Echocardiographic Evaluation of the Stent Mounted Aortic Bioprosthetic Valve in the Mitral Position

In Vitro and In Vivo Studies

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SUMMARY Echocardiograms were performed on 20 clinically stable patients following mitral valve replacement with glutaraldehyde-preserved porcine aortic heterografts and three patients with antibiotic sterilized aortic homografts mounted in the mitral position. Such valves were evaluated in a test chamber at varied flow rates resulting in improved understanding of movements seen with the echocardiogram in vivo. The technique for recording the valvular stent and leaflets is described and a method for measuring several parameters is demonstrated. Initial diastolic slope averaged 2.4 ± 0.5 cm/sec (range 1.9 to 3.3 cm/sec). Left ventricular outflow tract measured from the anterior portion of the stent to the interventricular septum averaged 1.5 ± 0.5 cm at end-diastole and 1.3 ± 0.6 cm at end-systole. Leaflet excision averaged 1.5 ± 0.3 cm (with a range from 1.0 to 2.1 cm). The ratio of internal to external stent diameters averaged 0.66 ± 0.05 (with a range from 0.56 to 0.74).

Heterograft.1-6 Thromboembolism after the initial postoperative period has been low.1-6 Persistence of this favorable experience over the next several years will likely lead to more widespread use of this valve.

In recent years a large number of patients have received bioprostheses in our hospital. For this reason, we sought to use noninvasive techniques to provide a better understanding of valvular function. Ultrasonic studies were performed in a series of clinically stable patients with the stented porcine heterografts and homografts in the mitral position. An in vitro ultrasonic study suggested the origin of each echo component and improved the understanding of the movements seen on the in vivo echocardiogram. This report describes the ultrasonic representation of the normal valve.
Heterografts that the angle protractor is seen on top of the apparatus. An ultrasonic transducer is mounted in the attached port on the left.

Methods

In Vitro Evaluation

The valve test chamber measured 21.5 x 15 x 11.5 cm (L x W x D). It was constructed of 6.35 mm plexiglass. A commercially available 13 mm active diameter ultrasound transducer (Smith Kline Instruments Co. T-10) was mounted in one end. The chamber was fabricated by the Division of Research Services, Biomedical Engineering and Instrumentation Branch, NIH. It contained an inner circular well, approximately 14 cm in diameter and a central baffle in which prosthetic valves of various sizes could be mounted (fig. 1). The central baffle could be rotated within the inner well so that the angle between the axis of the valve and the ultrasound beam could be varied. The central baffle was rotated until the optimum ultrasonic study of the heterograft was obtained (fig. 2). While recording the echocardiogram at this angle, stroke volumes were varied from 15 to 100 ml (fig. 3). Inlet and outlet ports on each end of the chamber were used to connect the chamber to a pulsatile flow apparatus. The pulsed flow activated the motion of the valve leaflets. Pulsatile flow of a saline solution through the valve test chamber was obtained using a Harvard Respirator Pump (Model 607D) after removal of the one-way inlet flow valve. Volume of flow per stroke and the number of strokes per minute were varied by varying pump volume and speed. The pressures on each side of the valve in the test chamber were controlled by the height of appropriate reservoirs.

Ultrasonic studies from the valve chamber were obtained with a Smith Kline Instruments Co. Ekoline 20 ultrasonoscope interfaced with a Honeywell 1856 visicorder.

In Vivo Evaluation

In vivo studies were obtained with the Ekoline 20 ultrasonoscope and recorded on either the Honeywell 1856 or the Electronics for Medicine DR8 strip chart recorder. Patient studies were performed with a C-11 Smith Kline Instruments transducer with a 13 mm active diameter and an acoustical lens providing beam collimation to 5 cm which was pulsed 1000 times/sec with a frequency of 2.25 MHz. Echocardiograms were performed on twenty clinically stable patients, aged 37–59, 20 to 38 months after mitral valve replacement with the glutaraldehyde-preserved porcine aortic heterograft. These patients were selected for proximity to the medical center as well as clinical stability and are not a consecutive series. Similar ultrasonic studies were performed on three clinically stable patients who had received mitral valve replacements with antibiotic sterilized homograft aortic valves premounted on rigid titanium stents 36–38 months prior to this study. Since the valve was sewn into the mitral annulus, the usual transducer location and angulation used for recording the normal mitral valve were

