Reduction of Vortex Formation in Mechanical Heart Valve During LV Filling

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Abstract. Mechanical valve implanted in mitral position has a tremendous effect on the flow dynamics in Left Ventricle (LV). The purpose of this study is to develop a new valve configuration to reduce the vortex ring formation caused by an artificial heart valve in an isovolumetric environment to generate a smoother flow field. Flow Inhibitors (FI) were built on the proximal end of the leaflet of various shapes and sizes to understand their effect on flow dynamics. The test geometries were designed based on the principles of Bernoulli’s law of fluid dynamics, pressure staging, and counter disturbance. In this research, equally spaced FI with centralized flow showed a lower and gradual pressure gradient as opposed to the control valve that was used earlier in the study done with a 27mm St. Jude mechanical valve. The pressure gradient dropped gradually from 1.4 Pa to 0.3 Pa as compared to a sudden drop in pressure in the control valve from 1.3 Pa to 0.2 Pa. The velocity value set was 0.8 m/s for simulation which dropped to 0.4 m/s in equally spaced FI centralized flow valve as compared to 0.3 m/s in the control valve. When compared on the basis of smoothness of flow field and gradual drop in the pressure, the former is weighted to be a better design. Flow inhibitor coupled with pressure staging method proved to be effective in enhancing the performance of bileaflet valve.

Keywords: Mechanical Valve, Heart, Emboli, Cavitation, Microbubble, Vortex, Vorticity, Turbulence, Leaflet, Mechanical Valve, Prosthetic Valve, Valve Geometry

1. INTRODUCTION

Cardiac looping during the embryonic development phase creates flow paths of an adult heart. These flow paths are such that they facilitate optimum flow through the chambers. Asymmetric flow patterns created by these paths allow the momentum of inflow streams to be redirected to the aortic valve (1). In the case of a mechanical valve, studies (2) have shown that this swirling of blood is largely compromised. The shear layers generated due to the pulsatile flow of blood over the leaflet edge, causes the layers to roll up and form a disturbed vortex ring.

The geometry of the heart becomes very complex in such cases of high-speed jets rolling out, constantly moving walls and pulsatile flow character and unsteady motion of leaflet which leads to the formation of complicated flow fields. The vortex converts the linear momentum of the flow stream to angular momentum dissipating a tremendous amount of flow energy as compared to a healthy valve (2).
Mechanical heart valves have shown great promise with the recent developments being focused more on patient-specific needs. The survival rate of patients with valve replacement surgery has been 94% (3). However, the natural hemodynamics of the heart limits the shelf life of the valve. Blood streams on the valve produce a vortex in the LV chamber that disrupts the flow. One primary reason for valve failure in the long haul is the thrombogenic activity of blood on the leaflet. The patient has to be kept on anticoagulant therapy to eliminate clotting activity. This study focusses on the development of a leaflet that can reduce the distortion streams generated during left ventricular filling.

Various studies have been done on the flow mechanics of mechanical valve and prosthetic tissue valves. However, little work has been done on valve geometry to reduce vortex formation. One study talks about using counterrotating vortex generators to reduce turbulence inflow streams during LV filling(4). Valve leaflet design is an important area that needs more work on and this study will lay the groundwork for further research in this field. This study focusses on geometric modification of the valve design to obtain a smoother flow field over the leaflet edge. The 3D modelling approach is used to simulate various valve configurations in normal and abnormal conditions.

2. RELATED WORK

Querzoli, Fortini and Cenedese (2) in their study of the behavior of different mechanical heart valves, observed that the volume of ventricle remains constant during diastasis which is a combined phase consisting of left ventricle repolarization and left atrium depolarization. During this phase, in a bileaflet valve, the inflow gets divided into three streams moving downward. These streams produce a single wide jet and a clockwise vortex ring which is located below the aortic valve. During diastasis, the vortex increases in size, and its core moves to the centre of the left ventricle. During the atrial contraction, although there is an interaction between the incoming jets and the vortex, the jets increase the overall rotation of blood. As a result, at the end of diastasis, the vortex dominates the blood moving and the streamlines on the anterior wall of the ventricle are pushed towards aorta.

Pierrakos and Vlachos (5) studied mechanism of vortex ring annihilation. They found out that the rotating vortex ring entraps the energy of surrounding fluids and leads to a conversion of linear momentum to angular momentum. However, there is a limit to which the ring can increase in its size which corresponds to the maximum energy it can sustain. Once this energy exceeds, the ring pinches off it sheds a trailing jet. This energy rejection mechanism not only reduces propagation velocity but also reduces kinetic energy and propulsive efficiency. In their study they concluded that mitral valve efficiency is dependent on the vortex ring formation mechanism and is governed by valve geometry and valve orientation.

