Yonsei Medical Journal
Vol. 35, No. 1, 1994

In Vitro Pressure Drop Comparison between Two Mechanical Valve Prostheses

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An hemodynamic evaluation of two mechanical heart valves is presented. A tilting disc valve and a bileaflet valve were incorporated in a mock circulatory system which consists of a closed flow loop with a pneumatically driven flexible diaphragm to simulate the physiologic pulsatile flow. Comparisons between the valves were made on the aortic pressure, ventricular pressure, as well as mean pressure gradient at a systolic duration of 45% and a heart rate of 90 beats per minute. The results showed that the tilting disc valve has higher ventricular pressure and mean pressure gradient than that of the bileaflet valve. This indicates that the tilting disc valve has higher transvalvular flow resistance and enery loss than that of the bileaflet valve. From this study it is demonstrated that the mock circulatory system can be a very useful device to evaluate the prosthetic heart valves in vitro.

Key Words: Mock circulatory system, prosthetic heart valve, mean pressure gradient

Tilting disc valves and bileaflet valves are major mechanical valve prostheses in common clinical use. Representative valves from two major classifications are shown in Fig. 1 and from their designs it is apparent that each will yield significantly different flow fields and pressure gradient. A knowledge of the flow charateristics generated by the valves is useful to understand the valve performance in a variety of situations. For example, valve prostheses should open with minimal transvalvular pressure drop to reduce the pressure loss, thus measurement of the pressure drop across the valve is useful to estimate the energy loss of the valve. Mechanical valve prostheses also should close with minimal back flow. Measurements of flow dynamics downstream from the valve will provide useful information for the amount of regurgitation of the valve.

The advantage of performing an in vitro study is that the fluid dynamic measurements, transvalvular pressure gradient, percentage of regurgitation, and velocity profile can be performed accurately with sophisticated measurement techniques under rigidly controlled conditions. A mock circulatory system is designed to replicate the physiological pulsatile flow in the human circulatory system. All the detailed characteristics of the human circulatory system, such as the distributed compliance and resistance of the blood vessels, the rheological characteristics of the blood flow with formed elements, and proteins, and the feedback characteristics of the autonomic nervous system, cannot be duplicated accurately in an in vitro setting. However, evaluation of valves of various geometries under controlled experimental measurements will yield information on the relative merits of one geometry over another.

Prosthetic valves have been studied extensively and previous quantitative work on the flow characteristics of prosthetic valves has

Received October 27, 1993
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This research was supported by Faculty Research Grant of Yonsei University (1992).
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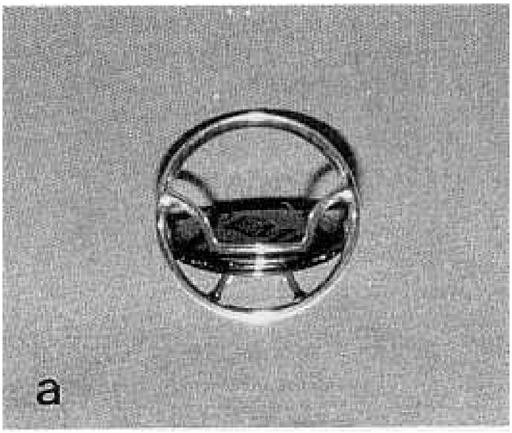

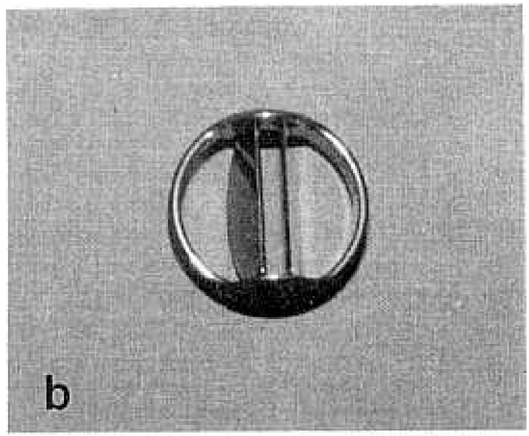

***Fig. 1.** Photographs of major mechanical valves*
(a) Tilting disc valve (Bjork-Shiley [R]) (b) Bileaflet valve (St. Jude Medical [R])

been summarized by Rashtian *et al.* (1986). Yoganathan *et al.* (1986) measured turbulent shear stress in the vicinity of aortic heart valve prostheses by the laser Doppler anemometer system to understand the turbulent shear fields created by different valve designs. Chandran *et al.* (1989) compared flow dynamics past a polyurethane trileaflet valve with that of a bioprosthetic heart valve in vitro. They reported velocity profiles and the turbulent shear stresses distal to the valves using laser Doppler anemometry

This work presents transvalvular pressure gradient, aortic pressure, and ventricular pressure of the two basic mechanical valve types, bileaflet valve and tilting disc valve. To study the fluid dynamics through the prosthetic valve in vitro, a mock circulatory system was developed and the resulting data from this were analyzed.

EXPERIMENTAL METHODS

Elements of the mock circulatory system simulating physiological flow are shown schematically in Fig. 2. The flow system consists of the diaphragm pump, a flexible atrium, a compliance box, resistance clamp, rotameter, and reservoir. The height of the system is 1. 3 m and the inside diameter of the connecting tube is 25.4 mm.

The fluid in a closed-loop is driven by a diaphragm pump connected to a pneumatic driver. The pneumatic driver is designed to control the pump rate and systolic duration. The maximum pump output of the diaphragm pump is 7 L/min. By adjusting the air pressure in the compliance box and resistance clamp, physiologically realistic pressure and flow rate pulses could be obtained. Fig. 3 shows the mock circulatory system designed for the prosthetic valve evaluation. The blood analog fluid used in the system consisted of a glycerol solution (36% by volume glycerine in distilled water) with a viscosity coefficient of 3.5 cP and a density of 1.10 g/cc at the room temperature in which the experiments were performed.

The valves to be tested were mounted in the aortic position in the circulartory system. Two mechanical valves, a St. Jude Medical[R] bileaflet valve and a Bjork-Shiley[R] tilting disc valve (Fig. 1) were used in this study. The tissue annulus diameter (sewing ring diameter) of this valve is 27 mm.

An electromagnetic flow meter which is a part of the Bio-pump[R] (Biomedicus, USA) was used to measure the mean flow rate of the system. Three fluid filled pressure transducers connected to taps on the inflow port, outflow port, and center of the ventricle were used to monitor pressure pulses. The pressure data signals were monitored by a Simultrace Recorder[R] (Electronics for Medi-

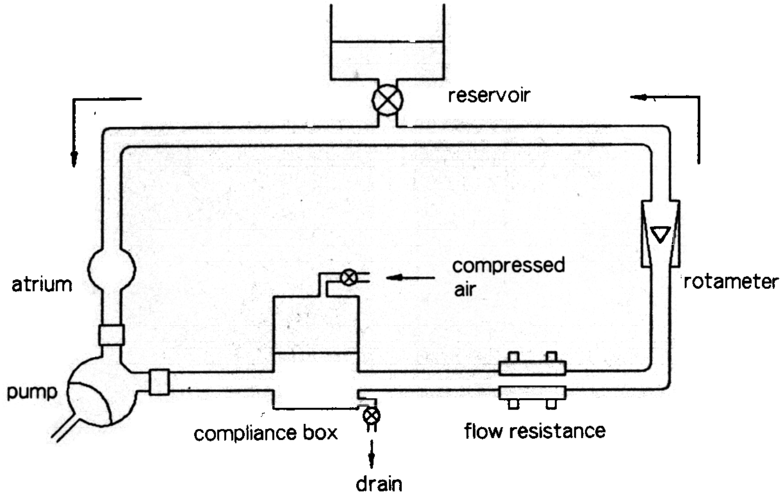

***Fig. 2.** Schematic view of the mock circulatory system.*

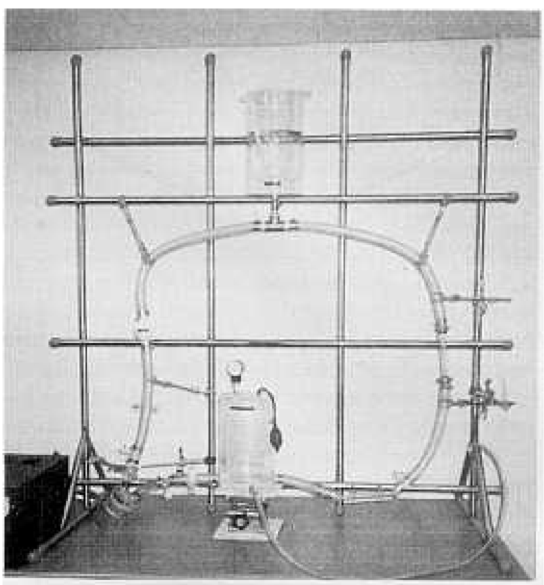

***Fig. 3.** Mock circulatory system designed in this study.*

cine, USA) and digitized on line and the data were stored in an IBM PC computer. In these experiments the systolic duration was set at 45% of the cardiac cycle and signals from 5 consecutive cardiac cycles were ensemble averaged.

The pressure signal data from the aorta and ventricle were used to monitor the instantaneous pressures of each position and calculate the pressure gradient between them. The mean pressure is computed between the time that the ventricular pressure exceeds the aortic pressure to the time that the aortic pressure exceeds the ventricular pressure.

RESULTS

The pressures were measured at a systolic duration of 45% and heart rate of 90 bpm. The left atrial pressure was maintained at 15 mmHg during the experiment by controlling the resistance of the system. The cardiac output of the pump was set at 5 L/min by adjusting the driving pressure of the pneumatic driver. At these conditions typical ensemble-averaged instantaneous ventricular and aortic pressures were estimated for both the Bjork-Shiley[R] tilting convexo-concave disc valve (BS) and the St. Jude Medical[R] (SJM) valve prostheses, and the results are shown in Fig. 4. The solid line represents the aortic pressure and the dashed line represents the ventricular pressure. It shows that the ventricular pressure has larger variations than

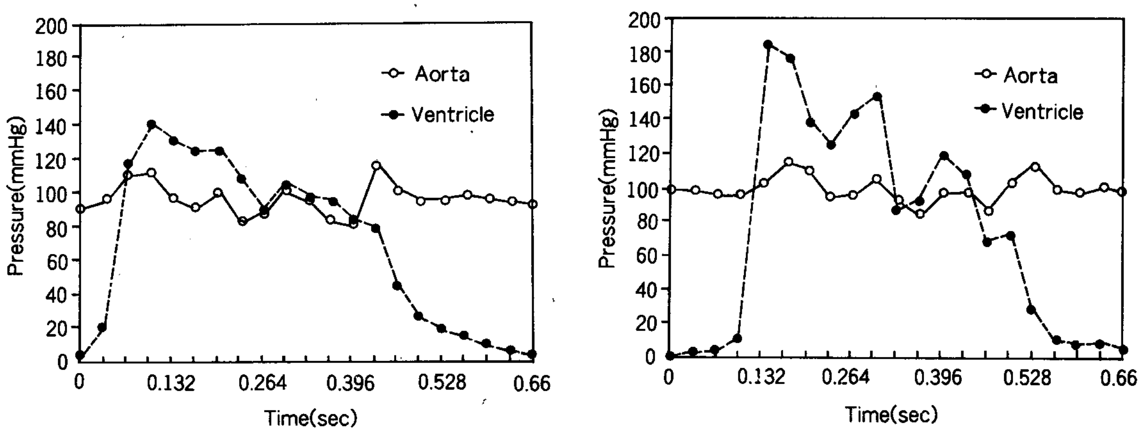

Fig. 4. Typical ventricular and aortic pressure flow signals.

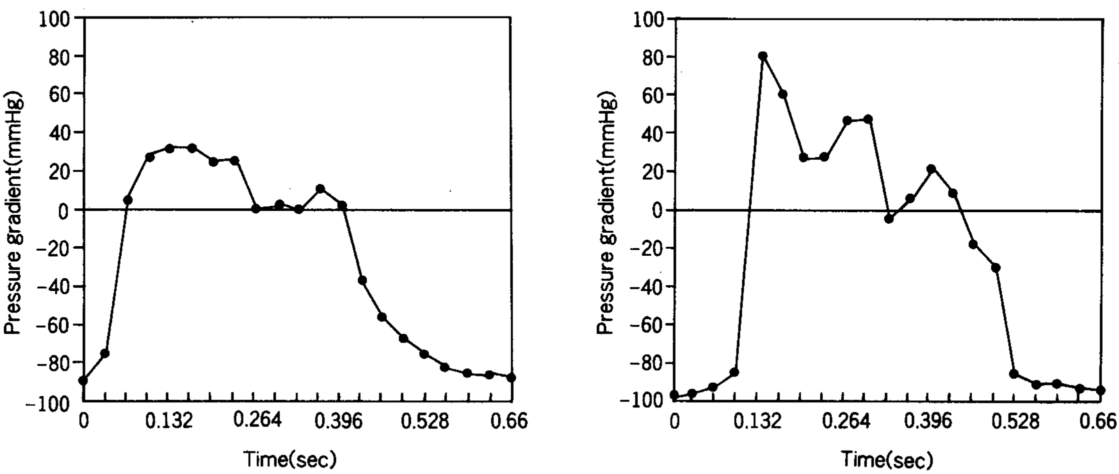

Fig. 5. Mean pressure gradient between ventricle and aorta.

the aortic pressure for both BS and SJM. Due to the rigidity of the flow chamber and flow tube, the pressures measured in this system have larger fluctuations than that of the human heart. The ventricular pressure of BS has a higher peak pressure than that of SJM. In addition the difference between aortic pressure and ventricular pressure for BS is greater than that of SJM during systole.

The pressure gradient between aortic pressure and ventricular pressure can be estimated by subtracting the aortic pressure from the ventricular pressure, which is shown in Fig. 5. As can be observed, the pressure gradient of BS is larger than that of SJM during systole. Comparisons of the mean systolic pressure gradient and mean diastolic pressure gradient for BS and SJM are shown in Table 1. They are estimated by averaging the pressure gradient above the zero gradient (mean systolic pressure) and also below the zero gradient (mean diastolic pressure). In the case of mean diastolic pressure gradient there is little difference between BS and SJM but the mean systolic pressure gradient of BS is much greater than that of SJM.

Table 1. Comparison of mean pressure gradients (mmHg) for the mechanical valves

	Systole	Diastole
St. Jude	15	74
Bjork-Shiley	33	80

DISCUSSION

In this study a hemodynamic comparison of a bileaflet valve (St. Jude Medical[R]) with a tilting disc valve (Bjork-Shiley[R]) is presented. The experiments were performed in a mock circulartory system designed to simulate physiologic pulsatile flow. Comparisons were made of the aortic pressure, ventricular pressure, transvalvular pressure gradient, mean systolic pressure, and the mean diastolic pressure. The pressures measured are quite different from that of the human heart. It is due to the fact that the mock circulatory system is constructed by the rigid chamber and PVC tube. Even though the compliance chamber is included to compensate for the rigidity of the system, the rigidity still remained all through the flow system.

The transvalvular pressure gradient of each valve can be estimated from the difference between the aorta and ventricle. Because the shapes of the ventricle and the aorta are different from that of the human heart, the flow resistance and energy loss of the system in this study are greater than that of the human heart. This creates a large pressure gradient between the ventricle and aorta for both SJM and BS.

The estimated mean systolic pressure gradient of BS is greater than that of SJM. This indicates that the energy loss of SJM is smaller than that of BS. Chandran (1986) measured the mean systolic pressure drop of the tilting disk and bileaflet mechanical valves in vitro. The flow rate of that study was 6 L/min and the valve size (tissue annulus diameter) was 27 mm. He reported a mean systolic pressure drop of 6 mmHg for the bileaflet valve and 6~8 mmHg for the tilting disk valve. These measurements are quite different from that of this study due to the different experimental conditions and elements of the system. However it is agreed that the pressure drop of the tilting disk valve is higher than that of the bileaflet valve.

An evaluation of the tilting disk valve and bileaflet valve by using the mock circulatory system has shown that it provides useful hemodynamic information for the valves in vitro. More study is required in the future using the sophisticated flow meter to record the instantaneous flow rate of the system. It makes it possible to calculate the percent regurgitation as a function of flow rate. The flow dynamic characteristics in the mock circulatory system do not simulate that of the human blood circulatory system completely. However it provides comparative data of each valve under controlled experimental conditions on the relative merits of one geometry over another. Such in vitro compartive studies also can be exploited to achieve design changes to improve fluid dynamic charateristics of the prosthetic valves. This system also can be used to evaluate the total artificial heart or ventricular assist device in vitro under various hemodynamic conditions.

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