![Figure 1. Water bath testing chamber. Inflow tubing in the foreground. Heterograft valve in the baffle within the central circular well is shown. A rotating indicator of valve position with protractor is seen on top of the apparatus. An ultrasonic transducer is mounted in the attached port on the left.](image1)

![Figure 2. In vitro echocardiogram (center) and photographs of a porcine heterograft aortic valve within the test chamber. The left panel shows the valve closed in systole and the right panel shows the valve open in diastole. Arrows indicate correspondence of the recorded echocardiographic signals and the proposed origin of these echoes on the heterograft. The photographs are oriented to indicate that the transducer would be at the top of each panel with the sound beam passing through the right half of the valve in each condition. A stroke volume of 100 cc was used to produce this maximal valve opening.](image2)
used to record the heterograft. Holding the transducer in the third or fourth intercostal space at the left sternal border with a mild superomedial angulation recorded the aorta and left atrium in most patients. After recording these structures, slight inferolateral angulation brought out the dense echoes of the stent along with the interventricular septum anterior to the stent and the left atrial or left ventricular posterior wall posterior to the stent. Moving the sound beam down from the aorta to the mitral area in this manner showed the continuity of the posterior wall of the aorta with the heterograft stent (fig. 4). High coarse gain, low reject and high damping settings were usually necessary to optimally record the weak echoes from the valvular tissue within the stent. Placement of the transducer 2 to 3 cm to the left of the left sternal border, with medial angulation, usually brought out the valvular tissue in technically difficult cases. Each record was measured by three observers. Figure 5 illustrates the method of measurement. The parameters observed were as follows:

A) Maximum leaflet excursion from the closed (systolic) to open (diastolic) position (fig. 3). In order to standardize the measurement of leaflet excursion, maximum excursion was only measured when both portions of the stent were simultaneously recorded.

B) Initial diastolic posterior slope of the valve. Consistent early diastolic (E-F) slopes of the leaflets were unobtainable in many records due to vibration of the leaflets. In the records without significant leaflet fluttering the E-F slope of the leaflets and valve stent were virtually identical and since the stent slope was easily measured in all cases, only this value was tabulated.

C) The external and internal diameters of the stents were determined in each record as indicated for the in vitro study (figs. 2, 3, 5). Secondary reverberations or ringing around the dominant echoes of the stent were eliminated by decreasing the damping control or increasing the reject on the Smith Kline Ekoline machine. In order to safeguard against gross error in beam orientation, we tabulated measurements made only on portions of each patient record in which measured external diameter agreed within a few millimeters of the known stent diameter. After determining the external and

**FIGURE 3. Top panel** Corresponding echocardiogram (right) and heterograft valve. The arrows indicate the proposed origin of the echocardiographic signals from the valve. Note that only one leaflet of the valve opens when a stroke volume of 15 cc/diastole was used. **Bottom panel** Corresponding echocardiogram and photograph of the heterograft valve in vitro. Note the larger excursion of the top cusp and some movement of the bottom cusp when the stroke volume was increased to 50 cc. Both the lack of opening of the third cusp and the change in echocardiographic pattern can be recognized by comparison of the top and bottom panels. Compare with figure 2.

**FIGURE 4. Ultrasonic M-mode sector scan with the transducer near the left sternal border showing the continuity of the aortic posterior wall with the heterograft stent and the left ventricular outflow tract between the anterior portion of the stent and the interventricular septum. Stent motion and heterograft leaflet and native aortic leaflet motion are also shown.** (The electrocardiogram is recorded above.) Note the changing pattern of recorded echoes from the valve stents and leaflets as the sound beam is moved through the valve. AoL = aortic leaflets; HL = heterograft leaflets; IVS = interventricular septum; LA = left atrium; LVPW = left ventricular posterior wall; MHS = mitral heterograft stent.
internal diameter of a technically satisfactory study, the ratio of internal to external diameter was calculated.

D) The left ventricular outflow tract dimensions. While the interventricular septum, mitral heterograft valve and left ventricular posterior wall were recorded, the distance from the mitral heterograft valve to the left side of the interventricular septum was measured at end-diastole and end-systole (fig. 5). The end-diastolic measurement was made immediately before the stent first began its anterior movement and the end-systolic measurement was made coincident with the end of the T-wave on the ECG (fig. 5).

Results

In Vitro

Optimal recording of the valve stents and leaflets occurred when the ultrasonic beam intersected the plane of the valve stent at an angle of 30°. Optimal transducer angulation relative to the plane of the heterograft stent caused the relatively broad ultrasonic beam to intersect the circular stent at two separate sites. This resulted in the recording of two separate and parallel bands of echoes. If the transducer was not properly aligned, only a single band of echoes was recorded from the near or far portion of the stent. The in vitro echocardiogram showed two strong and distinct parallel bands of echoes from the far and near portions of the circular stent of the valve. While each band of echoes measured 3–5 mm in thickness, the transverse diameter measured from the outer surface of one band to the outer surface of the other band measured 30 mm (fig. 2). These measurements corresponded to the actual diameter of the stent which measured 31 mm (fig. 2). This transverse diameter corresponded to the external diameter of the seated valve and not to the diameter of the sewing ring which extended laterally a few millimeters around the valve stent. Only slight movement of the stent echoes was seen and was caused by movement of the supporting structures of the water bath.

Within the two bands of dense echoes which represented the valve stent, finer echoes were seen to separate abruptly with the onset of pulsed flow, remain apart during this flow and rapidly merge together at the end of the flow. The movement of these finer echoes coincided with the movement of the tissue leaflets observed in the water bath (fig. 2). As the stroke volume increased, the full extent of leaflet excursion was noted to increase progressively on both direct observation and ultrasonic study. Figure 3 shows photographs and simultaneous echocardiograms of the valve at two different stroke volumes. Numerous random ultrasonic signals were encompassed by the opened valve leaflets at the higher flow states (fig. 2). These signals were reflected from tiny bubbles caused by the turbulent flow. Figure 3 shows the irregular and variable shape of the valve orifice at the different flow rates. With clockwise rotation of the valve in the plane of the stent, it was noted that when the upright portion of the stent used for commissural support was placed in the path of the sound beam, obliteration of all leaflet or any subsequent echoes occurred, i.e., uprights at 12, 4, and 8 o'clock positions with the beam approaching 12 o'clock. When the valve was turned to permit the sound beam to enter the near side of the stent between two of the three upright projections, only the one leaflet suspended between these two uprights was recorded, i.e., uprights at 6, 10 and 2 o'clock positions. When the valve was turned to place the uprights in the 11, 3 and 7 o'clock positions, then two of the three leaflets could be recorded (figs. 2, 3).

In Vivo

Unlike the in vitro echocardiogram which showed virtually no motion of the echoes representing the valve stent, the two bands of the valve stent attached to the mitral annulus exhibited considerable parallel motion in vivo. During systole, the stent echoes moved anteriorly (toward the chest wall) while during diastole they moved posteriorly. Within these strong stent echoes, weaker signals were seen to separate abruptly at the beginning of diastole and merge together at the onset of systole. These movements were identical to the signals recorded from the tissue leaflets in the water bath. They represented valve leaflets opening in diastole and closing with systole. The excursion of the heterograft aortic leaflets was similar to orthotopic aortic leaflets and was considerably less than the excursion of the native mitral valve tissue. Figure 5 shows the echocardiographic pattern of the normally functioning stented heterograft. This pattern is almost identical to that from the normally situated aortic valve except that the valve leaflets are open during diastole. Maximum leaflet excursion averaged 1.5 ± 0.3 cm with a range of 1.0 to 2.1 cm for these patients. The diastolic slope was taken after leaflet opening. At the time of leaflet motion the stent was not moving, and there was a smooth
transition from this end-systolic plateau to the rapid posterior stent motion which occurred during ventricular filling (fig. 5). At the time of leaflet closure the stent also reached a plateau and no abrupt movements were noted. The average diastolic stent slope was 2.4 ± 0.5 cm/sec with a range of 1.9 to 3.3 cm/sec. This slope was independent of heart rate which ranged from 55 to 122 (r = 0.47).

There was a narrow range of values for external stent diameter since there has been a narrow range of stent sizes used in adult patients. Internal diameter, usually judged by proximity to the leaflets, was measured to assess the proportion of the visualized area available for flow in the absence of thrombus or other restriction of leaflet motion (fig. 5). The mean ratio of internal to external diameters for the control series of 20 heterograft patients was 0.66 ± 0.05, with a range of 0.56 to 0.74. The technique for recording the homograft valve, the ultrasonic appearance and measurements were within the ranges given for the heterograft valve. (See table 1.)

The interventricular septum in the area of the left ventricle was well recorded in 16 of the 20 patients with heterografts and in the three patients with homografts. Eight patients showed definite paradoxical septal motion, seven showed abnormal but not paradoxical septal motion and four showed normal motion. As a result of the abnormal systolic septal motion, the outflow tract did not narrow during ejection in most patients. This left ventricular outflow tract measurement averaged 1.5 ± 0.5 cm with a range of 0.8 to 2.3 cm at end-diastole and 1.2 ± 0.5 cm with a range of 0.5 to 2.2 cm at end-systole.

Comparison of heterograft and homograft valves showed no consistent differences.

Discussion

The in vitro study of stent mounted valves illustrated maximum visualization of the leaflet and opening excursion when the sound beam was parallel to the path of leaflet travel. This occurred when the plane of the valve stent was approximately 30° to the incident sound beam. However, the cylindrical beam recorded parallel stent echoes of only slightly reduced apparent diameter despite this angulation. The number of leaflets recorded was determined by the orientation of the three leaflets, and the upright portions of the stent, relative to the incident sound beam.

Although the leaflet excursions and the effective valvar orifice size increased progressively with increasing flow the shape of this orifice, as observed in the water bath, was variable and irregular. Since the shape of this orifice was variable with varying flow, calculations of effective valvar orifice area using the maximum leaflet excursion as a diameter would be unreliable. The appropriate geometric formula could not be known a priori. However, maximum heterograft leaflet excursion was directly affected by the pulsed flow excursion as obvious from the water bath. This correlation also has been proposed for fascia lata valves in the mitral position. Thus, leaflet excursion may be reduced secondary to low flow rates aside from possible anatomic restriction by potential pathologic processes. The slight inequity in cusp size in porcine aortic valves, as well as debridement of

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Mean ± sd 3.1 ± 0.22 2.0 ± 0.23 0.66 ± 0.05 1.5 ± 0.5 1.2 ± 0.5 1.5 ± 0.3 2.4 ± 0.5 95 ± 24

| Abbreviations: a = abnormal; n = normal; p = paradoxical; T = technically inadequate for measurement; Ext = external; Int = internal. |
muscular tissue from one of the cusps during valve preparation, results in sequential cusp opening and closure at low flow rates (figs. 2 and 3).

We propose that partial cusp opening due to low flow rates might be inferred from a record showing low leaflet excursion but normal ratio of internal to external diameter (i.e., leaflets not contacting the internal stent echoes). Low leaflet excursion contacting internal echoes of decreased internal diameter and low ratio of internal to external diameter might suggest impairment of leaflet motion due to thrombus or other material encroaching upon the valve tissue.

An ultrasonic beam directed at these bioprostheses will be reflected with greater intensity from the stellite-polypropylene or titanium stent and with lesser intensity from the tissue leaflets. A satisfactory echocardiographic recording of normally thin leaflet tissue often is difficult but the stent is recorded with ease. Placement of the bioprosthesis in the mitral annulus results in stent motion solely due to annulus motion (in the securely attached valve) and the opening and closing motions of the valve leaflets are superimposed on this ongoing annulus motion. Motion of the stent toward the transducer on the anterior chest wall is apparently related to cardiac motion which brings the annulus toward the chest wall. Conversely, the rate of posterior diastolic stent and annulus motion reflects the rate of ventricular filling. The values found in this series of clinically stable patients are consistent with similar values from other laboratories. However, these values are in the range found with rheumatic mitral stenosis in the native valve. This may be explained by the small but definite degree of inflow restriction by these valves, and/or by the residual myocardial disease in these patients resulting in delayed ventricular filling rate due to myocardial stiffness.

Measurement of outflow tract dimension as done in this study gives a maximum dimension since a stent upright may intrude into the subaortic area and this may not be fully appreciated on ultrasonic records. However, if the valve is properly oriented at the time of surgical placement, two of these stent uprights will straddle the subaortic area and the third upright will project into the more spacious portion of the ventricle nearer the apex.

Echocardiographic evaluation of the stent mounted aortic heterograft used for replacement of the mitral valve was possible in the great majority of these patients. Standardized measurements of this valve's motion can be made from these noninvasive studies.

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