Numerical investigation on effect of aortic root geometry on flow induced structural stresses developed in a bileaflet mechanical heart valve

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Abstract. Structural stresses developed in an artificial bileaflet mechanical heart valve (BMHV) due to pulsed blood flow may cause valve failure due to yielding. In this paper, von-Mises stresses are computed and compared for BMHV placed in two types of aortic root geometries that are aortic root with axisymmetric sinuses and with axisymmetric bulb, at different physiological blood flow rates. With BMHV placed in an aortic root with axisymmetric sinuses, the von-Mises stresses developed in the valve were found to be up to 47% higher than BMHV placed in aortic root with axisymmetric bulb under similar physiological conditions. High velocity vectors and therefore high von-Mises stresses have been observed for BMHV placed in aortic root with axisymmetric sinuses, that can lead to valve failure.

1. Introduction
The natural aortic valve allows unidimensional blood flow from the left ventricle into the great aorta, through which blood is transferred to all other parts of the body. The native valve may be diseased due to inborn heart defects, rheumatic fever, bacterial infection etc. and thus can cause stenosis or valvular insufficiency [1]. Such valve can be replaced by a mechanical prosthetic Bileaflet Mechanical Heart Valve (BMHV), which is as shown in Figure 1. BMHV is known to be the most durable and biocompatible among other types of prosthetics available [2].

Figure 1. A typical BMHV [2].

Past research investigations on the dynamics of BMHV can be broadly classified into experimental (in-vitro and in-vivo) and numerical ones. Originating with the pioneer work of [3], the numerical methods have evolved as a promising tool to give deep insight into general dynamics of BMHV. However, numerical simulation of BMHV is a complex fluid-structure interaction (FSI) case as the interaction between fluid and the moving leaflets of valve is strong. Based on kinematical
description of domain, the FSI approaches can be classified either as moving or fixed grid methods. The moving grid technique is based on Arbitrary Lagrangian Eulerian (ALE) approach, and is more accurate compared to fixed grid methods [4-5]. With ALE, greater distortions of the continuum can be handled better than would be allowed by a purely Lagrangian method, with more resolution than that afforded by a purely Eulerian approach. Having applied ALE to 2-D geometry of BMHV, [6] obtained velocity profiles for different cardiac phases. [7] and [8] developed a 3-D model of the valve, and employed ALE to study haemolytic properties of blood flow during different phases of cardiac cycle. Their results were found in good agreement with experimental measures. It’s important to note that due to large structural displacements involved while simulating BMHV, subsequent remeshing and smoothing is required to maintain a good quality mesh [9].

The BMHV is located at the downstream of the left ventricle, and corresponds to the beginning of aorta. The aortic root, which is the initial tract of aorta, is characterized by three sinuses of Valsalva, from two of which, the coronary arteries originate as shown in Figure 2.

![Figure 2. Native aortic root [10].](image)

During the valve replacement process, the aortic root needs to be re-constructed or replaced with an artificial aortic root. Two of the available configurations for prosthetic aortic root are the aortic root with axisymmetric sinuses (mimics to natural root) or the aortic root with axisymmetric bulb [11], as can be seen in Figure 3. [12] compared the velocity profiles and blood flow shear stress contours of two types of aortic root models. High velocity vectors and therefore, high shear stresses were reported for the root with axisymmetric sinuses. Therefore, it is important to investigate the effect of sinuses configuration on blood flow hydrodynamics.

![Figure 3. Different aortic root geometries.](image)

The structural strength of BMHVs is an important matter while designing the valve as structural stresses are developed in the valve that may cause valve failure. During its lifetime operation, the valve is exposed to blood pressure force [13], force due to regurgitant flow at end of systole [14] and due to vortices formed in the wake region downstream the BMHV [15]. High equivalent stresses may cause yielding and thus failure of the structure.

In this study, we have placed the BMHV in two types of aortic root geometries, one with axisymmetric sinuses and the other with axisymmetric bulb and an algorithm based on ALE has been applied to account for the mesh motion. The von-Mises stresses developed in the structure have been computed and compared for the two aortic root geometries. The velocity profiles for the fluid domain are also reported at different physiological flow rates
2. Model development and boundary conditions

The aortic root model characterized by three axisymmetric sinuses has been developed based on the geometric parameters of sinuses presented by [16]. While the geometric model for the aortic root with an axisymmetric bulb has been designed following the study of [17]. The valve consists of two leaflets made up of pyrolytic carbon, which is fully closed at 25° and fully opens at 85°. The leaflets rotate about struts attached to their housing, which is made up of titanium. Simulations have been carried out using finite volume code ANSYS FLUENT coupled with finite element code Static Structure. The number of cells used in Static Structure and Fluent are 178,426 and 599,771, respectively (Figure 4) and maximum mesh skewness of 0.76 was maintained.

![Static Structural Model](image)

![Aortic root model](image)

**Figure 4.** Meshing of aortic root model.

To account for leaflet motion, a user defined function was developed and incorporated in ANSYS. The set of Navier Stokes equations solved by the software are written as:

\[
\nabla \cdot \mathbf{v} = 0
\]

\[
p \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \nabla \cdot \mathbf{\sigma} + p \mathbf{f}
\]

Where, \( p \) is the fluid density, \( \mathbf{v} \) is the fluid velocity, \( \mathbf{\sigma} \) is the Cauchy Stress tensor and \( \mathbf{f} \) the body force.

A no-slip boundary condition has been applied to wall boundary. Blood has been modelled as laminar, Newtonian fluid, since the Newtonian behaviour of blood in large vessels like aorta has been widely agreed [18]. The viscosity of blood becomes asymptotically constant at high shear rates, which is the case for aorta. The blood’s dynamic viscosity and blood density used in the model are 3.5 cP, and 1060 kg/m³ respectively.

A physiological pressure waveform, which was approximated using the Fourier series, has been incorporated as the inlet and outlet boundary condition, as mentioned in equations (3) and (4) respectively [8]. The governing equations for inlet and outlet pressures are listed below:

\[
p(\text{inlet}) = 44.24 - 50.76\cos wt + 44.4\sin wt - 0.4108\cos 2wt - 19.45\sin 2wt - 0.3481\cos 3wt + 6.66\sin 3wt + 8.032\cos 4wt + 2.597\sin 4wt + 0.3551\cos 5wt + 2.903\sin 5wt
\]

where \( w \) represents a factor in the pulsed wave equation and is equalled to 8.72.

\[
p(\text{outlet}) = 96.71 - 18.66\cos wt + 2.59\sin wt + 0.182\cos 2wt - 8.67\sin 2wt + 4.41\cos 3wt + 0.46\sin 3wt + 0.059\cos 4wt + 1.39\sin 4wt - 2.101\cos 5wt + 1.19\sin 5wt
\]

where \( w \) is equal to 8.438.

Three physiological flow rates were simulated which are 5 L/min, 5.5 L/min and 6 L/min corresponding to inlet Reynolds number of 1350, 1500 and 1700 respectively. It is known that blood flow rate through the human heart varies between the flow rates that have been mentioned [19-20].
3. Results and Discussion

The velocity profiles and the von-Mises stress contours at $Re = 1350$ for both the geometries are presented in subsequent figures, while results for other simulated Reynolds numbers have been tabulated in Table 1 and 2.

It has been observed that high velocity vectors are found in aortic root with axisymmetric sinuses as compared to aortic root with axisymmetric bulb. At $Re=1350$, the maximum velocity vectors in aortic root with axisymmetric sinuses at fully opened angle of the valve leaflets ($85^\circ$, $t=0.057$sec) are $1.96 m/s$, which are $28\%$ higher than those in aortic root with axisymmetric bulb at same time and angle (Figure 5).

![Figure 5. Velocity vectors at t=0.057sec (Re=1350).](image)

Similarly, at the same Reynold’s number, high velocity vectors are observed at leaflet’s start to close angle ($63^\circ$, $t=0.237$sec) and fully closed angle ($25^\circ$, $t=0.8$sec) in aortic root with axisymmetric sinuses as compared to aortic root with axisymmetric bulb. The velocity profiles for both geometries at time $t=0.237$sec and $t=0.8$sec are illustrated in Figures 6 and 7 respectively.

