THE CLOSING BEHAVIOR OF THE MECHANICAL HEART VALVE IN A TOTALLY ARTIFICIAL HEART

Hwansung Lee, Tomonori Tsukiya, Akihiko Homma, Yoshiyuki Taenaka, Eisuke Tatsumi, Hisateru Takano

Department of Artificial Organs, Research Institute, National Cardiovascular Center
5–7–1 Fujishiro–dai, Suita, Osaka 565–5865, JAPAN

ABSTRACT

The cause of cavitation in mechanical heart valves was investigated in both 25 mm Björk–Shiley and 25 mm Medtronic Hall monostrut valves. The closing event of these valves in the mitral position were simulated in an electrohydraulic total artificial heart of stroke volume 85 ml. Tests were conducted under physiologic pressures at heart rates from 60 to 90 beats/min with cardiac outputs from 4.5 to 7.5 L/min, respectively. The leaflet closing behavior was measured by a CCD laser displacement sensor. The closing behaviors were investigated with various atrial pressures. The greater the amount of atrial pressure, the shorter the closing duration of both valves. The maximum closing velocity of the Medtronic Hall monostrut valve ranged from 0.8 to 0.9 m/s, and the Björk–Shiley monostrut valve ranged from 0.73 to 0.78 m/s. In both valves, the maximum closing velocities were less than the reported cavitation thresholds.

INTRODUCTION

Since the discovery in the 1980s of erosion pit–induced, cavitation–causing fractures in implanted mechanical heart valves, it has been widely studied in mechanical heart valves[1-2]. Before impact, fluid in the gap space between the housing and the approaching leaflet is squeezed, resulting in a pressure drop. If the pressure drop falls below the vapor pressure of the liquid, cavitation bubbles must occur. When cavitation bubbles flow onward into a higher–pressure region, rapid collapse of these bubbles may generate a high–speed micro-jet[3]. The collapsing cavitation bubbles generate high pressure. If the bubbles collapse near the material surface, it may cause damage to the surface of the mechanical heart valves.

In previous studies, we have shown that cavitation erosion on the valve surface increases with an increase in the closing velocity[4]. Since the maximum closing velocity of the leaflet contributes to the occurrence of squeeze flow, it was used as an index for the cavitation threshold in our study. We investigated the hydrodymanic characteristics of the Medtronic Hall monostrut and Björk–Shiley monostrut valves in an electrohydraulic total artificial heart. The maximum closing velocity of the leaflet was investigated as a possible cause of cavitation in an electrohydraulic total artificial heart.

MATERIALS AND METHODS

An electrohydraulic total artificial heart that was developed by the National Cardiovascular Center in Japan (NCVC) consists of diaphragm type blood pumps, an actuator, and a controller. The actuator is connected to both blood pumps by a flexible tube. The flexible tubes are filled with silicon oil. An electrohydraulic total artificial heart works by silicon oil driving the blood pump to one side through an inverse rotation of the impeller, and to the other side through a reverse rotation of the impeller.

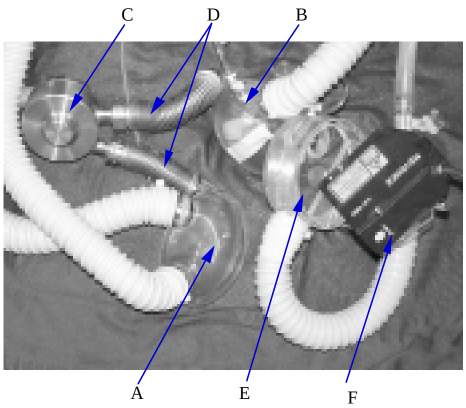

Figure 1. An electrohydrauic total artificial heart
A: Left blood pump, **B:** Right blood pump, **C:** Actuator, **D:** Flexible tube, E: Acrylic chamber, F: CCD laser displacement sensor

A CCD laser displacement sensor (LK–080, KEYENCE) with a resonance frequency of 1 kHz was used for measuring the opening and closing behavior of the leaflet. The chamber was constructed from acrylic resin for optical access, and the laser sensor was placed on the upper side of the acrylic chamber (Figure 1). In order to measure the leaflet motion, a triangulation method of laser light was used. The valves were mounted in the mitral valve position. The electrohydraulic total artificial heart was connected to the mock circulatory loop tester.

To examine the effects of the atrial pressure on the closing behavior of the valve, atrial pressure was changed from 10 to 30 mmHg, and aortic pressure was fixed at 100 mmHg. The blood pumps were run at a heart rate of 60, 70, 80 and 90 beats/min, and the cardiac outputs were 4.5, 5.5, 6.4 and 7.5 L/min, respectively.

RESULTS

At the heart rate of 80 bpm with aortic pressure of 100 mmHg, the closing behavior of Björk–Shiley valve and Medtronic Hall valve leaflets with various atrial pressures is shown in Figure 2 and 3, respectively. The vertical axis refers to the opening angle of the leaflet with radians. For example, 1.2 on the vertical axis is an opening state, and 0 is a closed state.In both valves, the smaller the atrial pressure, the shorter the closing duration was.

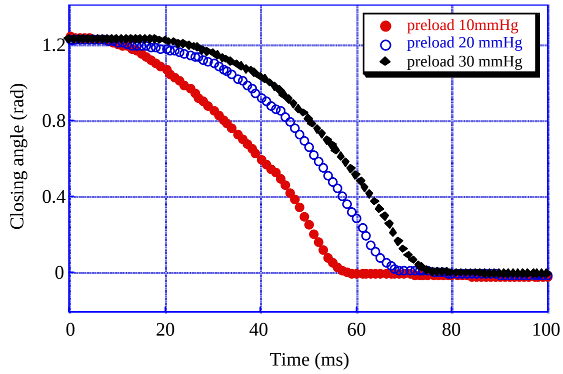

Figure 2. Closing movement of Björk–Shiley monostrut valve at various of atrial pressure with aortic pressure of 100 mmHg

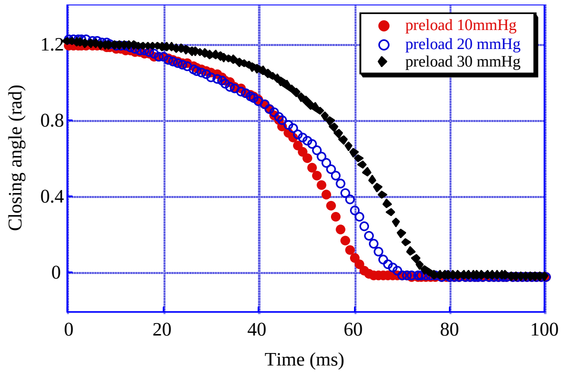

Figure 3. Closing movement of Medtronic Hall monostrut valve at various of atrial pressure with aortic pressure of 100 mmHg

The maximum closing velocities of the leaflets as a function of cardiac output are shown in Figure 4. The maximum closing velocity of the valve was calculated from twenty cycles. The closing velocities increased with an increase in the cardiac output. As a whole, the closing velocities of the Medtronic Hall monostrut valve were faster than the Björk–Shiley monostrut valve. The maximum velocities of the Björk–Shiley monostrut valve ranged from 0.73 to 0.78 m/s, and the Medtronic Hall monostrut valve ranged from 0.8 to 0.9 m/s.

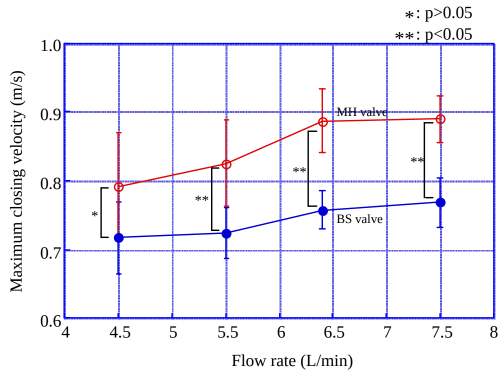

Figure 4. The maximum closing velocity with an atrial pressure of 10 mmHg and an aortic pressure of 100 mmHg

DISCUSSION

Cavitation bubbles are generated by squeeze flow and water hammer effect, which occur just before closure of the leaflet. As shown in Figure 2 and 3, at the exact moment of closure, the leaflet was accelerated and its maximum velocity was reached. And, the leaflet was decelerated right before being closed by squeeze flow. In previous studies, it was assumed that squeeze flow, occurring just before valve closure, causes the pressure drop that supports cavitation formation. However, there are no experimental results that show the squeeze flow velocity reaching the cavitation threshold. In our tests, both values of maximum closing velocities were lower than the reported cavitation thresholds of Graf[5]. In our testing, the maximum closing velocities of the Björk–Shiley and Medtronic Hall valves were lower than that of cavitation threshold. From this fact, we suggest that cavitation bubbles do not occur in a mechanical heart valve of an electrohydraulic total artificial heart.

CONCLUSION

The maximum closing velocity of the Medtronic Hall monostrut valve is faster than that of the Björk–Shiley monostrut valve. In view point of cavitation, the Björk–Shiley monostrut valve was safer than the Medtronic Hall monostrut valve in our electrohydraulic total artificial heart.

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