Discrepancies Between Doppler and Catheter Gradients in Aortic Prosthetic Valves In Vitro

A Manifestation of Localized Gradients and Pressure Recovery

Helmut Baumgartner, MD, Steven Khan, MD, Michele DeRobertis, RN,
Lawrence Czer, MD, and Gerald Maurer, MD

To evaluate possible causes of discrepancy between Doppler and catheter gradients across prosthetic valves, five sizes (19–27 mm) of St. Jude and Hancock valves were studied in an aortic pulsatile flow model. Catheter gradients at multiple sites distal to the valve were compared with simultaneously obtained Doppler gradients. In the St. Jude valve, significant differences between Doppler and catheter gradients measured 30 mm downstream from the valve were found: Doppler gradients exceeded peak catheter gradients of 10 mm Hg or more by 81±35% (15±3.6 mm Hg), and mean catheter gradients by 71±11% (10.3±2.5 mm Hg). When the catheter was pulled back through the tunnel-like central orifice of the valve, high localized gradients at the valve plane and significant early pressure recovery were found. When the catheter was pulled back through the large side orifices, gradients at the same level were only 46±6% of the central orifice gradients (mean difference, 7.6±4.5 mm Hg). Doppler peak and mean gradients showed excellent agreement with the highest central orifice catheter gradients (mean difference, 1.0±3.1 and 0.9±1.5 mm Hg, respectively). A significantly better agreement between Doppler and catheter gradients at 30 mm was found for the Hancock valve, although Doppler peak and mean gradients were still slightly greater than catheter gradients. Doppler gradients exceeded catheter gradients by 18±10% (3.4±1.9 mm Hg) and 13±11% (2.1±0.9 mm Hg), respectively. When the catheter was pulled back through the valve, the highest gradients were found approximately 20 mm distal to the valve ring. Doppler peak and mean gradients showed excellent agreement with these catheter gradients (mean difference, −0.6±2.1 and −1.2±0.9 mm Hg, respectively). Therefore, Doppler gradients accurately reflect the highest obtainable catheter gradients, which occur between the two leaflets (but not in the side orifices) of St. Jude valves and 20 mm distal to the prosthesis in the Hancock valves. However, Doppler gradients may be significantly higher than catheter gradients measured further downstream due to localized gradients and pressure recovery. The difference between Doppler and catheter gradients is, therefore, not due to overestimation by Doppler, but to the fact that the two techniques measure gradients in different locations. Doppler measurements reflect the maximum gradient along the interrogation line, whereas catheterization measures the recovered pressure distal to the valve. The magnitude of this discrepancy is not clinically significant in Hancock valves but may be substantial in St. Jude valves, particularly in smaller valve sizes at high flow rates. These findings suggest the importance of considering valve type, valve size, flow rate, and catheter position when using continuous wave Doppler to predict clinical catheterization gradients in prosthetic valves. (Circulation 1990;82:1467–1475)

From the Division of Cardiology and Cardiovascular Surgery Cedars-Sinai Medical Center and UCLA School of Medicine, Los Angeles, California.

Supported in part by the Western Cardiological Foundation.

H.B. was supported by a grant from the Fonds zur Förderung der wissenschaftlichen Forschung, Vienna, Austria.

Address for correspondence: Steven Khan, MD, Division of Cardiology, Cedars-Sinai Medical Center, 8700 Beverly Boulevard, Los Angeles, CA 90048.

Received January 17, 1990; revision accepted May 29, 1990.

The simplified Bernoulli equation has been widely used to determine pressure gradients across valvular stenoses noninvasively with continuous wave Doppler ultrasound. The accuracy of this technique has been validated in numerous clinical studies of stenotic heart valves1–3 and in experimental studies of simple and complex orifices.4–6 For prosthetic valves, however, conflicting
results have been published and the accuracy of the technique remains controversial. Although good agreement between Doppler and catheter derived gradients has been reported by some investigators,7-12 significant overestimation of gradients by Doppler in mechanical prostheses has been found by others.13-15 A potential cause of discrepancy between Doppler and catheter gradients is pressure recovery distal to the valve.16,17 Furthermore, mechanical prostheses, such as the St. Jude valve, have multiple orifices and tunnel-like configurations, resulting in complex flow and pressure characteristics,18-20 which could lead to the occurrence of localized pressure gradients.

This study addresses the hypothesis that discrepancies between Doppler and catheter gradients across prosthetic heart valves are not due to intrinsic errors of either measurement technique, but to spatial variability of pressure fields in prosthetic valves. To evaluate this, we designed a well-controlled in vitro model and tried to quantify the spatial variation of pressure and to isolate areas where Doppler and catheter measurements agree and disagree. To evaluate whether differences in the spatial variation of pressure between different valve types affected the Doppler-catheter gradient relations, we examined both a mechanical and a bioprosthesis.

**Methods**

**Model**

The flow model consists of a “ventricular” section, “aortic” section, and a compliance chamber constructed of Lucite and PVC tubing (Figure 1). The aortic section was designed to minimize the distance from the valve to the Doppler transducer and to allow optimal alignment of the Doppler beam with flow direction. Ultrasonic gel was used for acoustic coupling. The prosthetic valves were mounted between matched pairs of Lucite plates that had central orifices machined in 1 mm increments to fit the sewing rings of each valve exactly. The model was driven by a reciprocating pump (Harvard Apparatus Pulsatile Blood Pump, model 1423) with a stroke volume adjustable from 15 to 100 cc, a rate adjustable from 1 to 90 beats/min, and an ejection time variable from 30% to 70% of the cycle. Catheters were inserted through a side branch of the tubing for measurement of pullback pressures. A physiological upstream pressure of approximately 120/50 mm Hg was maintained by varying the outflow resistance and the outflow compliance. The system was primed with a 70% water-30% glycerol solution (viscosity, 3.5 cp). For Doppler measurements 10 g/l cornstarch was added. In preliminary studies, gradients obtained with and without cornstarch were compared and were similar (y=0.2+1.0x, SEE=1.9 mm Hg, r=0.98).

Flow was measured with an ultrasonic flowmeter (Transonic System Inc., model T201). The probe was attached to the noncompliant connection tubing between pump and test model. The accuracy of the flow measurements was tested by a series of timed collections. The flowmeter measurements accurately predicted the flow rates calculated from timed collections (y=1.97+0.95x, SEE=0.87 cc/sec, r=0.99).

Aortic and ventricular pressures were measured with fluid-filled catheters of matched length and electronic pressure transducers (Abbott Critical Care System) connected to a 12-channel physiologic recorder system (Electronics for Medicine, VR 12). The frequency response of the pressure measuring system was greater than 10 harmonics of the fundamental frequency21 as measured with the shock excitation method.22

Flow and pressure tracings (Figure 2) were digitized for further calculation using an image analysis computer (Microsonics CAD 886). The mean systolic flow rate was obtained by integrating the flow curve over the systolic time period. The peak systolic gradient was defined as the maximal instantaneous gradient between “ventricle” and “aorta” of the flow model. The mean systolic pressure gradient was obtained by integrating the difference between the simultaneously recorded “aortic” and “ventricular” pressure waves over the systolic time period, defined as the time
by guest on April 24, 2017 http://circ.ahajournals.org/ Downloaded from

LV, "ventricular"

Doppler

and

recordings.

fixed

was

were

calculated with

calculated from

period
during which forward aortic flow occurs. Each set of measurements was obtained by averaging two readings of each of three consecutive beats.

Doppler Echocardiography

Continuous wave Doppler measurements were performed with an Ultramark 4 CAD system (Advanced Technology Laboratories) using a Duplex probe (3.5 MHz-imaging, 2.0 MHz-CW Doppler). The ultrasound beam was carefully aligned to record the highest Doppler velocities, and the transducer was fixed in place with an adjustable clamp system. Peak and mean Doppler gradients were calculated using the on-board quantitation package. Gradients were calculated with the simplified Bernoulli equation: \[ \Delta p = \frac{1}{2} \rho v^2 \]. The velocities proximal to the valve were calculated from the measured peak and mean flow rates and the size of the inflow. Proximal velocities ranged between 0.20 and 0.50 m/sec and were, therefore, neglected. Doppler measurements were made on three beats and averaged. Doppler velocities (Figure 2) were recorded on paper (Video- graphic Printer YP 1810) and videotape.

