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Blood flow in mildly stenosed aortoiliac bifurcation: A numerical study

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Abstract
Cardiovascular diseases (CVD) are the leading cause of mortality and morbidity. Atherosclerosis is a major CVD resulting in stenosis development in the arterial lumen. Computational Fluid Dynamics (CFD) techniques provide a better understanding of the causes of the disease and its early diagnosis. The present study aims at analysing the blood flow in a mildly stenosed aortoiliac bifurcation using the finite volume-based software ANSYS. It is inferred that even a mild stenosis in the arterial bifurcation also affects the flow of blood and hemodynamic parameters like pressure and velocity.

Keywords: CFD, $k-\varepsilon$ model, stenosis, velocity

Introduction
Cardiovascular diseases are diseases that effect the circulatory system including the heart and blood vessels. Nowadays the burden of cardiovascular diseases is on an increase Roth *et al*. (2020). The severity of cardiovascular diseases are very well understood and medical practitioners are trying to detect the root causes of initiation and development of these pathologies. Many attempts have been made in recent times by engineers and mathematicians to decode the fluctuations in hemodynamic descriptors caused by the changes in geometry as in case of branches, bifurcations and blockages. The geometry of the cardiovascular system is complicated hence realistic conditions should be considered.

Computational Fluid Dynamics (CFD) techniques provide a better understanding of the causes of the disease and its early diagnosis. The study of blood flow through arteries if carried out using classical fluid dynamics can only be carried out on idealised geometries and for limited conditions. The nonlinearity of the equations makes it difficult and even impossible to resolve for most of the conditions. To overcome these limitations CFD is the best tool and in the past two decades, it has been used widely to understand the pathophysiology of atherosclerosis.

Many CFD studies on cardiovascular conditions have been carried out in recent times. Kabir *et al*. (2021) [3] assessed the changes in various flow parameters in idealised geometries of a healthy artery and arteries with symmetrical single and double stenosis. Carvalho *et al*. (2021) [1] simulated blood flow using the $k-\varepsilon$ model in simplified and realistic aorta-iliac bifurcation models. Harris *et al*. (2023) [2] studied the effect of increasing degree of stenosis on blood flow in the aortoiliac bifurcation.

2. Material and Methods
The methodology for this study requires the selection of the geometry of interest, its meshing, selection of the appropriate mathematical models with boundary conditions and their discretization. The study is based on a realistic 3D geometry of mildly stenosed aortoiliac bifurcation. The geometry is constructed using dimensions from open access data and the assumption of mild stenosis for which the degree of stenosis is taken to be 32%. The commercial software ANSYS was used for generating the volumetric mesh with 86186 cells. The grid independence test was carried out for number of cells ranging from 25405 to 145020 cells and the optimal mesh was used.

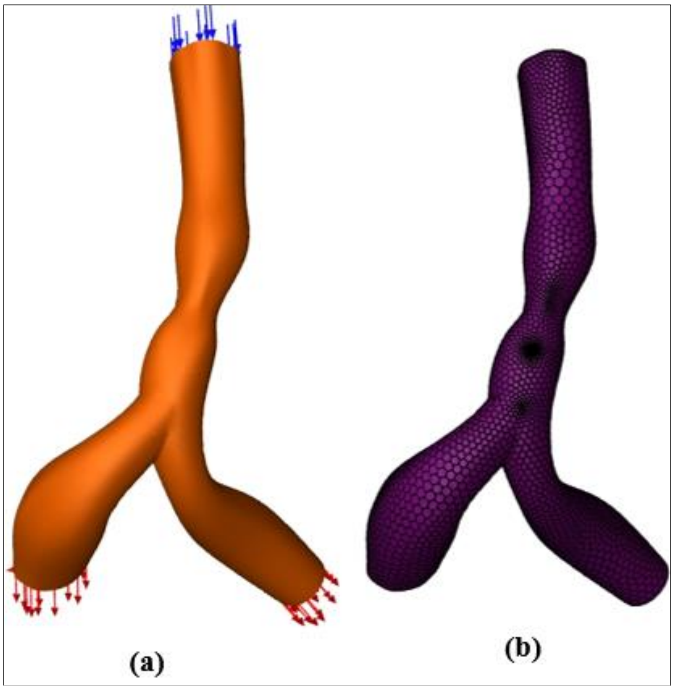

Fig 1ab: 3D model of the mildly stenosed aortoiliac bifurcation (b) Volumetric mesh of the mildly stenosed aortoiliac bifurcation model