The same trend, that is high velocity vectors in aortic root with axisymmetric sinuses compared to root with an axisymmetric bulb was observed for the other two physiological flow rates corresponding to inlet Reynold number of 1500 and 1700 (Table 1 and 2).

![Figure 6. Velocity vectors at t=0.237sec (Re=1350).](image)

It's also important to note that the flow recirculation and vorticity is higher in aortic root with axisymmetric sinuses, as compared to aortic root with axisymmetric bulb.
Based on above results, it can be well said that significantly high velocity vectors are found in aortic root with axisymmetric sinuses as compared to aortic root with axisymmetric bulb. Consequently, on coupling the fluid and structure domains, it has been observed that high von-Mises stresses are developed in BMHV placed in axisymmetric sinuses compared to axisymmetric bulb. The von-Mises stresses contours at different physiological phases for the two geometries can be seen in Figure 8 at Re= 1350. At fully closed phase of leaflets (angle 25°, t= 0.8sec), the maximum von-Mises stress developed in BMHV placed in aortic root with axisymmetric sinuses is 56 MPa, nearly 48% higher than that in BMHV placed in aortic root with axisymmetric bulb, which is 35.5 MPa. These stresses occurred at the leaflet pin in a short time, however it may cause valve failure in the long run due to yielding as the allowable stress is 32 MPa [21]. At leaflet angle 63° and 85°, the maximum von-Mises stresses in BMHV placed in axisymmetric sinuses are respectively 37% and 22% higher than those in BMHV placed in axisymmetric bulb at Re=1350.

It is worth mentioning that for all the Reynold’s numbers and both the aortic root geometries, the von-Mises stresses developed in BMHV at fully open phase (angle 85°, t=0.057sec) are lower than the allowable stresses. Other than that, higher von-Mises stresses than allowable are developed in BMHV placed in aortic root with axisymmetric sinuses. Therefore, the valve structure is more likely to fail if it has been implanted in such aortic root geometry, that closely mimics to natural aortic root.
Figure 8. von-Mises stresses contours at Re= 1350.
Table 1. Velocity and von-Mises stresses for axisymmetric sinuses.

| Valve Leaflet position (°) | Re = 1350 | Re = 1500 | Re = 1700 |
|---------------------------|-----------|-----------|-----------|
|                           | von-Mises Stress (MPa) | v_{\text{max}} (m/s) | von-Mises Stress (MPa) | v_{\text{max}} (m/s) | von-Mises Stress (MPa) | v_{\text{max}} (m/s) |
| 25                        | 56        | 1.60      | 65        | 1.67      | 71.5        | 1.68      |
| 63                        | 35        | 1.88      | 58.5      | 1.96      | 63.5        | 2.01      |
| 85                        | 14        | 1.96      | 31        | 2.10      | 32          | 2.34      |

Table 2. Velocity and von-Mises stresses for axisymmetric bulb.

| Valve Leaflet position (°) | Re = 1350 | Re = 1500 | Re = 1700 |
|---------------------------|-----------|-----------|-----------|
|                           | von-Mises Stress (MPa) | v_{\text{max}} (m/s) | von-Mises Stress (MPa) | v_{\text{max}} (m/s) | von-Mises Stress (MPa) | v_{\text{max}} (m/s) |
| 25                        | 35.5      | 0.96      | 40.5      | 0.88      | 47.5        | 0.74      |
| 63                        | 25.5      | 1.35      | 40        | 1.45      | 43.5        | 1.18      |
| 85                        | 11.5      | 1.54      | 20.5      | 1.75      | 29          | 1.97      |

4. Conclusion

Velocity profiles and von-Mises stresses developed in bileaflet mechanical heart valves placed in two types of aortic root geometries have been determined and compared at different physiological flow rates. It has been found that high velocity vectors and high von-Mises stresses, especially at the leaflet pins are developed in valves placed in aortic root with axisymmetric sinuses as compared to that placed in aortic root with axisymmetric bulb. Since the structural stresses developed in BMHV for both the geometries are higher than allowable stresses for most of the physiological conditions, the valve structure is expected to fail due to yielding and this could be one of the unknown reasons of valve failure.

5. References

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