Test Protocol

Five sizes (19–27 mm) of St. Jude bileaflet mechanical prostheses and of Hancock bioprosthetic valves were studied. The sizes 19 to 25 mm of the porcine valves had the modified orifice (model 250), whereas the 27 mm had the standard orifice (model 242). Three experiments were performed.

1) Pressure gradients were measured between a proximal end-hole catheter (2 cm from the valve) and a side-hole horizontal catheter that was pulled through the orifice (Figure 3). Glycerol solution without cornstarch was used in this experiment to allow visual guidance of the catheter. The side hole was initially moved to the level of the end-hole catheter to ensure that the pressure waves were identical for both catheters. Then, the catheter was pulled back through the prosthetic valve; in the St. Jude valve, this was done through both the center (between the two leaflets) as well as through one of the large side orifices (Figure 3). Distance 0 was defined as the plane of the very first structure of the open prosthesis encountered by the flow stream (i.e., sewing ring in Hancock valves and proximal leaflet tips in St. Jude valves). The linear distance from the 0 level to the pressure tap was 30 mm (Figure 3). The curvilinear distance that the catheter traversed from this point to the pressure tap was 35 mm; pressure gradients were measured at 1, 3, 5, 7, 10, 15, 20, 25, 30, and 35 mm in the St. Jude valves and at 1, 5, 10, 15, 20, 25, 30, and 35 mm in the Hancock valves. The measurement locations were determined by a pilot study where the spatial pressure distribution was examined for each valve type. The side hole of the catheter was oriented to avoid the underestimation of the lateral pressure gradient that would occur if the pressure port were to face into the flow stream. This experiment was performed for all valve sizes at two different mean systolic flow rates (245.5±12 and 190.1±6 cc/sec) with systolic time periods between 350 and 375 msec.

2) To obtain information about the pressure distribution further downstream, a 20 cm long Lucite

made on three beats and averaged. Doppler velocities (Figure 2) were recorded on paper (Video- graphic Printer YP 1810) and videotape.

Test Protocol

Five sizes (19–27 mm) of St. Jude bileaflet mechanical prostheses and of Hancock bioprosthetic valves were studied. The sizes 19 to 25 mm of the porcine valves had the modified orifice (model 250), whereas the 27 mm had the standard orifice (model 242). Three experiments were performed.

1) Pressure gradients were measured between a proximal end-hole catheter (2 cm from the valve) and a side-hole horizontal catheter that was pulled through the orifice (Figure 3). Glycerol solution without cornstarch was used in this experiment to allow visual guidance of the catheter. The side hole was initially moved to the level of the end-hole catheter to ensure that the pressure waves were identical for both catheters. Then, the catheter was pulled back through the prosthetic valve; in the St. Jude valve, this was done through both the center (between the two leaflets) as well as through one of the large side orifices (Figure 3). Distance 0 was defined as the plane of the very first structure of the open prosthesis encountered by the flow stream (i.e., sewing ring in Hancock valves and proximal leaflet tips in St. Jude valves). The linear distance from the 0 level to the pressure tap was 30 mm (Figure 3). The curvilinear distance that the catheter traversed from this point to the pressure tap was 35 mm; pressure gradients were measured at 1, 3, 5, 7, 10, 15, 20, 25, 30, and 35 mm in the St. Jude valves and at 1, 5, 10, 15, 20, 25, 30, and 35 mm in the Hancock valves. The measurement locations were determined by a pilot study where the spatial pressure distribution was examined for each valve type. The side hole of the catheter was oriented to avoid the underestimation of the lateral pressure gradient that would occur if the pressure port were to face into the flow stream. This experiment was performed for all valve sizes at two different mean systolic flow rates (245.5±12 and 190.1±6 cc/sec) with systolic time periods between 350 and 375 msec.

2) To obtain information about the pressure distribution further downstream, a 20 cm long Lucite
tube (inner diameter, 32 mm) was positioned between the prosthesis and the original aortic chamber. Pressures were recorded in the centerline of the tubing at 20, 30, 40, 50, 60, 75, and 100 mm from the 0 level (pull back as described before). The 19 and 23 mm prostheses of both the St. Jude and the Hancock valve were selected for these measurements. Flow rates of 201±3.2 and 253.5±4.7 cc/sec were used.

3) After determining the location of the highest pressure gradient ("highest obtainable catheter gradient"), the distal catheter was positioned at this site. For each valve size and type the flow rate was varied in five steps from 149.0±9.2 to 258.2±20.9 cc/sec, and simultaneous Doppler and catheter gradients were recorded. Cornstarch was added to the glycerol solution in this experiment. The distal catheter was then pulled back to the tap 30 mm downstream from the valve and the measurements were repeated. The 30 mm distance was chosen to emulate typical gradient measurements in clinical catheterization laboratories. During these experiments, the "heart" rate was maintained at 50 beats/min, and the systolic time periods were maintained between 325 and 370 msec.

Statistical Analysis

The relation of catheter and Doppler gradients was assessed by linear regression analysis. Pearson correlation coefficients were calculated. A two tailed t test was performed to test hypotheses about two regression lines. To test the agreement between the two techniques, the mean differences between Doppler and catheter gradients were calculated.\(^{23,24}\)

Mean values and standard deviation were calculated for the percent decrease of pressure gradient with increasing distance from the valve. The 27-mm St. Jude valve was excluded from these calculations because of the very small gradients.

Results

Peak and mean gradients measured by Doppler and catheter (at 30 mm downstream from the valve) for St. Jude and Hancock valves are shown in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Doppler (mm Hg)</th>
<th>Catheter (mm Hg)</th>
<th>Doppler (mm Hg)</th>
<th>Catheter (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>42.7±13.6</td>
<td>26.4±10.0</td>
<td>24.7±8.5</td>
<td>14.6±5.2</td>
</tr>
<tr>
<td>21</td>
<td>26.6±11.0</td>
<td>14.4±8.3</td>
<td>14.4±6.2</td>
<td>7.2±2.2</td>
</tr>
<tr>
<td>23</td>
<td>17.8±8.1</td>
<td>4.9±4.0</td>
<td>9.7±4.6</td>
<td>3.4±2.6</td>
</tr>
<tr>
<td>25</td>
<td>7.8±3.2</td>
<td>3.8±1.6</td>
<td>4.3±1.6</td>
<td>2.9±1.2</td>
</tr>
<tr>
<td>27</td>
<td>4.8±2.0</td>
<td>0.7±0.7</td>
<td>3.1±1.1</td>
<td>0.7±0.7</td>
</tr>
</tbody>
</table>

Values are mean±SD.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Doppler (mm Hg)</th>
<th>Catheter (mm Hg)</th>
<th>Doppler (mm Hg)</th>
<th>Catheter (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>38.7±12.4</td>
<td>35.0±13.3</td>
<td>23.5±6.9</td>
<td>21.0±7.4</td>
</tr>
<tr>
<td>21</td>
<td>23.7±8.2</td>
<td>18.7±7.0</td>
<td>14.9±5.7</td>
<td>12.0±4.1</td>
</tr>
<tr>
<td>23</td>
<td>16.5±5.0</td>
<td>13.5±6.6</td>
<td>10.4±3.5</td>
<td>9.3±3.2</td>
</tr>
<tr>
<td>25</td>
<td>12.4±4.1</td>
<td>10.8±3.4</td>
<td>7.2±2.7</td>
<td>7.5±2.3</td>
</tr>
<tr>
<td>27</td>
<td>17.7±4.7</td>
<td>14.9±6.0</td>
<td>10.5±2.7</td>
<td>9.7±3.1</td>
</tr>
</tbody>
</table>

Values are mean±SD.

Correlation Between Doppler and Catheter Gradients

St. Jude valve (Figures 5 and 6): The peak and mean Doppler gradients substantially exceeded the peak and mean catheter gradients measured 30 mm beyond the valve at the wall, although there was a strong linear relation between the two measurements (r=0.98–0.99). Peak Doppler gradients exceeded peak catheter gradients of 10 mm Hg and more by 81±35% (15±3.6 mm Hg), and mean Doppler gradients exceeded mean catheter gradients greater than or equal to 10 mm Hg by 71±11% (10.3±2.5 mm Hg) on average. The greatest discrepancy was seen for the smallest valves.
FIGURE 4. Plots of mean catheter gradient and distance from valve. Panel A: Gradients obtained when the catheter was pulled back through the central orifice of the St. Jude valve (size, 19–27 mm; flow rate, 245.5 ± 12 cc/sec). Panel B: Gradients obtained for two sizes of St. Jude valves when the catheter was pulled back through either the central or the side orifice. Panel C: Gradients as a function of distance from the valve ring for Hancock valves (size, 19–27 mm; flow rate, 245.5 ± 12 cc/sec).

FIGURE 5. Plot of correlation of the highest obtainable peak catheter gradients (at valve level) and the peak catheter gradients at 30 mm from the valve with the peak Doppler gradient for the St. Jude valve (19–27 mm). Dashed line represents the line of identity. Difference between the slopes of the two regression lines is significant (p < 0.001).

FIGURE 6. Plot of correlation of the highest obtainable mean catheter gradients (at valve level) and the mean catheter gradients at 30 mm with the mean Doppler gradient for the St. Jude valve (19–27 mm). Dashed line represents the line of identity. Difference between the slopes of the two regression lines is significant (p < 0.001).
Doppler gradients, however, showed excellent agreement with the highest obtainable catheter gradients that were found between the two leaflets of the valve. At the site of the highest obtainable gradient, the peak Doppler and catheter gradients differed by only $1.0\pm3.1$ mm Hg. The mean gradient at this site differed by only $0.9\pm1.5$ mm Hg.

**Hancock valve** (Figures 7 and 8): A significantly better agreement was found between Doppler gradients and catheter gradients at 30 mm for the Hancock valve, although Doppler gradients were still slightly greater than catheter measurements. Peak catheter gradients of 10 mm Hg and more were exceeded by $18\pm10\%$ ($3.4\pm1.9$ mm Hg) and mean gradients were exceeded by $13\pm11\%$ ($2.1\pm0.9$ mm Hg) on average. At the site of the highest obtainable gradient, excellent agreement was found between Doppler and catheter gradients. Mean differences between Doppler and catheter gradients were $-0.6\pm2.1$ mm Hg for the peak gradient and $-1.2\pm0.9$ mm Hg for the mean gradient.

**Discussion**

The accuracy of gradient estimation by continuous wave Doppler using the simplified Bernoulli equation has been validated in clinical studies of stenotic heart valves\(^1\)\(^-\)\(^3\) and in vitro studies of simple and complex orifices.\(^4\)\(^-\)\(^6\) Similar results have been reported for bioprosthetic valves.\(^8\)\(^-\)\(^1\(^1\)\(^1\) For mechanical prostheses, however, some investigators have reported good agreement between Doppler and catheter gradients,\(^8\)\(^-\)\(^1\(^1\)\(^1\) whereas others have reported that Doppler substantially overestimates catheter gradients.\(^13\)\(^-\)\(^1\(^5\) The reason for these conflicting reports is not known. Several investigators have demonstrated the adequacy of the assumptions that the simplified Bernoulli equation is based on\(^1\(^,\)\(^6\)\(^,\)\(^17\)\(^,\)\(^2\(^5\)\); however, several potential sources of error remain. The gradient may be underestimated if the Doppler beam and poststenotic jet are improperly aligned. Gradients may be overestimated if the velocity proximal to the lesion is high and is neglected.\(^1\)\(^,\)\(^2\)

Both errors can be either eliminated or their magnitude estimated in controlled in vitro measurements.

