Retrograde Flow through Bileaflet Mechanical Heart Valves

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Abstract: In vitro experiments were conducted to investigate the time-varying retrograde flow characteristics of 27 mm bileaflet aortic valves. The retrograde flow fields of bileaflet valves range from uniform squeeze flow and regurgitant jet flow fields to flow fields involving complex secondary flows. Stress levels are sufficiently high to cause cell damage or activation in both the squeeze and jet flows. The squeeze occur over a shorter time span but encompass a larger area of flow and potential exposure to more cells. It is speculated that valves exhibiting complex flow patterns have lower incidence of thrombus due to increased washing of the hinge region and valve perimeter cell elements. This process continues until the leaflets are fully closed. Once the leaflets are fully closed, a second source of retrograde flow is the regurgitant jets, which may be important in blood element damage. These jets issue forth from the small openings in the hinge regions and flow with a relatively high velocity on the order of 5 m/s at the orifice of the jet. The high velocity and intrinsically turbulent nature of these jets may impose large shear stresses on the formed blood elements [1]. The retrograde flow fields of bileaflet valves and their clinical implications have not been studied in great detail.

In vitro experiments were conducted to investigate the time-varying retrograde flow characteristics of 27 mm bileaflet aortic valves. Three-component, coincident Laser Doppler Anemometry velocity measurements were obtained facilitating the determination of the 3-D principal stresses in the valve flow fields. Since both the squeeze and regurgitant jet flows are strongly time-varying flows, lucid presentation of the variation of the shear stresses as a function of time was imperative. Animation of the data was essential for extracting the needed information quickly.

Methodology:

The experiments were performed in the Georgia Tech aortic valve in vitro model under physiologic pulsatile flow conditions of 5 l/min mean cardiac output and 30 L/min peak systolic flow rate. Three-component coincident LDA measurements were obtained over a region approximately 90 mm², 1 mm upstream of the valve housings around the hinge region. The mapping was performed with an incremental resolution of 0.127-0.254 mm. A reconfigurable clock was employed to gate pulsatile data acquisition throughout end systole and diastole. Phase window averaging was conducted over several hundred cycles for the generation of mean velocity and turbulence statistics in 20 ms intervals. All data were transit time weighted averaged for velocity bias correction, and low-pass digital filtering was employed to remove high frequency LDA noise if present. A 3-D principal stress analysis was applied to the measured Reynolds stress tensor to identify peak stresses in the flow [2]. A blood analog fluid was used providing a physiologic kinematic viscosity of approximately 3.5 cSt and a refractive index of 1.49.

Animation of the data allowed the investigation of the full temporal characteristics of the flow. Animation was accomplished by importing the experimental data base into CFD post processing graphical data reduction algorithms (Fieldview, Intelligent Light Inc. NJ, USA).

Two bileaflet valves were studied in the course of this investigation: St. Jude Medical, and a prototype design. In addition to the retrograde flow stress levels, the investigation also assessed washout capacity around the valve housings and the potential for thrombus formation around the valve perimeters.

Results and Discussion:

The St. Jude bileaflet valve retrograde flow fields within the hinge regions are characterized by squeeze flow during valve closure, and regurgitant jets after closure. The squeeze flow occurs through the central gap between the two leaflets, and persists for a period starting from the onset of valve closure to the complete closure of the valve. This lasts approximately 40 to 60 ms of end systole. This region of flow encompasses a large cross sectional area of the valve and involves a significant volume of blood. The squeeze flow profile between the leaflets is nearly uniform and resembles a two-dimensional jet with peak velocities reaching 0.6 m/s. The corresponding peak principal normal stresses and maximum shear stresses are 3800 and 800 dynes/cm², respectively. Stress levels are sufficient to potentially cause damage to blood elements considering the close proximity to the valve leaflets.

Significant secondary flow patterns are observed around the perimeter of the valve in the region investigated in this study. These flow patterns are observed around and behind the pivot guards of the St. Jude valve, indicating that substantial washing of this area may occur during both the forward and closing flow phases of the cycle. This may have clinical significance in reducing or slowing the rate of thrombus growth within the hinge regions of this valve. These flow features are illustrated in the vector plots shown in figure 1.

For the St. Jude valve tested, the regurgitant jet flow field is characterized by the presence of three jets. The
major jet originates from the central plane between the leaflets through a gap in the seam between the leaflets and the intersection with the housing. This jet persists throughout diastole and is approximately 1.5 mm in diameter. The peak velocity is roughly 0.8 m/s, with peak turbulent normal and shear stress levels of 4300 and 1800 dynes/cm², respectively.

The other two regurgitant jets are considered to be minor jets as they persist for only 40 ms at early diastole with lower (<50%) velocity and stress levels than in the primary jet. One jet appears to originate from the hinge socket of the valve while the other jet emanates from a gap between the leaflet and housing at roughly 45 degrees from the central seam between the leaflets.

Contrary to the flowfield of the St. Jude valve, the prototype valve is characterized by a uniform squeeze flow pattern occurring within the gap between the two leaflets. The flow field behind the leaflet or adjacent to the housing is relatively stagnant with little or no secondary flow patterns. The squeeze flow occurs over a smaller cross sectional area of the valve than in the St. Jude, and exhibits peak velocity and stress levels which are slightly higher than in the St. Jude valve. The peak velocity is roughly 0.7 m/s with peak turbulent normal and shear stress levels of 5000- and 1800 dynes/cm² respectively.

The prototype valve exhibits a regurgitant jet through each of its hinges. These jets are nearly 2 mm in diameter and persist throughout the retrograde flow phase (late systole and diastole). Figure 2 illustrates the retrograde flow field of the prototype valve in late systole. The uniform squeeze flow between the leaflets and the regurgitant jet issuing from the hinge socket are visible. The regurgitant jet of the prototype valve has velocity and stress levels which are twice that of the St. Jude valve, 1.8 m/s with normal and shear stresses of 10,000 and 3800 dynes/cm².

The lack of significant flow around the periphery of the valve coupled with the higher turbulent stress levels may be important factors in the high rate of thrombus formation observed with the prototype valve design.

Conclusions:

The retrograde flow fields within the hinge region and immediately adjacent to the housing of the St. Jude Medical and a prototype bileaflet valve have been studied. Local turbulent stresses encountered in the squeeze flow regurgitant jet regions of both valves encompass a large volume of blood and may be sufficient to cause blood element damage. The regurgitant jets generally persist throughout diastole.

The St. Jude valve exhibits strong secondary flow patterns around the perimeter and behind the valve leaflets indicating good washout particularly around the pivot guards. These secondary flow patterns may significantly impact the relatively low thrombogenicity of the St. Jude design. In contrast, the prototype valve exhibits higher stress levels and greatly reduced secondary flow field features. Near stagnant flow is observed behind the leaflets and adjacent to the housing throughout late systole and diastole.

References:
