosis: 25% (32,066 nodes, 61,339 elements, 0.070 mm, 2 layers), 50% (31,418 nodes, 60,031 elements, 0.060 mm, 2 layers), 75% (31,020 nodes, 59,348 elements, 0.050 mm, 1 layer).

Mesh for 25%, 50%, 75% Semi-circular Stenosis Severity shown in figure 2.3 and Mesh for 25%, 50%, 75% Trapezoidal Stenosis Severity shown in figure 2.4 These figures are presented below :

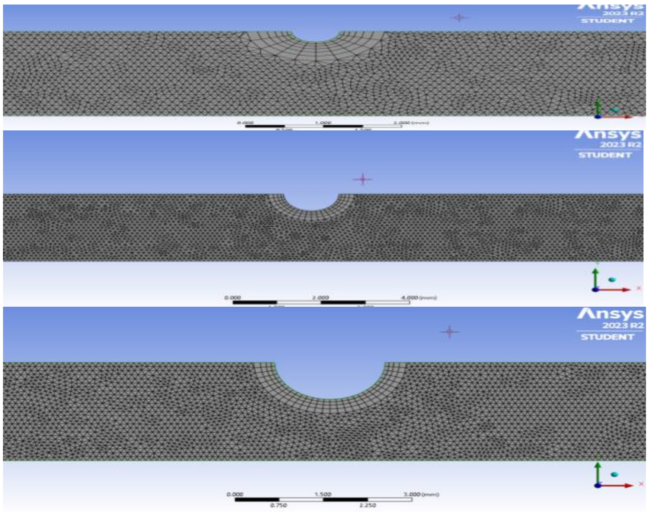

Fig 2.3: All Triangular Mesh for 25%, 50%, 75% Semi-circular Stenosis respectively.

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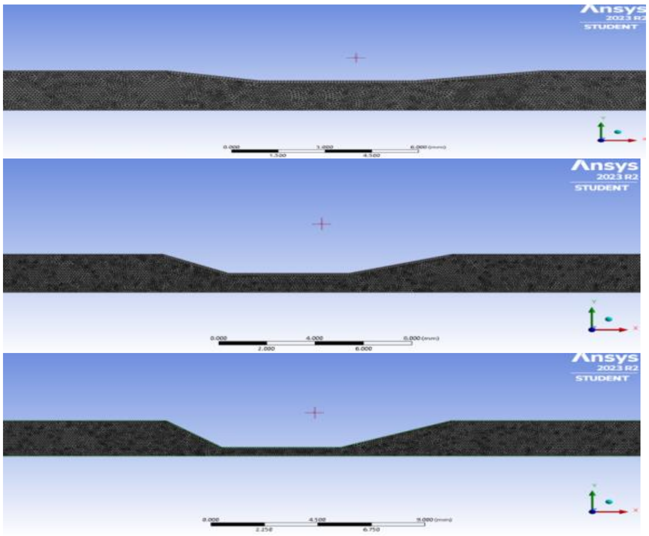


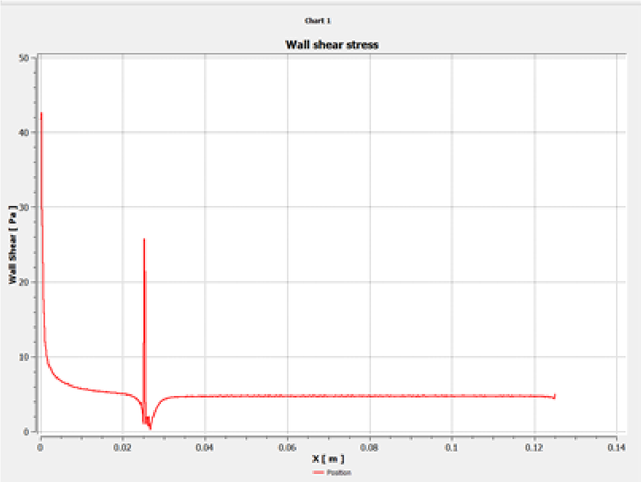
Fig 2.4: All Triangular Mesh for 25%, 50%, 75% Trapezoidal Stenosis respectively.

3 Result and Discussion

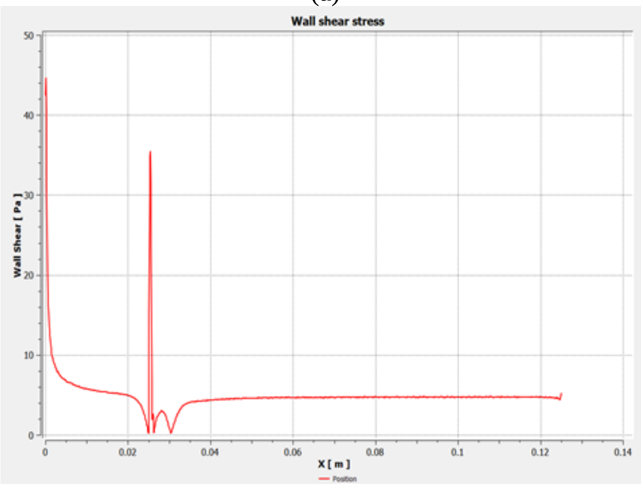
Results are calculated for wall shear stress, velocity streamlines, and the effects of Reynold's number and compare the percentage of stenosis and two types of stenosis.

3.1 Wall Share Stress

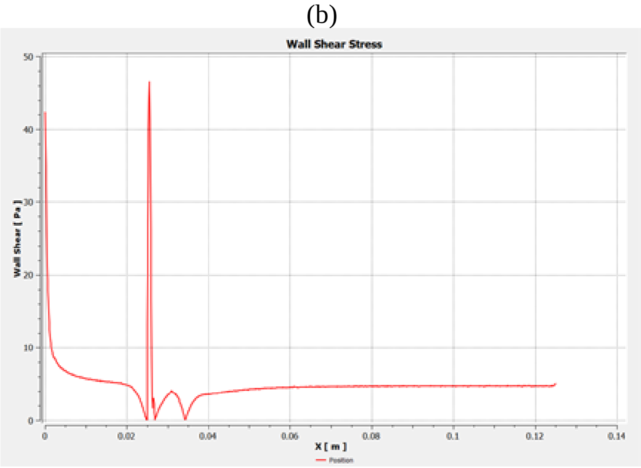
Wall shear stress for three different cases of stenosis severity is discussed here with a graphical representation. For both cases the peak wall shear stress develops highest 75% stenosis (by area) than 50% and least 25% percentage of stenosis.



(a)



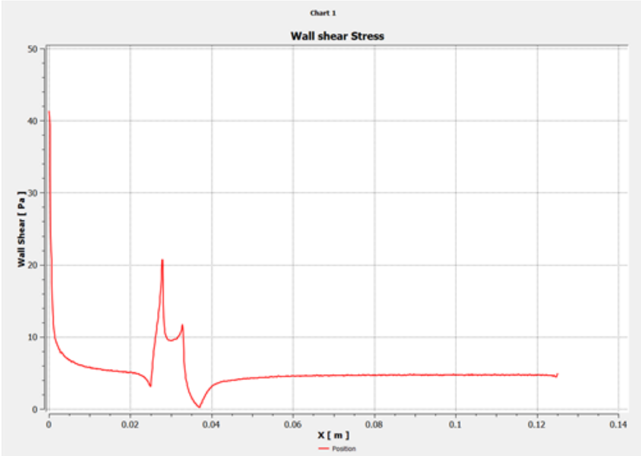
(b)



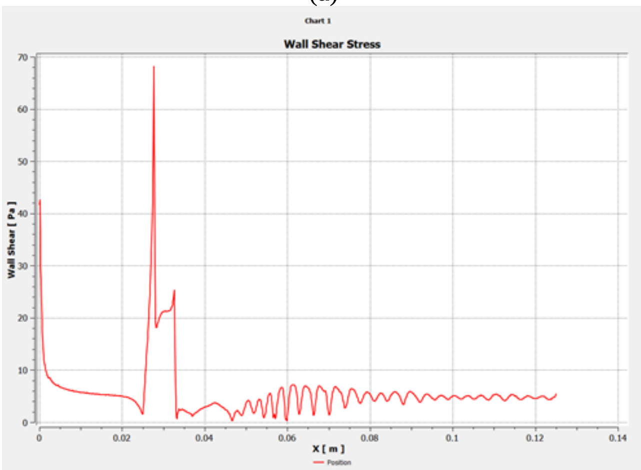
(c)

Fig 3.1: Variation of wall shear stress and position graph for (a)25% (b) 50% (c) 75% semi-circular stenosis respectively.