**Pressure Recovery**

One possible cause of discrepancy between Doppler and catheter measurements is pressure recovery. The pressure in a stenotic lesion will be lowest where the velocity is highest, that is, at the vena contracta, and will increase again distal to the stenosis. The actual amount of pressure recovery will depend on how much energy has been lost at the stenosis due to viscous and turbulent energy losses. Therefore, Doppler gradients that correspond to the gradients at the vena contracta will be higher than catheter gradients that are usually measured further downstream at varying distances from the valve. Significant pressure recovery has been shown in vitro in models of aortic stenosis\(^2\(^6\)\(^,\)\(^2\(^7\)\) and in several valve prostheses,\(^1\(^6\)\(^,\)\(^2\(^8\)\(^,\)\(^2\(^9\)\) although the available data have limitations. For example, Tindale et al\(^2\(^8\) and Schramm et al\(^2\(^9\) used only steady flow models. Although Yoganathan et al\(^1\(^6\) reported pulsatile flow experiments, the closest pressure measurements were taken 30–40 mm distal to the valve. Furthermore, neither of these studies used Doppler ultrasonography. The present study used pulsatile flow, and the
valve was crossed with a catheter to determine where the highest gradients occur. When Hancock valves or the large side orifice of St. Jude valves were crossed with the catheter, the highest gradients were found approximately 20 mm distal from the first valve structure. The same distance has been reported by Tindale et al\textsuperscript{28} for bioprostheses in a steady flow model and by Clark\textsuperscript{26,27} in a model imitating aortic stenosis. Pressure recovery has been described up to 150–275 mm from the prosthetic valve.\textsuperscript{16,28} However, in vivo, pressure waves change along the aorta. Time delay and reflections from the periphery change the wave shape and the maximum systolic pressure may increase.\textsuperscript{30} We found similar changes of the aortic pressure waves in our model, and we excluded from further analysis recordings that were obtained more than 100 mm downstream from the valve. The mean decrease of the pressure gradient between 20 and 100 mm was approximately 15% and most of the pressure recovery occurred within the first 50 mm. A similar change in pressure gradient was found between 20 mm (at the center) and 30 mm (at the wall), indicating a significantly higher flow velocity in the center of the aorta.

Differences Between St. Jude and Hancock Valves

In the St. Jude valve, significantly higher gradients were found within the valve’s central orifice (between the two leaflets). These gradients decreased rapidly when the catheter was advanced a few millimeters downstream (still between the two leaflets). This observation suggests that the highest localized gradient in this mechanical prosthesis occurs at the valve plane. The gradients measured at the side orifices were lower, demonstrating that localized gradients also occur across the cross-section of the flow channel. These local gradients cannot be explained by the multiple orifices in this valve. Teirstein et al\textsuperscript{8} demonstrated that Doppler velocities for pairs of large and small orifices were identical and that the calculated gradients correlated well with those measured by manometer. If pressure gradients across two orifices are the same, the flow velocity generated by those pressure gradients must also be the same, according to the Bernoulli equation.

However, the unique geometry of mechanical valves is more complex than the simple plates studied by Teirstein. Flow velocities across disk prostheses, in particular, are not uniform\textsuperscript{18–20} and demonstrate more spatial variation than in Hancock valves.\textsuperscript{31} Current methods are limited in their ability to visualize flow within the mechanical valve itself. Therefore, no data are available on flow velocities or gradients between the two leaflets of a St. Jude valve, although velocities further downstream have been reported.\textsuperscript{18} Tindale et al\textsuperscript{28} reported higher and earlier occurring gradients in the minor orifice than in the major orifice of a Bjork-Shiley valve. An explanation for these conflicting results might be that mechanical prostheses are not simple flat plates with multiple orifices, but complex, three-dimensional structures with tunnel-like configurations. This is particularly obvious in the St. Jude valve, which has a central “tunnel” between the two leaflets. The role of pressure recovery in causing apparent overestimation of pressure gradients by Doppler in tunnel-like orifices has recently been reported.\textsuperscript{17,32}

From the results of the present study, one could hypothesize that high velocities and low pressures occur in the tunnel between the two leaflets of a St. Jude valve. The reversed conical shape of the tunnel creates a streamlined stenosis beyond which flow expands gradually back into the larger lumen. Therefore, energy loss across the central orifice is reduced and pressure recovery increased, causing a steep decay of the pressure gradient (Figure 4A). In the present study, the observed decrease of pressure gradient between 5 and 30 mm (wall) distance was considerable (mean, 41.8±9.1%).

Correlation Between Doppler and Catheter Gradients

In the present study, Doppler gradients significantly exceeded catheter gradients measured 30 mm distal from the valve, although a strong linear relation was found. The differences were less in bioprosthetic valves but substantial in mechanical valves. Doppler gradients, however, showed excellent agreement with the highest obtainable catheter gradients determined by catheter pull back through the valve. Therefore, Doppler ultrasound can accurately measure the highest spatial gradients across these valves that occur at approximately 20 mm beyond the valve ring in the Hancock valve and within the prosthesis itself in the St. Jude valve. When catheter gradients are measured further downstream, as is usually done in clinical catheterization studies, discrepancies between the Doppler and catheter gradients may occur.

These discrepancies are not due to an intrinsic limitation of either technique, but to the fact that pressure fields have spatial variability and gradients are measured in different locations by the two techniques. Continuous wave Doppler gives us the maximum velocity along the line of interrogation and, therefore, reflects the highest gradient along the path of the beam. The catheter technique, on the other hand, measures pressure only at the site of the sampling port. Gradient measurements are, therefore, highly dependent on the sampling sites and, when performed at a distance from the valve, reflect recovered pressures.

One might argue that the Doppler gradient is of greater clinical impact because it reflects the maximum gradient experienced by the working left ventricle. The work done by the ventricle in systole, however, is given by the integral of the instantaneous pressure-flow product. Therefore, the absolute pressure generated in the ventricle and the volume of blood ejected from the ventricle determine ventricular work. Attempts to estimate this absolute ventricular pressure by adding Doppler gradients to the systolic aortic pressure may lead to erroneous results due to pressure recovery and inhomogeneous velocity and pressure distribution in mechanical valves. The high-
est obtainable gradients in St. Jude valves are localized phenomena occurring only in the center of the valve but not across the larger side orifices. Therefore, the gradients reflected by Doppler may differ substantially from the average gradient present across the entire valve orifice area at any point in time.

The important finding of this study is that spatial variation of pressure distal to prosthetic valves may cause Doppler and catheter to measure gradients in different locations. This spatial variation has to be considered when interpreting Doppler and catheter gradients and, particularly, when comparing these gradients. We have demonstrated how the two techniques differ, not the inherent superiority of either technique.

Comparison to Previous Studies

Although the difference between Doppler gradients and catheter gradients measured 30 mm downstream from the valve was significant for the Hancock valve, its magnitude is probably of no clinical relevance. It is not surprising, therefore, that previous in vitro and clinical studies of agreement between Doppler and catheter gradients in bioprosthetic valves—even though the latter were measured at various distances from the valve.

The observation of substantial discrepancy between Doppler and catheter gradients in St. Jude valves agrees with similar results that have been reported previously for mechanical valves in published and unpublished sources. In absolute terms, the differences are less significant for the 25- and 27-mm prosthesis where gradients below 10 mm Hg can be expected. However, in the smaller 19- and 21-mm sizes, the difference between Doppler and catheter gradients may be more than 20 mm Hg, particularly at high flow rates. Differences of this magnitude can lead to erroneous conclusions about valve function in clinical situations. Previous studies where good agreement between Doppler and catheter gradients was shown may not have included this subgroup of small valve sizes with measurements at high flow rates. Thus, Wilkins et al. only studied mitral prostheses, where valve sizes are larger and flow velocities lower. In the study by Sagar et al. only three patients with mechanical valves are reported, and in each case, Doppler overestimated the nonsimultaneous catheter gradient, in one instance by 30 mm Hg. Burstow et al. reported good agreement for simultaneous Doppler and catheter gradients in a variety of mechanical aortic prostheses including two 21-mm St. Jude valves. Cardiac index was only given in one of these two patients and was consistent with a low output state.

Limitations

In applying these results to clinical situations, it must be remembered that in vitro models like the one used in this study cannot precisely duplicate the complex flow dynamics in a patient with an implanted aortic prosthesis. For example, pressure recovery is partly determined by the size of the receiving chamber. The diameter of the aortic chamber used in this study is larger (32 versus 25.4 mm) than that reported by Yoganathan et al. The larger size of the aorta may have caused a smaller amount of pressure recovery. Thus, using a smaller aorta would have resulted in an even greater discrepancy between Doppler and catheter gradients measured downstream from the valve. In addition, the maximum flow rates used in this study were limited by the pump characteristics. It is possible that under clinical conditions of high flow rates discrepancies between Doppler and catheter measurements may be even greater.

There are also technical limitations to our study. Placing the catheter across the prosthesis causes an unphysiological situation that may be more important in a mechanical valve because complete closure during diastole is prevented. It is unlikely, however, that having the valve partially open at the beginning of systole would significantly affect the correlation of Doppler and catheter gradients. In addition, the accuracy of the fluid filled catheter system used in this study is limited, particularly when measuring small gradients. Transducer tip catheters would have been more accurate but do not allow the special set up (Figure 3) that was necessary for precise placement of the distal pressure port.

Clinical Implications

Doppler ultrasound accurately reflects the highest obtainable gradients across prosthetic valves, which occur at approximately 20 mm beyond the valve ring in the Hancock valve, and within the prosthesis itself in the St. Jude valve. However, discrepancy between Doppler and catheter gradients may occur when catheter measurements are obtained further downstream as is usually the case in clinical catheterization studies. This discrepancy is probably of no clinical relevance in Hancock porcine valves but may be substantial in the mechanical St. Jude prostheses, particularly with smaller valve sizes studied at high flow rates. The discrepancies between Doppler and catheter gradients are not due to erroneous measurements by either technique, but to spatial variation of pressure within and distal to the valve prostheses. This variation is more pronounced in St. Jude valves with the occurrence of high localized gradients between the two leaflets of the valve. Agreement or disagreement between Doppler and catheter measurements depends on the site where catheter measurements are obtained. Furthermore, one should exercise caution when trying to determine mechanical valve stenosis from Doppler gradient measurements alone. Calculation of valve area using the continuity equation may also be inappropriate in mechanical prostheses because velocity distribution across the valve orifice may be inhomogeneous. This study demonstrates the importance of considering valve type, valve size, flow rate, and catheter position when using continuous wave Doppler to predict clinical catheterization gradients in prosthetic valves.
Acknowledgment

We thank Ajit Yoganathan, PhD, for helpful discussions during this work.

References


7. Williams GA, Labovitz AJ: Doppler hemodynamic evaluation of prosthetic (Starr-Edwards and Bjork-Shiley) and bioprosthetic (Hancock and Carpentier-Edwards) cardiac valves. Am J Cardiol 1985;56:325-332


Key Words • prosthetic valve • echocardiography, Doppler • localized gradients • pressure recovery
Discrepancies between Doppler and catheter gradients in aortic prosthetic valves in vitro. 
A manifestation of localized gradients and pressure recovery.
H Baumgartner, S Khan, M DeRobertis, L Czer and G Maurer

*Circulation*. 1990;82:1467-1475
doi: 10.1161/01.CIR.82.4.1467

*Circulation* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1990 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/82/4/1467

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in *Circulation* can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to *Circulation* is online at:
http://circ.ahajournals.org//subscriptions/