Hatoum and Dasi (4) studied the effect of vortex generators in reducing vortex formation in bileaflet mechanical valves. Vortex Generators are passive devices that are placed on the surface of valve leaflets that manipulate the flow field. Their study concluded that vortex generators lower the transvalvular pressure gradient yields lower shear stress values than without vortex generators resulting in better hemodynamic performance and reduced cavitation.

Zapantd et al. (6) observed that there are two types of in-vitro cavitation in the bileaflet mechanical valve. Vortex cavitation is a result of a high-velocity roll-up of streamline jet. Bubble cavitation is a result of the vaporization of fluid due to pressure drop below vapor pressure.

Alemu and Bluestein (7) in their study found that a change in the alignment of valve position induces spiral vortex formation. Spiral vortices draw platelets to the core flow of higher shear stress.
which contributes to platelet damage. The helical vortices entrain the platelets towards the heart valve wake. This reaffirms the role of wake dynamics in platelet activation under high shear stress.

Yin et al. (8) studies platelet activation in the bileaflet valve. They concluded that, platelet activation is dependent on the type of valve used. The rate of platelet activation in bileaflet valve 8.11 \times 10^{-4} \text{ min}^{-1} whereas for a monoleaflet valve the rate is 3.14 \times 10^{-4} \text{ min}^{-1}.

Most of the studies so far point out to the fact that streamline flow is a characteristic of valve geometry and position. Hence to reduce vortex formation in a mechanical heart valve it is important to design the valve in a way that aids inflow energy conservation.

3. METHODOLOGY

This study focusses on the development of different valve geometries to find the optimum design to reduce vortex formation that is quantified by the pressure dip across the valve.

The entire project is executed in four stages. They are as follows:

a. Understanding of fluid dynamics of LA and LV across a natural heart and artificial heart.

b. Development of 3D model of various configurations of valve leaflets.

c. Testing under isovolumetric conditions in normal conditions for fluid flow at 0\(^\circ\) (9).

d. Compilation of results for both studies.

This study focusses only on the fluid dynamics of valve-blood interaction. It takes into account the rheological changes that occur in the blood due to changes in the physiology. Blood taken into this consideration is non-Newtonian in nature.

There are total of three valve geometries designed for this study which includes one control valve and two test configurations. The designs are as follows and each of the designs is described in detail with the concepts applied in designing each particular geometry.

A. Artificial Control Valve

The control valve is a 3D model of a standard St Jude 27 mm mechanical mitral heart valve. The mechanical valve is 2 mm thick and is 27 mm in diameter. The material used in developing a leaflet is graphite coated pyrolytic carbon. Recent advancements in the hydrophilic coating have enabled partial elimination of thrombogenic activity on the metal surface. Modern bi-leaflet valves are coated with polyurethane foam that increases the shelf life of the valve.

![Artificial Control Valve](Fig 1. Artificial Control Valve)
Figure 1 shows a standard 27 mm artificial bileaflet valve by St. Jude’s Medical that is used as a control geometry in this study.

Table 1. Dimensions of St Jude 27 mm Valve

| Feature                  | Dimension (in mm) |
|--------------------------|-------------------|
| Diameter                 | 27                |
| Leaflet Arc Length       | 42                |
| Leaflet Thickness        | 2                 |
| Inter Leaflet Distance   | 2.5               |
| Effective Orifice Area (mm2) | 190±7            |

Table 1 shows the geometric specifications of the artificial control valve.

B. Unequal Flow Inhibitor (FI) Spacing Valve

Hatoum and Dasi (4), experimented to reduce the pressure gradient using Vortex Generators (VG). They observed that co-rotating VGs were able to reduce the pressure gradient from 14.88 mm of Hg to 10.45 mm of Hg. This was due to a counter field disturbance generated by these VGs that reduced the turbulence to an extent. Utilizing this phenomenon, we have designed a valve with fixed protrusions at unequal distance on the proximal end of the leaflet that will generate counter disturbance in the flow field; which should eventually reduce the turbulence.

Figure 2 shows the unequally spaced FI test geometry that is developed based on the concept of counter turbulence to reduce vorticity. Unequal distance between each FI and the periphery is designed to produce uneven counter turbulence on the proximal end of orifices.

When the blood flows through the valve, vortexes start forming due to shear stress between endocardium and fluid. The flow through the peripheral orifice on either side is responsible for this shear. Hence the leaflets are designed such that the flow inhibitors (FI) are on the rear surface when the valve is in the open position. When the blood travels through the valve in the vessel, the velocity of fluid increases, and its pressure decreases. The point at which the fluid velocity is maximum and the pressure is minimum is called Vena Contracta. Flow streamlines converge at this point and are nearly horizontal, their cross-sectional area is the least. It corresponds to the Effective Orifice Area (EOA) of the valve and is used in Echocardiography to assess valve function.
This design will play a key role in understanding the behavior of equally spaced and unequally spaced FIs and will give a clear insight into their efficiency in reducing the turbulence which will be quantified by Transvalvular Pressure Gradient.

### Table 2. Dimensions of Unequal FI Spacing Valve

| Feature                                | Dimension (in mm) |
|----------------------------------------|-------------------|
| Diameter                               | 27                |
| Leaflet Arc Length                     | 36                |
| Inter Leaflet Distance                 | 3                 |
| Leaflet Thickness                      | 2                 |
| Effective Orifice Area (mm2)           | 190±7             |
| FI 1 to Left Edge distance             | 2.51              |
| FI 1 to FI 2 distance                  | 4.7               |
| FI 2 to FI 3 distance                  | 4.2               |
| FI 3 to FI 4 distance                  | 3.7               |
| FI 4 to Right Edge distance            | 3.847             |
| FI Height                              | 1                 |

Table 2 shows the dimensional specification of the unequally spaced FI valve including inter FI distance.

### C. Equally Spaced FI Valve

The principles of fluid dynamics that apply in plumbing also apply to blood vessels. Veins have valves that regulate flow in the peripheral circulation similar to the butterfly valves in pipes. Similarly, the human heart is analogous to the pump. The heart has four valves that control the flow in and out of chambers analogous to which industrial pumps have a control valve that controls the amount of water entering the piping network.

Invitro cavitation observed near the periphery of the leaflet is also observed in control valves in industrial pumps. Valve cavitation is a primary reason for the deterioration of control valves in pumps. In pumps, cavitation occurs due to complex pressure profiles throughout the pump. In the case of centrifugal pumps, there is a huge drop of pressure near the impeller end. The fluid pressure increases and decreases when fluid is drawn from rest to the pumping chamber to when it is expelled.

In this process of pumping, if there is a drop in pressure, it leads to a loss in throughput and increased vibrations and noise. If the pressure of the fluid at any point is lower than the vapor pressure of the fluid, then the fluid will boil and it will lead to bubble formation. When the bubbles travel to a region of higher pressure, the fluid condenses and bubble implodes releasing energy damaging the surfaces near to it. Power consumption in such cases will be higher to achieve a similar throughput. This behavior is exactly similar to microbubble formation in LV where the kinetic energy is lost due to microbubble formation and vortex formation.

One of the most efficient ways to reduce pump cavitation is multi staging. Multi-stage pumps have multiple impellers rotating on a single shaft. Each stage in the pump elevates the pressure gradually. The more stages the pump will have, the higher the discharge pressure will be. It does so by centralizing
the flow and preventing sudden pressure drop. This concept of pressure staging and fluid centralization is used to design this geometry of valve for this study.

![Fig 3. Equally Spaced FI Centralized Flow Valve](image)

Figure 3 shows the equally spaced FI centralized flow valve. The two central orifice FI used for converging flow over leaflet surface with gradual transvalvular pressure gradient.

The FIs in this design are unlike those in the FI unequal spacing valve. These FIs are derived from the concept of Pressure Staging and Bernoulli Law of Fluid Dynamics. Without the FI, the velocity is maximum at the proximal end of the leaflet and it will be minimum at the distal end. This results in a pressure drop at the periphery of the leaflet when the flow exits the leaflet. The inverted FI design is developed to increase the velocity instead of the velocity drop at the end of the leaflet.

The positioning of FIs is crucial in this geometry. Hence the FIs are designed such that the flow field on either side of the leaflet is targeted and counter disturbance is generated in those field vectors specifically. This valve geometry should show the best result.

| Table 3. Dimensions of Equal FI Spacing Centralized Flow Valve |
|-------------------------------------------------------------|
| Feature                     | Dimension (in mm) |
|----------------------------|-------------------|
| Diameter                  | 27                |
| Leaflet Thickness          | 2                 |
| Leaflet Arc Length         | 36                |
| Inter FI Distance          | 7.5               |
| FI Area                    | 11.3 mm³          |
| FI to Edge distance        | 7.5               |
| FI Height                  | 1                 |

Table 3 shows the dimensional specification of equally spaced FI centralized flow valve.

4. CFD ANALYSIS

A. Simulation Parameters

Fluid-Structure Interaction (FSI) study is done using ANSYS Fluent and modelling is done using Autodesk Fusion 360. Here, the blood taken into consideration is Non-Newtonian in nature. Material used for leaflets is graphite coated Pyloritic Carbon. Each valve geometry is simulated at 0°. Blood flow velocity is set 0.8 m/s and blood viscosity is 0.0003 Pa. s in all the simulations.
B. Simulation

The 3D models are saved in IGES format and imported in Fluent. An enclosure is defined of dimensions 15mm*15mm*15mm. Top is defined as velocity inlet and bottom is defined as outlet. The remaining 4 sides are defined as walls. Then the models are meshed for accurate fluid dynamics. Fine meshing is used to study behavior of vortex at the edges and near FIs. Two important parameters that we are focusing on in this study is Transvalvular Pressure Gradient and Velocity across valve. These two parameters are enough to understand the effect of valve geometry on the vortex and hence valve performance.

C. Analysis

1. Artificial Control Valve

Figure 4 shows meshing of artificial control valve used in this study. The meshing is fine over the distal end of the valve where the shear roll up takes place to capture precise data.

Figure 5 shows the velocity gradient at the outflow. It can be seen that the velocity has dropped from 0.8 m/s to 0.3 m/s at the central orifice.
Figure 6 shows the transvalvular pressure gradient across the control valve. It can be seen that the pressure drops steeply at the proximal end of valve. In order to reduce the effect of vorticity on the blood flow in the chamber, the pressure drop across the valve needs to be gradual and minimum loss. The artificial control valve in this case shows a steep drop and drastically reduces to 0.019 Pa.

2. Unequal FI Spacing Valve

In figure 7, fine meshing is done around FIs to focus on its effect on the flow dynamics. The hinge attachment is designed to have a tapering end to reduce water hammer effect. The FIs are created on the outer surface of leaflet to reduce the turbulence in the peripheral jet.
Figure 8 shows the velocity outflow at the distal end of the unequally spaced FI valve. The flow coming out of the central orifice is better than the control valve in terms of turbulence.

This valve configuration shows a distorted flow field in the peripheral jet at the valve outlet and a relatively smoother flow through the central orifice.

![Fig 8. Velocity Outflow at Distal End](image)

**Fig 9. Pressure Gradient across Leaflet**

In figure 9, the pressure drop across FIs is till 0.2 Pa and shows a gradual drop across leaflet surface.

3. **Equal Spacing FI Centralized Flow (CF) Valve**

![Fig 10. Meshing of Equally Spaced FI CF Valve](image)

Figure 10 shows meshing of equally spec FI centralized flow valve. The ends of FI experience most stress hence finer mesh is designed in those areas.

![Fig 11. Velocity Field at the outlet](image)
Figure 11 shows the velocity at the distal end of the valve. It can be clearly seen that the velocity field through the peripheral orifice in this configuration is smoother and uniform as compared to other valves.

Figure 12 shows that the pressure loss in this configuration is less due to the FIs creating a centralized flow.

5. RESULTS

The control valve used in this study is a standard SJM 27 mm mechanical mitral valve. Its simulation showed high-pressure areas on the inlet of leaflet. However, the flow across the valve is more through the peripheral orifice and less through the central orifice. Sotiropoulos, Le and Gilmanov (10) showed that the roll-up shear generated through the peripheral orifice, over time harms endocardium in the mitral position that eventually triggers biochemical processes on the surface. This is one drawback of the mechanical valves currently used in the market.

Unequal spacing geometry was designed to understand the difference in hemodynamics behavior. At 0º inclination, this geometry is the only geometry at this inclination to produce curl on the periphery. Hence the vorticity of the unequal spacing valve is higher than other designs used in this study. FIs in unequal spacing valve prevented sudden pressure drop and maintained a constant pressure, the same behavior was observed in this case. To verify this, the rear side of the leaflet which was facing the central orifice showed sudden pressure drops.

The pressure gradient of equal spacing centralized flow valve showed a gradual decrease in its valve over leaflet surface and the velocity through the valve at inlet and outlet are better than other test geometries. The pressure dropped to 0.3 Pa at the leaflet end and the velocity valve dropped to 0.5 m/s from 0.8 m/s. This result establishes the claim made at the start of this study that this geometry should be the most promising geometry due to the combined effect of pressure staging and counter vortex generation.
Table 4 shows a summarized view of the values of velocity and pressure gradient.

### Table 4. Velocity and Pressure Gradient Valves

| Type of Leaflet       | Velocity Drop (m/s) | Pressure Gradient (Pa) |
|-----------------------|---------------------|------------------------|
| Control Valve         | 0.8 to 0.3          | 1.3 to 0.2             |
| Unequally Spaced FI   | 0.8 to 0.2          | 1.3 to 0.2             |
| Equally Spaced FI CF  | 0.8 to 0.4          | 1.4 to 0.3             |

### 6. CONCLUSION

Unequally spaced FI valve shows highest vorticity due to unbalanced counter vortex generation in the flow field. The pressure gradient across the valve shows a gradual reduction as compared to the control valve used for the study.

The equally spaced FI centralized flow valve, as expected, shows the best result. The velocity profile across this valve is smoother and uniform among all three valves. The transvalvular pressure gradient also shows a uniform reduction across leaflet.

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