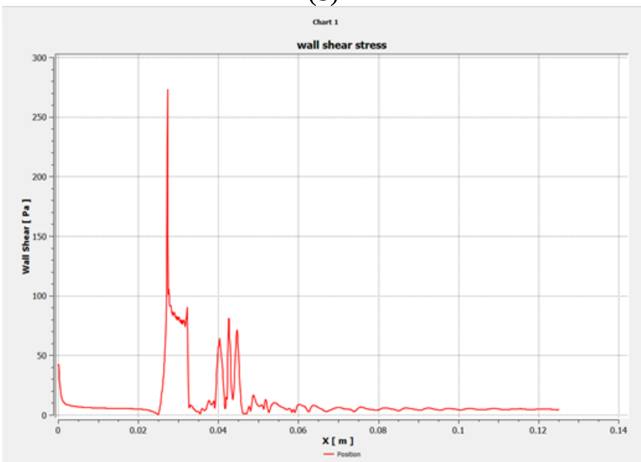
The velocity of blood increases and the pressure decreases when it passes through a stenotic artery. Wall Shear Stress is one of the important parameters to analyse haemodynamics.



(a)



(b)



(c)

Fig 3.2: Variation of wall shear stress and position graph for (a)25% (b) 50% (c)75% Trapezoidal stenosis respectively.

It can also be inferred from Figure 3.1 and 3.2, That Wall Shear Stress will be high near the stenosis (i.e 50% narrowing) throat and low near no-throat Because wall shear stress increases with velocity, wall shear stress is maximum at stenosis throat, minimum at non-stenotic region Wall shear stress increase with the depth of the flow.

3.2 Velocity Profile

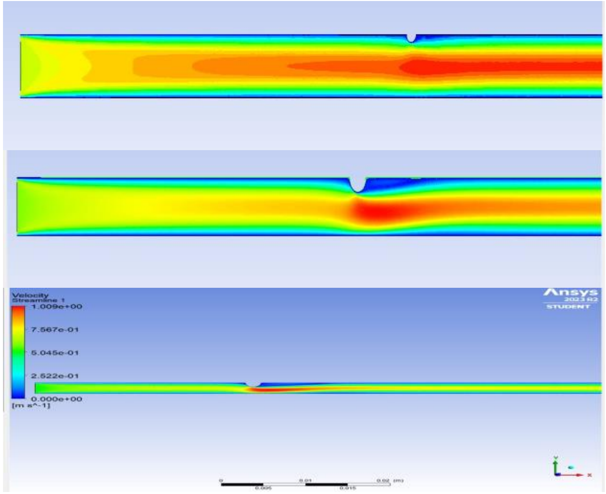


Fig 3.3: Velocity Streamline for 25%, 50%, 75% semi-circular stenosis respectively.

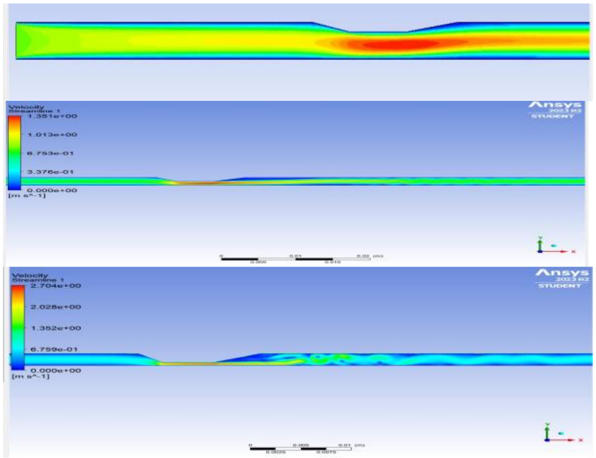


Fig 3.4: Velocity Streamline for 25%, 50%, 75% Trapezoidal stenosis respectively.

The velocity streamlines for 25%, 50%, and 75% stenosis are shown in Figure 3.3 and 3.4. It is visible that the velocity of the blood flow is maximum at the stenotic throat. The velocity of blood flow is increased with the increase in the percentage of stenotic severity.

4. Conclusion

This study illustrates the importance of stenosis geometry and degree of severity in determining arterial hemodynamics. Computational results showed that the trapezoidal stenosis increases more WSS disturbance than semicircular stenosis and leads to an increase in the maximum WSS level at least for severe degrees of stenosis. These hemodynamic response contrasts emphasize that plaque morphology should be employed in cardiovascular diagnostics and treatment planning. The clinical implication is that trapezoidal/transected as well as irregular stenosis material walls shape their poses a higher tendency to provoke arterial damage and an increased risk of thrombosis/rupture than smoother wall geometries. It also further demonstrates the usefulness of CFD as a predictive approach for studying pathological flow situations. For the future work, it is important to include patient-specific geometries, pulsatile flow dynamics and compliant arterial walls in order to advance computational predictions towards clinical implications.Overall, this work advances the understanding of stenosis-induced flow dynamics and contributes to the design of more precise, personalized interventions in vascular medicine.

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