Aorta has been categorised as a large artery due to its radius and length, hence blood is assumed to be Newtonian with velocity 1060 kg/m^3 and viscosity 0.004 kg/ms. The conservation of mass and momentum are guaranteed by the equation of continuity (1) and Navier Stokes equation (2). The standard two-equation $k-\varepsilon$ model given by (3) and (4) was used for turbulence modelling in blood flow.

$$\nabla . \vec{v} = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \rho(\vec{v}.\nabla)\vec{v} = -\nabla p + \nabla.(\bar{\bar{\tau}}) \quad (2)$$

$$\frac{\partial}{\partial t}(\rho k) + \nabla.(\rho\vec{v}k) = \nabla\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \quad (3)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla.(\rho\vec{v}\varepsilon) = \nabla\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\frac{\varepsilon^2}{k}$$
(4)

where, $\vec{v}$ is the velocity vector, ρ fluid density, p pressure, τ the stress tensor, k turbulent kinetic energy, ε dissipation rate, μ the viscosity. G_k represents the generation of turbulent kinetic energy, σ_k and σ_ε are turbulent Prandtl numbers for k and ε, 1.0 and 1.3, respectively, $C_{1\varepsilon}$ = 1.44 and $C_{2\varepsilon}$ = 1.92 are constants. The turbulent viscosity μ_t is a combination of k and ε given by Eq. (5) as

$$\mu_t = \rho\, C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

where C_μ = 0.09

At the inlet a pulsatile velocity profile is given by a user-defined function, at the outlets pressure boundary condition of 13332 Pa is applied as in Sinnott *et al*. (2006) [8] while a no-slip condition is assumed at the geometry wall. The numerical solution of the mathematical model was obtained by solving the set of equations using appropriate discretization schemes based on the finite volume approach on ANSYS.

3. Results and Discussion

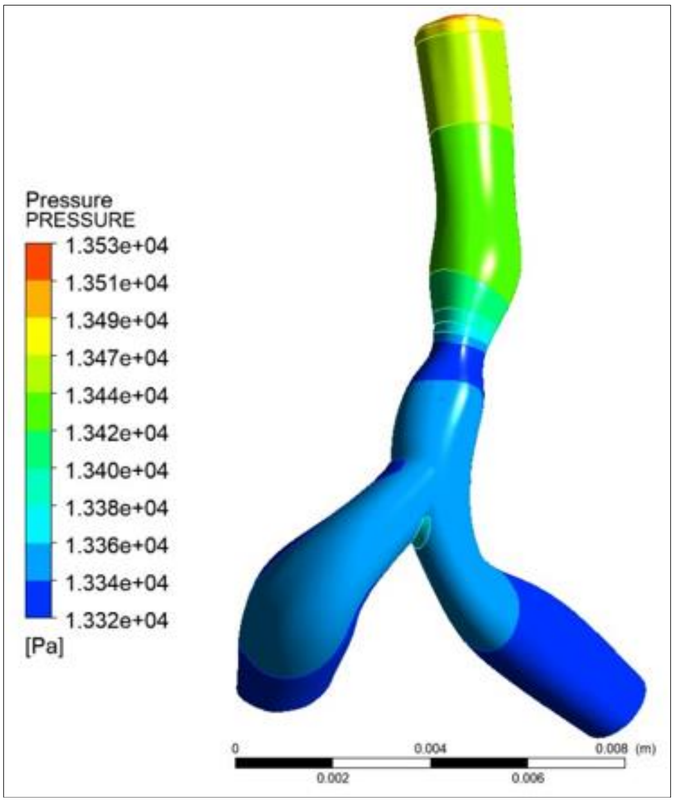

Fig 2: Pressure distribution along the geometry**.**

Pressure and velocity throughout the geometry were post-processed and studied. The contour plot of pressure distribution along the geometry walls is shown in Fig. 2. Blood flow is governed by pressure gradient and flows from region of higher pressure to regions of low pressure. The pressure gradient in the arterial bifurcation is impacted due to the mild stenosis. As we move closer to the throat of the stenosis from the pre-stenotic region it is seen that the pressure starts decreasing abruptly in the stenotic region. In the post stenotic region, the pressure fluctuations arise due to the bifurcation and stenosis.

