Color Doppler Regurgitant Characteristics of Normal Mechanical Mitral Valve Prostheses In Vitro

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Background. To evaluate normal regurgitant characteristics of St. Jude (SJ) and Medtronic-Hall (MH) mitral valves, four sizes (25-31 mm) of each were studied in a pulsatile flow model.

Methods and Results. Regurgitant flow was measured by flowmeter at left ventricular pressures of 80, 130, and 180 mm Hg. Peak regurgitant flow rates ranged from 6.2 to 12.7 cm³/sec in SJ valves and from 7.9 to 17.5 cm³/sec in MH valves. Regurgitant orifice areas calculated from the Doppler continuity equation ranged from 1.6 to 2.0 mm² in SJ valves and from 2.2 to 2.9 mm² in MH valves. Regurgitant volumes across the closed valve at a left ventricular pressure of 130 mm Hg were normalized to an ejection time of 280 msec and ranged from 1.5 to 1.9 cm³ in SJ valves and from 2.1 to 2.8 cm³ in MH valves. Jets were imaged by color Doppler in six rotational planes, and jet size and morphology were compared with those of regurgitant jets from circular orifices with sizes comparable to the calculated prosthetic valve regurgitant orifices (1.1-3.1 mm²). SJ valves showed two converging jets from the pivot points, one central jet, and a variable number of peripheral jets. The mean color jet area derived from the six image planes ranged from 1.6 to 5.3 cm². Aliasing occurred only close to the valve (maximal distance 0.5-2.0 cm). MH valves showed a large central jet with a maximal length of aliased flow between 2.0 and 5.5 cm. Depending on valve size, driving pressure, and image plane, one or two small peripheral jets were found. These jets did not show aliasing in any case. The mean color jet area ranged from 5.1 to 11.0 cm². Jets originating from circular orifices of comparable size showed jet areas from 5.5 to 13.9 cm² and aliasing distances from 3.3 to 7.3 cm. At similar regurgitant orifice areas, driving pressures, and regurgitant flows, the measured color areas and aliasing distances were smallest in SJ valves, larger in MH valves, and largest in simple circular orifices.

Conclusions. Large, complex regurgitant jets can be found in normal closed SJ and MH valves by color Doppler, although regurgitant flow volume is minimal. Jet size and velocity distribution differs markedly between SJ valves, MH valves, and circular orifices, even with comparable driving pressure, regurgitant orifice area, and regurgitant volume. The characteristic patterns of normal regurgitation must be recognized to avoid incorrect diagnoses of pathological regurgitation in SJ and MH prosthetic valves. MH valves should not be removed solely on the basis of a central regurgitant jet with a long aliasing distance. Peripheral jets in MH valves and all jets in SJ valves should be considered normal as long as no or only minimal aliasing is present. In contrast, peripheral jets with significant aliasing may represent strong evidence of pathological regurgitation. (Circulation 1992;85:323-332)

Transesophageal echocardiography has been shown to demonstrate regurgitation in normally functioning mechanical valves. Indeed, such valves are known to have variable amounts of normal regurgitation resulting from backflow during valve closure and from regurgitation after full closure of the valve. Distinguishing between normal and pathological regurgitation by transesophageal color Doppler can be difficult, however. A number of valves that have been explanted because of what was felt to be pathological regurgitation by transesophageal color Doppler have been returned for pathological regurgitation. This may represent evidence of correct diagnoses of pathological regurgitation. The characteristics of normal regurgitation can be recognized and false diagnoses avoided.

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to the manufacturer and found to be normal (personal communication, Medtronic Inc., Minneapolis, Minn.). For some valve types, jet dimensions have been used to define normal regurgitation with normal jets described as primarily of low velocities. However, even the normal regurgitant volume of 4–15 cm$^3$ in bileaflet and tilting disk mechanical valves would be expected to create high-velocity jets, given the high systolic pressure difference between left ventricle and left atrium. Furthermore, it is unknown how prosthetic valve jets compare with the jets from simple circular orifices used in previous quantitative Doppler studies of the relation between hemodynamics and jet characteristics such as jet area and velocity distribution. The knowledge provided by studies of simple orifices may not apply to prosthetic regurgitant jets because of the much more complex geometry of prosthetic valve regurgitant orifices.

This in vitro study was, therefore, designed to address the hypothesis that transesophageal Doppler echocardiography may demonstrate large, complex regurgitant jets in normal mechanical valves despite low flow volumes. Regurgitant characteristics of two commonly used mechanical mitral valves—the bileaflet St. Jude (SJ) and the tilting disk Medtronic-Hall (MH)—were studied with color Doppler echocardiography in a pulsatile flow model providing images analogous to those from the transesophageal approach in a clinical setting. Furthermore, to address the hypothesis that regurgitant jet size and velocity decay along the jet may differ significantly between SJ, MH, and simple circular orifices, despite comparable flow rates and driving pressures, the prosthetic regurgitant jets were compared with jets from simple holes of comparable calculated orifice area. The major purpose of the study was to define the normal color Doppler regurgitant characteristics of mechanical valves to avoid their erroneous explanation because of misinterpreted Doppler studies.

Methods

Flow Model

The flow model (Figure 1, solid and dotted lines) has been described in detail previously and consists of "ventricular," "aortic," and "atrial" chambers and of two compliance chambers, all constructed of Lucite and PVC tubing. To evaluate mitral regurgitation, a cylindrical atrial chamber (inner diameter, 50 mm) with a hemispherical back wall (maximal inner length of the atrium, 8.5 mm) was added. The prosthetic valves can be mounted in either the aortic or mitral position between matched pairs of Lucite plates that have central orifices precisely machined to fit the sewing ring of each valve. A reciprocating pump (model 1423, Harvard Apparatus Pulsatile Blood Pump) draws fluid from the reservoir through the atrial section into the ventricle and ejects it into the aortic section of the model. To study regurgitation across the closed mitral prostheses, the circulation was simplified and pulsatile flow was preserved as follows: the ventricle was closed at the aortic side, and the pump was allowed to draw fluid directly from the reservoir (Figure 1, solid lines). Regurgitation across the closed valve was created by adjusting the pump to generate ventricular pressures of 80, 130, and 180 mm Hg. The ejection times ranged from 280 to 360 msec, pulse rates ranged from 60 to 65 beats per minute, and atrial pressure was maintained at 10 mm Hg. Four sizes (25–31 mm) of SJ and MH mitral valves and seven plates with single circular orifices (areas of 0.8, 1.1, 1.5, 2.0, 2.5, 3.1, and 3.4 mm$^2$) were mounted in the mitral position in a vertical plane. The orientation of the valves is shown schematically in Figure 2.

The system was primed with a 70% water–30% glycerol solution (viscosity, 3.5 cp) with 10 g/l cornstarch added to facilitate Doppler measurements. Regurgitant flow was measured with an ultrasonic flowmeter (model T1201, Transonic System Inc.) calibrated on the same tubing using timed collections of
fluid. In the present study, the probe attached to the noncompliant connection tubing between pump and test model was used (F1 in Figure 1). Ventricular and atrial pressures were measured with fluid-filled catheters and electronic pressure transducers (Abbott Critical Care System) connected to a 12-channel physiological recorder system (VR 12, Electronics for Medicine).

**Flow, Pressure, and Orifice Area Calculations**

Flow and pressure tracings were analyzed with an image analysis computer (Microsorics CAD 886). The flow curve was integrated over the systolic time period to obtain the mean systolic flow rate. The peak systolic gradient was defined as the maximal instantaneous gradient between ventricle and atrium of the flow model. The mean systolic pressure gradient was calculated by integrating the difference between the simultaneously recorded atrial and ventricular pressure waves over the systolic time period. Two readings of each of three beats were averaged. Regurgitant volumes were calculated from the mean flow rate and normalized to an ejection time of 280 msec to provide a more understandable comparison of the amount of regurgitation.

Effective regurgitant orifice areas were calculated for each prosthetic valve, and simple circular orifices of similar area were constructed to allow comparisons of regurgitant jets in prosthetic valves with jets produced by similar flow rates and driving pressures through the simple orifices used in previous in vitro studies of regurgitation. Pressure gradients across the valve measured with fluid-filled catheters and pressure transducers were used to calculate flow velocities with the simplified Bernoulli equation (Equation 1). The modified continuity equation (Equation 2) was then used to calculate the regurgitant orifice areas from the calculated velocities and the measured regurgitant flow:

\[ v = \sqrt{\frac{p}{4}} \]  
\[ \text{ROA} = \frac{Q}{v} \]  

where \( v \) is the maximal velocity across the prostheses, \( p \) the peak gradient, \( \text{ROA} \) the regurgitant orifice area, and \( Q \) the peak flow across the valve. ROA was calculated as the mean of three measurements at different pressures. The pressure and flow measurements and ROA calculations were repeated on a second day to confirm their reproducibility.

To evaluate the accuracy of this approach, the areas of the circular orifices were calculated from pressure and flow measurements in the same manner and compared with the known areas of the orifices. Calculated orifice areas were slightly smaller than anatomic orifice areas on average (mean difference, 0.1±0.38 mm²). Assuming that the continuity equation calculates the vena contracta cross-sectional area and that the coefficient of contraction in this orifice type may be 0.6–0.7, one might expect a mean difference between anatomic and measured orifice area of 0.6–0.8 mm². This small difference of 0.5–0.7 mm² between expected and measured areas may be a result of experimental error when hemodynamic measurements are used to calculate such small areas. It must be emphasized, however, that the Bernoulli equation and the continuity equation may be inadequate to calculate the actual area of the complex regurgitant orifices of prosthetic valves, which may consist of multiple small gaps and tunnel-like orifices. The regurgitant orifice area, therefore, should be used only as a theoretical number. The only reason it was calculated in this study was to construct circular orifices with similar regurgitant flow rates at the same driving pressures as the prosthetic valves studied.

**Doppler Echocardiography**

Doppler studies were performed with an Aloka 870 with a 3.5-MHz transducer. The pulse repetition frequency was 6 kHz, providing a maximal unaliased velocity of 0.53 cm/sec. Gain was set just below the level at which background noise appears, and low velocity filters were set at 4 (middle setting). Images were acquired with a frame rate of 10 Hz, using a 45° color sector.

The transducer was fixed in a central position at the back wall of the atrium. A special clamp system allowed rotation of the probe in 30° increments. In this way, images were acquired in six planes. Figure 2 shows how the imaging planes were related to valve geometry. Jet areas were calculated in each plane using the on-board quantification package. When multiple jets were seen, a summed jet area was calculated. The image with the largest jet found during the cycle was selected for the measurement. A mean of three beats was taken. The aliasing distance for each jet was measured as the maximal distance from the orifice at which aliasing could be detected.

Area and aliasing measurements were repeated by an independent observer to evaluate the interobserver variability.

**Dye Injections**

To visualize the patterns of regurgitation, dye was injected under pressure using 29-mm valves of each type. Ventricular pressure was maintained between 120 and 140 mm Hg when 2 cm³ of a 75% solution of green food dye was injected directly into the ventricle. The contrast jets were recorded on 8-mm videotape using a Sony F-70 video camera with macro focus setting (1/4,000 shutter speed). A different atrium of identical volume with flat walls (45×45×75 mm) was used in this study to allow clear jet visualization.

**Results**

**Regurgitant Flow and Regurgitant Orifice**

Peak regurgitant flow rates across the closed SJ valves ranged from 6.2 to 12.7 cm³/sec; they were similar in MH valves (7.9–17.5 cm³/sec). At the same driving pressure, the difference in flow rates among the four sizes was minimal for a given valve type.
TABLE 1. Regurgitant Orifice Areas, Regurgitant Volumes, Color Jet Areas, and Aliasing Distances for St. Jude and Medtronic-Hall Mitral Valves

<table>
<thead>
<tr>
<th>Valve size (mm)</th>
<th>25</th>
<th>27</th>
<th>29</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regurgitant orifice area (mm²)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SJ</td>
<td>2.0±0.3</td>
<td>1.8±0.2</td>
<td>1.6±0.2</td>
<td>2.0±0.2</td>
</tr>
<tr>
<td>MH</td>
<td>2.4±0.4</td>
<td>2.2±0.2</td>
<td>2.6±0.4</td>
<td>2.9±0.4</td>
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<tr>
<td><strong>Regurgitant volumes across the closed valve (cm³)</strong></td>
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<td></td>
<td></td>
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<tr>
<td>SJ</td>
<td>1.9</td>
<td>1.8</td>
<td>1.5</td>
<td>1.8</td>
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<tr>
<td>MH</td>
<td>2.3</td>
<td>2.1</td>
<td>2.5</td>
<td>2.8</td>
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<tr>
<td><strong>Mean summed color jet area (cm²)</strong> obtained from six imaging planes at three different ventricular pressures</td>
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<tr>
<td>SJ</td>
<td>80 mm Hg</td>
<td>3.1</td>
<td>2.7</td>
<td>3.5</td>
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<tr>
<td>130 mm Hg</td>
<td>4.2</td>
<td>3.8</td>
<td>4.4</td>
<td>2.3</td>
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<tr>
<td>180 mm Hg</td>
<td>5.3</td>
<td>4.0</td>
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<tr>
<td>MH</td>
<td>80 mm Hg</td>
<td>5.3</td>
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<td>130 mm Hg</td>
<td>7.7</td>
<td>8.1</td>
<td>9.9</td>
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<td>180 mm Hg</td>
<td>9.3</td>
<td>10.4</td>
<td>11.0</td>
<td>10.9</td>
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<tr>
<td><strong>Maximal aliasing distance (cm)</strong> at three different ventricular pressures</td>
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<tr>
<td>SJ</td>
<td>80 mm Hg</td>
<td>0.6</td>
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<td>130 mm Hg</td>
<td>1.0</td>
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<td>180 mm Hg</td>
<td>1.3</td>
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<td>MH</td>
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<td>2.7</td>
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<td>4.9</td>
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</table>

SJ, St. Jude valve; MH, Medtronic-Hall valve.

*Mean±SD of six measurements (two sets of measurements at three different ventricular pressures).
†Mean of two measurements (ventricular pressure, 130 mm Hg; ejection time, 280 msec).

Increasing left ventricular pressure from 80 to 180 mm Hg, however, caused the flow to increase by 50–100%. The regurgitant volumes across the closed valve at a left ventricular pressure of 130 mm Hg adjusted to a standard ejection time of 280 msec ranged from 1.5 to 1.9 cm³ in SJ valves and from 2.1 to 2.8 cm³ in MH valves. Theoretical regurgitant orifice areas between 1.6 and 2.0 mm² were found in SJ valves. The areas in MH valves ranged from 2.2 to 2.9 mm². No increase of the regurgitant area was found with increasing valve size in SJ valves. In MH valves, the regurgitant areas of 29- and 31-mm valves were slightly larger than those of 25- and 27-mm valves. The mean difference between the measurements obtained from the two sets of experiments was 0.4±0.2 mm².

Jet Morphology

*St. Jude valve.* The morphology of the jets in normal SJ valves varied depending on the imaging plane, with two to four jets visible simultaneously. The basic pattern of the jets was similar for all valve sizes and driving pressures: two converging jets originating from the pivot points, a central jet originating from the gap between the two disks, and a variable number of peripheral jets originating from the circumferential gap between disks and valve ring (Figure 3). The best-defined patterns were seen in the 0° (parallel to the coaptation line of the two disks) and the 90° image plane. The 0° plane showed two converging jets and partially showed a third jet from a common origin with one of the converging jets but directed perpendicularly into the chamber. The 90° plane showed one central jet and two diverging peripheral jets (Figure 3). The maximal number of four simultaneous jets was usually seen in the 60° plane. The fourth jet was usually seen only at driving pressures of 130 or 180 mm Hg and not at 80 mm Hg.

*Medtronic-Hall valve.* In each imaging plane, a large central jet originating from the central hole of the valve was present (Figure 4). Depending on the image plane, one, two, or no small peripheral jets were seen. The number of peripheral jets seemed to increase at higher driving pressures and was also dependent on the orientation of the valve. When valves were mounted with the open disk in a horizontal plane (i.e., 0° position straight up), jets originating from the upper circumference were more likely to be visualized or were larger in size. However, the circumferential jet from the minor orifice was usually dominant.

Although the color images showed a large central jet with only small peripheral jets, the majority of regurgitation appeared to originate from the circumference of the valve. To demonstrate this, we measured the regurgitant flow across an intact 33-mm MH valve before and after occlusion of the central hole of the disk and found that the central regurgitant orifice area represented only 30% of the entire regurgitant area.
Jet Area, Velocity Decay Along the Jet, and Comparison With Circular Orifices

Jet area. For each valve type, the mean jet area (mean of the largest summed jet areas in the six planes) increased with driving pressure and flow rate (Table 1, Figure 5) and was more dependent on these variables than on the valve size. Figure 5 compares the color areas of SJ, MH, and circular orifice jets. At comparable regurgitant flow rates and driving pressures (and therefore similar orifice area), color jet areas were smallest for SJ valves and largest for circular orifices.

Velocity decay along the jet (aliasing distance). The maximal distance at which aliasing occurred (velocities greater than 0.53 m/sec) increased with rising driving pressure and flow rate (Table 1, Figure 6). In SJ valves, aliasing occurred predominantly in jets originating from the circumference and was seen only close to the valve. A maximum aliasing distance of 2.0 cm was found in SJ valves at a driving pressure of 180 mm Hg. In MH valves, aliasing was seen only in the central jet and never in the circumferential jets. However, aliasing in the MH valve occurred at distances up to 5.5 cm from the valve. In circular orifices, aliasing occurred at even greater distances than in the MH valve and frequently reached the back wall of the atrium. Figure 6 shows the marked differences in aliasing distances between SJ valves, MH valves, and circular orifices even at similar flow rates and driving pressures. The shortest aliasing distances were observed in SJ valves and the longest in circular orifices.

Interobserver variability. The reproducibility of the color area and aliasing distance measurements are shown in Figure 7. The color areas (mean of the six planes) measured by observer 1 showed excellent correlation with those measured by observer 2 ($r=0.99$, $y=-0.08+1.06x$, $SEE=0.37$ cm$^2$) with a mean difference of only 0.25±0.40 cm$^2$ (mean±SD). Similarly, the aliasing distances measured by the two observers correlated well ($r=0.98$, $y=0.08+0.98x$, $SEE=0.32$ cm), and the mean difference between the two measurements was 0.03±0.32 cm.

Dye Injections

Examples of regurgitant jets visualized by dye injection in SJ and MH valves are shown in Figures 8 and 9. These experiments confirmed the pattern of regurgitation found by Doppler flow imaging, but appeared to reflect the volume distribution of regurgitation better. This is particularly obvious for the MH valve, in which the high density of the peripheral dye jet indicates that the majority of regurgitation originates from the circumference of the disk and not
from the central hole, as suggested by color Doppler. Conversely, the low density of the central jet suggests that the actual volume of regurgitant flow through the central orifice is small.

Discussion

Transthoracic and Transesophageal Imaging

Regurgitation in normal mechanical mitral valves has been found in only a minority of patients when transthoracic Doppler echocardiography is used. With conventional Doppler, an incidence between 0 and 38% has been reported.\(^10\)\(^-\)\(^16\) Transthoracic color flow imaging has shown an even lower rate of 0–6%.\(^13\)\(^,\)\(^17\)\(^,\)\(^18\) Because a certain amount of backflow occurs in every mechanical valve,\(^3\)\(^,\)\(^4\) these Doppler results probably reflect a high percentage of false-negative studies and not the true incidence of regurgitation in normal prostheses. Regurgitant volumes for prosthetic valves are heart rate and cardiac output dependent.\(^4\) At a pulse rate of 60–80 beats per minute and normal cardiac output, regurgitant volumes of approximately 4–12 cm\(^3\) have been described in vitro for SJ and MH valves.\(^3\)

