Analysis of Pulsatile Blood Flow Through a Bileaflet Mechanical Heart Valve with Moving Leaflets

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Abstract

There are more than five million patients diagnosed with heart valve disease and about 85,000 heat valve replacements in the US annually. Heart valves act as fluidic control structures to ensure unidirectional blood flow and prevent backflow. When valves malfunction, a replacement is often necessary in severe cases. For example, without valve replacement the survival rate in severe aortic stenosis patients is about 50% two years after the onset of symptoms. Artificial heart valves, both bioprosthetic and Commercial valves, have been utilized for many years to replace dysfunctional heart valves. The first part of the current study presents an investigation on a Commercial bileaflet mechanical heart valve with various percentages of valve opening angle. Comparison of velocity, pressure, shear stresses and vorticity profiles for different leaflet angles that represent valve dysfunctions is discussed in the current research. Valve leaflets are propelled to open and close during the cardiac cycle due to the forces applied by pulsatile blood flow on heart leaflets. Hence in the second part, a computational method is exploited to simulate the flow dynamics through the heart valve during leaflet motion influenced by pulsatile blood flow from the full open and closure positions. The results show variations in velocity and pressure gradients through the heart valve which can be an indication of heart valve dysfunction and the cardiac flow through normal valve and in the vicinity of the mechanical leaflets during valve motion.

Methods: Modeling

- **Bileaflet Mechanical Heart Valve**

A 3D bileaflet mechanical heart valve, **Fig.1a**, similar to the Commercial 25-mm St. Jude heart valve [1], **Fig.1b**.

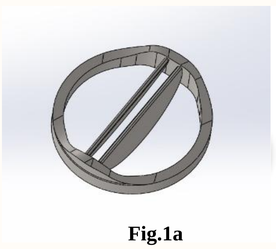


Fig.1a



Fig.1b

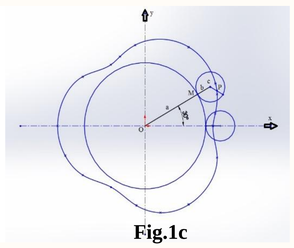


Fig.1c

- **Aortic Root Sinuses**

Cross-section of a three-leaflet aortic root sinuses can be represented as an epitrochoid, **Fig. 1c**. Tracing a point inside a small rotating circle rolling on the perimeter of a bigger circle results in a shape called epitrochoid [2]:

$$x = (a+b)cos\alpha - \lambda bcos\left(\frac{a+b}{b\alpha}\right)$$

$$y = (a+b)sin\alpha - \lambda bsin\left(\frac{a+b}{b\alpha}\right)$$

Methods: CFD Analysis

Flow domain is divided into four main parts in sequence respect to flow direction (Fig.2): upstream (1), bileaflet mechanical heart valve (2), aortic root sinuses (3) and downstream (4).

- **Steady-State Blood Flow (Validation)**

The in vitro analysis requires the ambient outlet pressure, inlet mass flow rate of 18 l/min., laminar, incompressible, and Newtonian with a density of 1050 kg/m3 and viscosity of 0.0035 kg/m.s, which represents human blood properties at 37C.

- **Blood Flow at Peak Systolic Phase**

The in vitro analysis requires the ambient outlet pressure, pulsatile blood flow at a pulse rate of 74 beats per minute (bpm) and systolic duration of 300 ms.

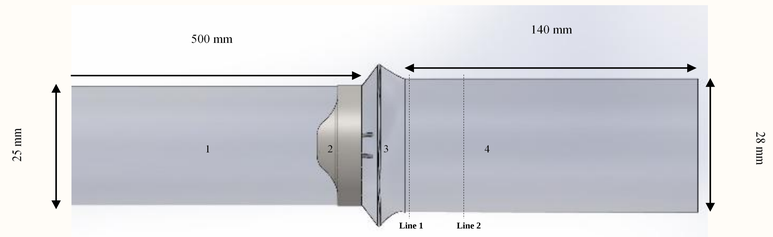


Fig.2 Flow Domain: upstream (1), bileaflet mechanical heart valve (2), aortic root sinuses (3) and downstream (4).