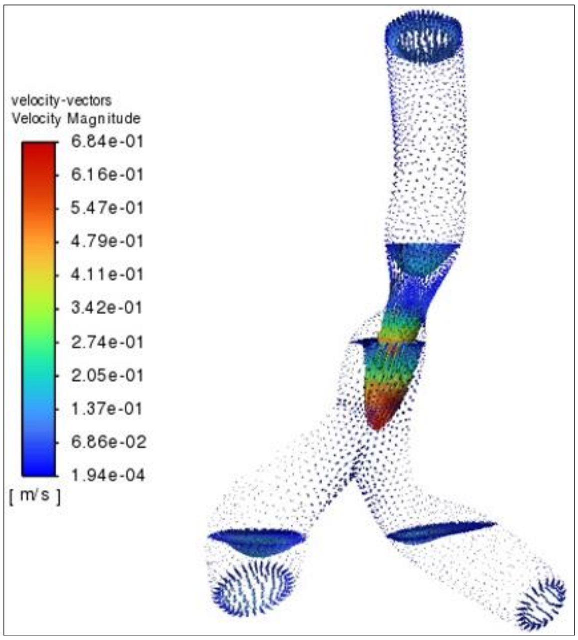

Fig 3: Velocity vectors along the wall and planes P1, P2 and P3.

The velocity of blood flow may affect the arterial wall and aid in the development of arterial pathologies. Planes P1, P2, P3 and P4 are set in the pre stenotic, throat of stenotic, post stenotic region and the iliacs region. The velocity vectors on the arterial wall and planes P1, P2, P3 and P4 are plotted in Fig 3. The effect of mild stenosis on the flow features can be seen through the velocity vectors which show the magnitude and direction of velocity. The flow velocity increases at the throat of stenosis and in the post stenotic region. The flow gets bifurcated into the left and right iliacs and velocity vectors are seen to be skewed due to the curved geometry.

In Fig. 4 the velocity profiles at the three planes are seen to be highly affected due to the mild stenosis. The flow at P1 follows a parabolic profile, as the flow reaches the throat of the stenosis it gets comparatively blunt due to the constriction. At P3 the velocity profile returns back to its parabolic shape as at P1 with increased amplitude.

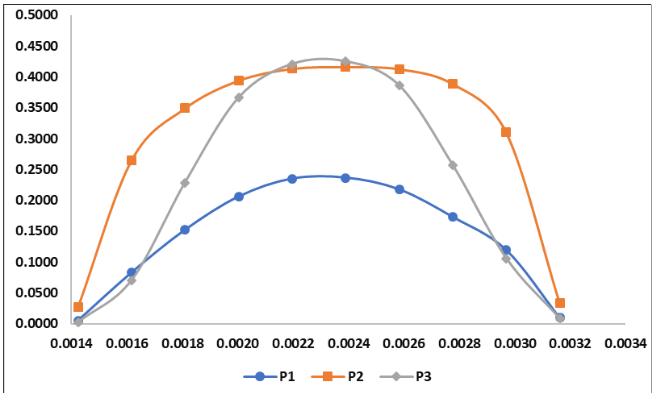

Fig 4: Velocity profiles at planes P1, P2 and P3.

4. Summary and Conclusion

Computational fluid dynamics provides a platform for investigation of the fluid flow in realistic geometrics providing insight into the realistic scenario. This study highlights the disturbances in pressure gradient and velocity distribution. It is inferred that even a mild stenosis in the arterial bifurcation also affects the flow of blood and hemodynamic parameters like pressure and velocity.

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