Mechanical Valve Closing Dynamics: Relationship between Velocity of Closing, Pressure Transients, and Cavitation Initiation

KRISHNAN BALA CHANDRAN and SRINIVAS ALURI

Department of Biomedical Engineering, College of Engineering, University of Iowa, Iowa City, IA

Abstract—In this study, the closing dynamics of mechanical heart valves was experimentally analyzed with the valves mounted in the mitral position of an in vitro flow chamber simulating a single closing event. The average linear velocity of the edge of the leaflet during the final 2.065° of the traverse before closing was measured using a laser sweeping technique, and the negative pressure transients at 2 mm from the leaflet inflow surface in the fully closed position was recorded at the instant of valve closure. The cavitation number was computed for the various mechanical valves at a range of load at valve closure. The data were correlated with cavitation bubble visualization previously obtained with the same experimental set up. Cavitation incipience with mechanical valves was found to be independent of the flexibility of the valve holder. For the same loading rate at valve closure, valves with flexible (polyethylene) leaflets were found to close with comparable velocity to those with rigid (pyrolytic carbon) leaflets, but the negative pressure transients did not reach magnitudes close to the vapor pressure for the fluid with flexible leaflets. For the same leaflet closing velocity (and hence the cavitation number), valves with a seat stop or a seating lip in the region of maximum leaflet velocity were observed to cavitate earlier, suggesting that the effect of "squeeze flow" may be an important factor in cavitation incipience.

Keywords—Valve closing dynamics, Occluder tip velocity, Negative pressure transients, Cavitation number, Squeeze flow phenomenon, Occluder flexibility.

INTRODUCTION

Clinical implantation of mechanical valves, even though resulting in a relatively normal life for the patients, suffers from incidences of thromboembolic complications and the requirement of long-term anticoagulant therapy. Over the past 30 years, numerous studies have attempted to relate bulk turbulent stresses distal to the valve in the fully open position, as well as regions of flow reversal and separation with clinically observed thrombus deposition (2,3,6,27,28). Despite design improvements to minimize the turbulent stresses, as well as regions of flow separation, thromboembolic complications with mechanical valves continue to be a significant problem. The bulk turbulent stresses that the formed elements in blood are subjected to during the forward flow phase occur in blood volume moving away from the valves, and hence other causes for thrombus initiation should not be ruled out.

More recently, a number of investigations have concentrated on the closing dynamics of mechanical valves and stresses generated during that phase as a possible factor for thrombus initiation. Several reports have been published on structural failure of valve components, as well as pitting and erosion on the surface of the valve leaflets and housing. Structural failure with mechanical valves have included leaflet fracture (17), and fracture of pivot components and housing (7,8,15,18). Pitting and microcracking observed in the valve components tested in simulators, animal studies, and clinical explantations and the correlation of observed damage with locations where cavitation bubbles have been visualized in vitro suggest that the damage is due to cavitation bubble collapse (16). Since then, numerous reports on cavitation bubble visualization, measurement of velocity of the leaflets at the instant of valve closure, and transient pressure measurements in the vicinity of the leaflets from in vitro experiments have been reported in the literature (4,9,11,12,20–23,25,26,30). Leuer (23) measured the pressure transients at ~2 mm from the inflow surface of the leaflet at the instant of valve closure of Medtronic Hall (MH) valves, and the data showed negative pressure transients close to the vapor pressure of the fluid for a very short duration. He suggested the possibility of cavitation bubble incipience and subsequent collapse as the cause for the presence of pitting and erosion found on the leaflet surface. Graf et al. (11,12) visualized cavitation bubbles near the inflow surface of mechanical valves in a pulse duplicator and correlated the threshold for bubble appearance to peak left ventricular (LV) dp/dt. A ring of cavitation bubbles in the major orifice region of MH valves in the Penn State Electrical Heart have also been reported (9,30). However, in these works,
no attempts were made to measure the pressure transients close to the leaflets or the velocity of the leaflets at the instant of valve closure. Wu et al. (25,26) measured the velocity of the leaflet of mechanical valves at the instant of valve closure and showed that leaflet closing behavior depended on the leaflet and hinge design of the valves. They suggested that the closing behavior of the leaflets may be an important factor in cavitation initiation, and squeeze flow of fluid between the leaflet and the seat create an environment that favors microcavitation inception. Chandran et al. (4) and Lee et al. (20–22) performed a detailed study on the pressure transients close to the leaflet of mechanical valves and correlated the regions of low pressure transients with the presence of cavitation bubbles. The experiments were performed in a flow chamber similar to that of Leuer (23) by simulating a single closing event of mechanical valves. The cavitation bubbles visualized with a MH valve, indicating a ring of bubbles around the seat stop in the major orifice region in these experiments, were qualitatively similar to those obtained in pulse duplicators and electrical hearts (9,11), even though no quantitative comparison was attempted. Hence, the validity of using a single closing event for these studies was established. Since the peak value of LV \( \frac{dp}{dt} \) occurs only after the valve is fully closed, they defined a loading rate during valve closure \((\frac{dp}{dt})_l\) and correlated increased negative pressure transients and intensity of cavitation bubbles with increased loading rate at valve closure. Their study also suggested that squeeze flow mechanism, in addition to the presence of negative pressure transients, is important for cavitation incipience. The flexibility of the occluder was shown to reduce the magnitude of the negative pressure transient and no cavitation bubbles were present (4,21). On the other hand, the flexibility of the valve holder did not affect the pressure transients or presence of bubbles (20), and these results were confirmed by Wu et al. (25), who showed that the velocity of impact did not alter with the flexibility of the valve holder. Even though the whole valve assembly will move during the ventricular pressure rise with flexible valve holders, the pressure transients measured very near the leaflets on the inflow side will depend on the relative motion between the valve housing and the leaflets. Hence, it is not surprising that flexibility of the housing will not be a dominant factor in cavitation initiation.

The subject of the present study is on the analysis of closing dynamics of mechanical heart valve prostheses and its correlation with cavitation initiation. Measurements on velocity of the occluder at the instant of valve closure, and the negative pressure transients distal to the occluder at the instant of valve closure, were obtained at various loading rates during valve closure \((\frac{dp}{dt})_l\) in the same experimental set-up simulating a single closing event of mechanical heart valves. The measurements were repeated with rigid and compliant valve mounts to delineate the effect of holder compliance on the closing dynamics. The data were compared with photographs of cavitation bubbles, if present, at the corresponding loading rates. The effect of valve design, presence of seating lip/seat stop interacting with the closing leaflet, and the flexibility of the occluder material on the closing dynamics of the mechanical valves are discussed.

**EXPERIMENTAL METHODS**

**Flow Chamber and Loading Rates at Valve Closure**

The experimental set-up, simulating a single closing event of mechanical valves in the mitral position, has been described in detail elsewhere (4,20–22). Briefly, the valve to be studied is sandwiched between two rectangular valve holders and incorporated between the ventricular and atrial flow chambers (as shown in Fig. 1). The large atrial chamber is vented to the atmosphere and maintained at a constant atrial pressure of between 5 and 7 mm Hg during valve closure. The valve is initially in the fully open position and starts to close by the pressure applied to the fluid in the ventricular chamber by activating the pneumatic valve. The fluid used in the experiments was a glycero1 solution with a viscosity coefficient of 3.5 cP and a density of 1.1 g/ml at room temperature. After filling with the blood analog fluid, the fluid was left in the chamber for 24 hr before bubble visualization, so that any trapped air bubbles will migrate to the free surface and will not interfere with the cavitation bubble visualization. However, no attempts were made to degas the fluid or to measure and control its conductivity.

The loading rate that the occluder is subjected to during closure is the pressure difference between the ventricular and atrial chambers during the time that the occluder is in the closing motion (~35 msec after the initiation of pressure rise in the ventricular chamber). The ventricular chamber pressure rise is recorded with a Millar pressure transducer placed at ~3 cm from the valve seat. The instant of valve closure is indicated by a large positive pressure spike from another Millar pressure transducer placed at ~3 mm from the valve seat (Position B in Fig. 1) on the ventricular side. The frequency response of the Millar transducer and the signal conditioning system was 10 kHz, and the data were recorded using CODAS data acquisition system at a rate of 2 kHz. Since the data from the Millar transducer was used only to determine the rate of pressure rise during the valve closure, this rate of digitization was deemed adequate. The average pressure rise in the ventricular chamber is computed from the signals recorded by the pressure transducer placed at 3 cm from the valve seat (Position A in Fig. 1). We used a transvalvular (ventricular minus atrial) pressure rise rate averaged during the valve closing period as an index of loading rate, since the driving