Results

- **Steady-State Blood Flow (Validation [3] and Velocity Profiles)**
  - **Line 1 (7 mm Downstream)**

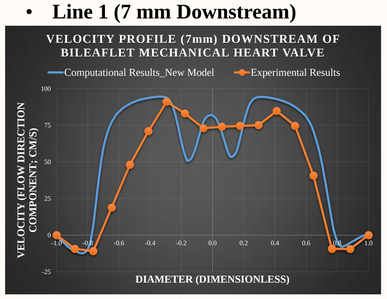


Fig.3a

  - **Line 2 (22 mm Downstream)**

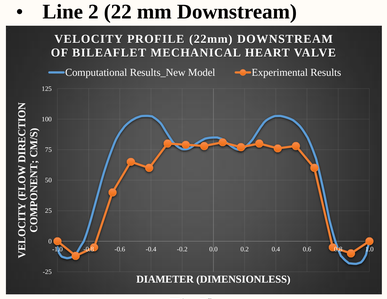


Fig.3b

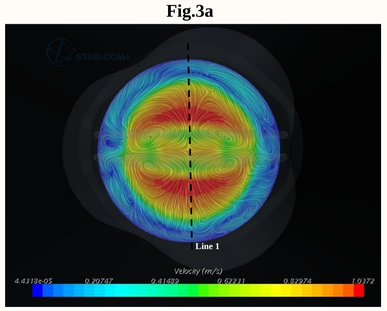


Fig.3c

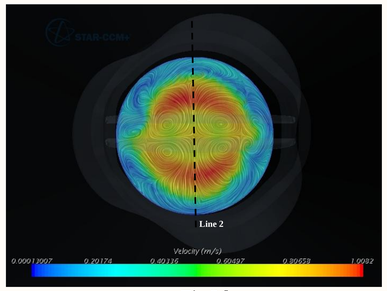
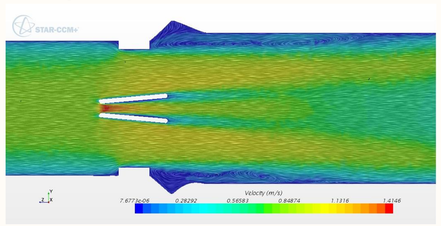
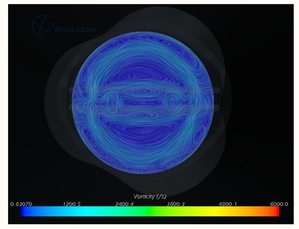


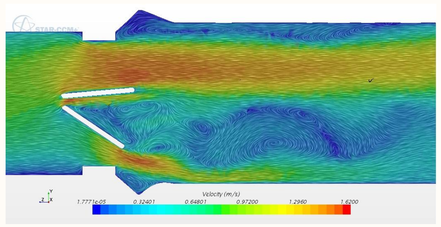
Fig.3d

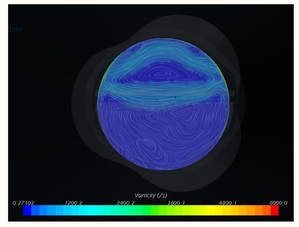
- **Blood Flow at Peak Systolic Phase**
- 0% Dysfunctional Leaflet





- 50% Dysfunctional Leaflet





- 100% Dysfunctional Leaflet

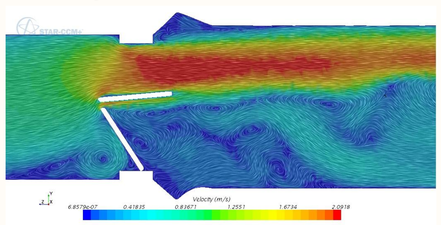


Fig.4a Velocity

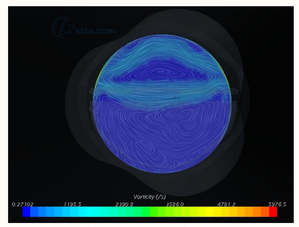


Fig.4b Vorticity

Conclusion

- Velocity Profiles
  - ❖ 0% Dysfunction (Maximum velocity of 1.43 m/s)
  - ❖ 50% Dysfunction (Maximum velocity of 1.62 m/s)
  - ❖ 100% Dysfunction (Maximum velocity of 2.09 m/s)
- The flow upstream and downstream of a dysfunctional mechanical heart valve was highly influenced by malfunction severity.
- In 50% dysfunction of one leaflet, the relatively high shear stress areas covered most of the domain downstream of the valve.
  - ❖ Higher potential level of platelet activation
  - ❖ Larger vortices downstream of the BMHV

Acknowledgment

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References

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[2] H. Ruel, A. Vahlbruch, M. Giersiepen, T. Schmitz-Rode, V. Hirtz and S. Effert, "The Geometry of the Aortic Root in Health, at Valve Disease and after Valve Replacement," J. Biomechanics, vol. 23, no. 2, pp. 181-191, 1990.
[3] R. Fatemi and K. B. Chandran, "An in vitro comparative study of St. Jude medical and Edwards-Duromedics bileaflet valve using laser anemometry," J. Biomech. Engng, vol. 111, pp. 298-302, 1989.