Velocity profiles and turbulent shear stress distributions downstream of the St. Vincent valve in pulsatile flow condition

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Introduction

Prosthetic heart valves are commonly used for replacement of natural valves, in ventricular assist devices (VADs) and total artificial hearts (TAHs). Clinical success of a given valve design is based on many factors, one being the fluid flow phenomena, particularly in vitro velocity profiles, shear stresses, regurgitation and energy losses. If a prosthetic heart valve is to be used in human or in VADs and TAHs, then the causes and develop solutions for the valve-related problems, such as blood cell damage, thrombus formation calcification and infection, should be studied (Imachi K., et al., 1989 and Imachi K. et al., 1988). In the present study, velocity profiles and turbulent shear stress distributions were determined at three specific locations of the cardiac cycle at downstream of the St. Vincent valve. St. Vincent valve was considered one the most suitable valves for use in VADs (Umezu, M. et al., 1990). Regurgitation, energy loss and mean systolic pressure drop results of the St. Vincent valves were reported somewhere else (Sakhaeimanesh et al., 1999).

Methods

Mock circulation is shown in Fig. 1. Flow was driven by a servo-controlled piston pump (VSI pump) that compressed the ventricle to simulate the physiological flow. A model of the left ventricle and load was incorporated with the drive unit for testing artificial valves in the aortic position under practical flow and loading conditions. A blood analogue fluid of water-saline solution was contained inside the ventricle chamber and was separated from the piston pump by the polymeric flexible ventricle. All experiments were conducted at a heart rate of 1.2 Hz (72 beats/min) with compliance pressure set at 80/120 mm Hg. DANTEC, two-colour 5 Watt Argon-Ion laser was used to determine the velocity and turbulent components of the valve. A data transmission adapter was specially designed for the system to allow synchronization between the trigger signals of the waveform generator and the arrival time clock register of the encoder. The axial and radial mean velocities, $\bar{U}$ and $\bar{V}$, the r.m.s. of axial and radial fluctuation components, turbulent intensity, $T$, and the cross, $\overline{uv}$, were calculated. More details of mock circulatory system and LDA technique are given somewhere else (Sakhaeimanesh et al., 1996 & 1999).

Figure 1: Diagram of the pulse duplicator used in this study (not in scale), (1) ventricular, aortic and compliance pressure taps; (2) aortic valves; (3) mitral chamber; (4) pump piston; (5) adjustable resistance; (6) mitral valve; (7) electromagnetic flow meter probe; (8) air releaser and air pump; (9) index matching box.
Results

Results of velocity measurements and turbulent shear stress estimations are presented. Velocity measurements were made across the valve in a plane perpendicular to the minor and major outflow of the valve in 19 points.

Acceleration Phase: In mid of the acceleration phase (between 122-127 ms of the cycle) data was processed to find the values of velocities and shear stresses. Graphs of velocity profiles at 0.5D downstream of the valve at cardiac outputs of 3.5, 4.5 and 6.5 l/min are presented in figure 2. At 0.5D downstream jet flow was evident in the major outflow region and a small wake area behind the occluder were observed at all cardiac outputs. In the minor outflow region, velocity profiles were nearly flat and peak velocities were not found in the 0.5D measuring plane. This indicated that flow was less disturbed in the minor outflow region during the early to mid acceleration phase than at the peak systole and during deceleration.

Flow in the region between 1D and 3D were becoming developed turbulent tube flow. Processing of the data at the other sampling windows during the acceleration phase revealed that, as the flow accelerated, the velocity profiles became more organized, particularly in the minor outflow region, until the peak flow condition was reached. The magnitudes of estimated shear stresses were lower than those of peak systole. Peak Systole: Peak systole occurred in the St. Vincent valve at 157 ms of the cycle. Data was processed in a sample window of 5 ms, between 155-160 ms of the cycle. An initial jet flow stage, which was extended to about 1D downstream of the valve, was observed. Velocity profile downstream of the valve at the 0.5D measuring plane consisted of two unequal jets at cardiac output of 6.5 l/min (figure 3). The major jet reached to 2.938 m/s maximum and was more energetic than the smaller jet. At lower cardiac outputs (3.5 and 4.5 l/min), jet flow was not found in the minor outflow region. The shape of the velocity profile was due to minor and major orifice configuration of the valve.

Furthermore, due to low fluctuation of velocities and low velocity gradients, estimated shear stresses were found to be about half of those found in the major outflow region (figure 4). A wake area behind the occluder was also observed in the core of the valve chamber at 0.5D at cardiac output 6.5 l/min. In a natural aorta, this encourages thrombus formation. At the 3D measuring plane, flow became convergent at cardiac outputs of 3.5 and 4.5 l/min. At cardiac output of 6.5 l/min, flow convergent occurred and peak velocity diminished at the 5D measuring plane.

Graphs of shear stress distributions at cardiac output 6.5 l/min are presented in figure 4. Maximum shear stresses of 55, 74 and 82 N/m² were estimated at 0.5D downstream of the valve at major outflow regions at cardiac outputs of 3.5, 4.5 and 6.5 l/min respectively. High turbulent intensities and high velocity fluctuations in the major outflow region of the valve created higher shear stresses than in the area of the minor outflow region beyond the 0.5D. At 3 and 5D downstream of the valve, shear stresses were in the range of 0-16, 0-40 and 0-49 N/m² at cardiac outputs of 3.5, 4.5 and 6.5 l/min respectively.

Deceleration Phase: Mid-deceleration was found to be at 250 ms of the cycle. Results of velocity measurements at 0.5D downstream of the St. Vincent valve at cardiac outputs of 3.5, 4.5 and 6.5 l/min are presented in figure 5.

Velocity profiles in mid-deceleration phase consisted of two asymmetric jets in the major and minor outflow regions and wake area behind the occluder at 0.5D downstream location. Maximum velocities up to 1.528, 1.868 and 2.289 m/s at the larger jet region were found at cardiac outputs of 3.5, 4.5 and 6.5 l/min respectively. Fluctuation of velocities of up to 0.548 m/s created moderate shear stresses up to 55 N/m² at the 0.5D measuring plane at cardiac output of 6.5 l/min.

Uniform velocity profiles were observed at the 5D measuring plane and shear stresses beyond the 0.5D measuring plane were found to be low. Maximum shear stress of 34 N/m² were estimated at cardiac output 6.5 l/min at 3D.
Figure 2: Mean axial velocity profiles at 0.5D downstream of the St. Vincent valve at different cardiac outputs in mid acceleration phase.

Figure 3: Mean axial velocity profiles obtained at three downstream locations of the St. Vincent valve at cardiac output of 6.5 l/min at peak systole.

Figure 4: Shear stress distributions downstream of the St. Vincent valve at peak systole at cardiac output of 6.5 l/min.

Figure 5: Mean axial velocity profiles at 248-253 ms of the cycle, mid deceleration phase, at 0.5D downstream of the St. Vincent valve at different cardiac outputs.

References:


