Shear Stress Wave Propagation by the Passive Opening and Closure Motion of a Prosthetic Heart Valve

Hyun-Goo Kang* · Keun-Shik Chang** · Byung-Goo Min***

1. Introduction

Since the St. Jude bi-leaflet mechanical heart valve was introduced in 1977, research has been actively made to improve the performance of prosthetic heart valves. A variety of heart valves have appeared but none of them matched the performance of natural heart valve. The materials of artificial heart valve have also imposed insurmountable problems. Abnormally high local shear stress or large- scale flow separation with excessively low shear stress due to the artificial heart valve might cause thrombosis and hemolysis in the end.

In this study, the CFD(Computational Fluid Dynamics) techniques are used to investigate the mechanical function of a two-dimensional artificial heart valve. We introduce some preliminary results obtained by creating a full three-dimensional computer code that can simulate local cardio-vascular blood flows. It helps to understand how the complex shear flow is caused around the moving artificial heart valve.

The opening and closure motion of a heart valve is very difficult to calculate since the physical domain consists of a pulsatile blood flow and artificial heart valve moving passively in the periodic flow. Given the bi-leaflet valve in two dimensions, we investigate the shear flow in a cycle of opening and closure motion of the valve.

2. Numerical Method

2.1 Incompressible Navier-Stokes equations

We solved the 2-dimensional incompressible Navier-Stokes equations using the pseudo-compressibility method. The governing equation can be expressed in a vector form[1].

$$\frac{\partial \hat{Q}^{n+1}}{\partial \tau} = -\hat{R}^{n+1} - \hat{S}^{n+1} \tag{1}$$

The inviscid flux terms are differenced using a third-order upwind differencing scheme whereas the viscous flux terms using a second-order central difference. On the wall the no slip condition is imposed. On the inlet and outlet boundaries, the explicit boundary conditions based on the method of characteristic are used.

A first-order implicit formula is used to discretize the pseudo-time derivative following Reference 1. A nonlinear matrix equation is resulted which is solved by Point Symmetric Gauss-Seidel (SGS) relaxation scheme. It showed good convergence rate.

2.2 Chimera overlapping grid

For the prosthetic heart valve moving passively in response to the pulsatile blood flow, we used the Chimera overlapping grid. Polyurethane prosthetic heart valve has been developed in the Seoul National University Hospital[3] and the present computer model represents one of them in two dimensions. The Chimera grid consists of the minor grid around the valve overset on the major grid covering the blood vessel. The body and the minor grid move as a solid body in the stationary major grid.

Numerical difficulty arises as the valve moves in the narrow artery. Even the solid-solid contact occurs when the valve is completely closed. We introduced the concept of Dynamic Domain Dividing Lines (DDDL)[4] that halves the gap between the valve and the arterial wall: see Fig. 1. Here both the upper and lower boundaries of the minor grid consist of DDDL's. The present bi-leaflet valve has a small central gap that remains open even at the closure of the valve. It corresponds to a small central hole in the actual disk- type polyurethane valve that allows a small jet to wash out the recirculating blood behind the valve.

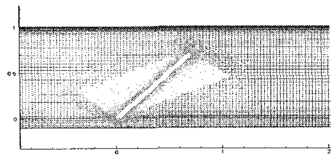

Fig 1. Chimera grid system for 2-D prosthetic heart valve

3. Results and Discussion

In this study, the prosthetic heart valve moves passively in a pulsatile flow. The inlet condition is either a uniform flow of simple harmonic time function or a more complex Wormersley's flow. The prosthetic heart valve is assumed rigid in the present analysis and

* 한국과학기술원 기계공학과 항공우주공학 박사과정
** 한국과학기술원 기계공학과
*** 서울대학교 의과대학 의공학과

subject to fluid-structure interaction. The valve motion is limited in this study between two valve angles, 30° and 88° with respect to the symmetric plane. The valve is fully open at angle 30° and closed at angle 88°.

The computation has converged to periodic flows. Fig. 2 indicates that the passive valve is closed and opened in a rigorously periodic manner. Closing of the valve is slow in the low angles but accelerated with time. On the contrary, the valve opens slow at the beginning but is accelerated as the valve approaches the fully open position. Fig 3. shows the velocity vector variation around the moving valve. We can observe here that the local blood flow is not simple due to the tip vortex shedding and wake. At the maximum opening phase, a small but strong jet is formed through the wash-out hole at the symmetric plane. In the closing phase, the jet is reversed due to the back flow. We can conclude that the central gap removes the wake region behind the closing valve periodically by washing out the stagnant flow at a small cost of the valve efficiency. It would help to reduce the risk of thrombogenetic deposit *in vivo*.

Fig. 4 represents the instantaneous shear stress distribution shown by color map. At the valve tip and in the wash-out hole, the shear stress is highest. It is clearly observed that the shear stress wave propagates upstream as the valve is closed and collides with the oncoming flow in the forward phase. We can argue that the maximum shear stress near the valve tip is reduced with the central washout hole. In fact, the prototype polyurethane circular disk valve is thin and more flexible toward the rim of the disk. It would make the actual maximum shear stress much smaller than predicted in the present solid model due to opening and closure motion of the valve.

4. Conclusion

We have developed a 2-D incompressible Navier-Stokes solver based on the Chimera grid to analyse the characteristics of a novel prosthetic heart valve. The valve turned out to give higher stress around the valve tip and at the wash-out hole, due respectively to the tip vortex and the jet in the accelerated phase of the valve motion. The valve played a role of check- valve to let the blood flow in the forward direction with reduced impact and shear stress distribution.

Acknowledgement

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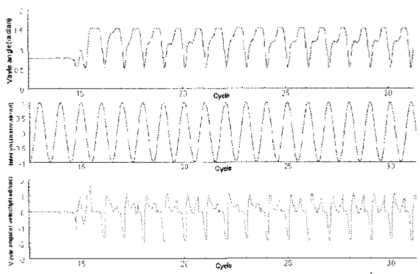

Fig 2. Passive valve moving development(Valve displacement, inlet velocity, valve angular velocity)

Fig 3. Velocity vector distribution around passive moving heart valve in pulsatile flow(1/5T,2/5T,3/5T, 4/5T,5/5T)

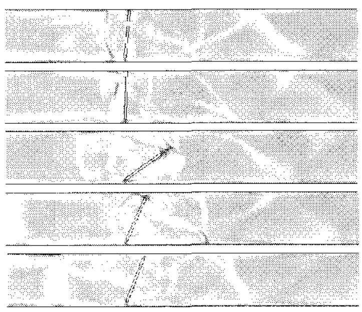

Fig 4. Field shear stress variation around passive moving heart valve in pulsatile flow(1/5T, 2/5T, 3/5T, 4/5T, 5/5T)