There are two reasons why this amount of backflow can be detected in only a small percentage of patients. First, a considerable part of the regurgitant volume results from backflow during valve closure.\(^4\)\(^,\)\(^19\) This backflow occurs over a very short time period without forming a well-defined jet. It may therefore be difficult to detect and may not be interpreted as regurgitation in the common sense. The regurgitant flow that continues...
Figure 6. Graph of aliasing distance vs. flow rate for St. Jude (SJ) valves (25–31 mm), Medtronic-Hall (MH) valves (25–31 mm), and circular orifices (1.1–3.1 mm²). Different driving pressures are indicated by data point symbols. Data from SJ valves, MH valves, and circular orifices are indicated by different hatched backgrounds. LV, left ventricular.

across the closed valve throughout systole is minimal and ranged from only 1.5 to 1.9 cm³ in SJ and 2.1 to 2.8 cm³ in MH valves in the present study. To get a measurement more independent of pressure and ejection time, we calculated regurgitant orifice areas and found these to range from 1.6 to 2.0 mm² in SJ and from 2.2 to 2.9 mm² in MH valves.

The second, more important, reason for the low detection rate of mitral prosthetic regurgitation by transthoracic echocardiography, however, may be that the left atrial flow is usually masked by the material of the valve and flow is therefore difficult to visualize. Transthoracic Doppler echocardiography, on the other hand, allows interrogation of the left atrium from its posterior surface without shadowing of the jet image by the prosthesis. The short distance between ultrasound probe and region of interrogation further reduces attenuation of ultrasound energy. Under these circumstances, holosystolic regurgitation has commonly been reported in normal SJ and MH valves.

The characteristics of normal prosthetic valve regurgitation, however, have not been well defined; thus, distinction between normal and pathological regurgitation is difficult. In the MH valve, large regurgitant color Doppler jets have resulted in explantation of valves that were later found to be normal. The present study tries to provide a better understanding of normal regurgitation by identifying the morphology of normal regurgitant prosthetic valve jets. Despite the small regurgitant volumes in these valves, complex regurgitant jets were seen in both SJ and MH mechanical valves. This confirms preliminary reports previously presented by other investigators. MH valves consistently showed a large central jet originating from the central disk hole and a variable number of peripheral jets. Although the central jet dominates color Doppler regurgitation in the MH valve, it represents only about 30% of the regurgitant flow. The remaining 70% of the regurgitant flow originates from the gap between disk and valve ring but is represented only by small color jets peripherally. In contrast, depending on the image plane, two to four jets were seen in SJ valves: two converging jets from the pivot points, one central jet from the gap between the two disks, and a variable number of peripheral jets from the circumference of the valve.

Jet Size and Velocity Decay Along the Jet

Jet size increased with increasing driving pressure and increasing flow rate, consistent with previous studies that demonstrated that color Doppler jet size depends on multiple variables including flow rate, driving pressure, and the size and compliance of the receiving chamber. The current study kept these factors identical for all the prosthetic valves and circular orifices, allowing comparison of the theoretical orifice areas and jet measurements (Figure 5). Under similar conditions, jet sizes differed markedly between SJ valves, MH valves, and circular orifices. To account for the complex shape and multiplicity of regurgitant jets, planimetry of color areas was performed in six rotational planes, and the mean of summed jet areas was calculated. The summed jet areas obtained from each of these six planes varied considerably, particularly in SJ valves. The mean areas, however, were significantly smaller than in MH.

Figure 7. Graphs showing agreement between observer 1 and observer 2 for measurements of color areas and aliasing distances. Solid line is the line of identity.
valves, which showed smaller areas than jets through circular orifices. Because all other variables were similar, only differences in orifice geometry can be responsible for the difference in jet size.

A striking finding of this study is the difference in velocity distribution between the two valves and the circular orifices. It has been shown for circular and irregular orifices that the decrease in velocity over the length of a regurgitant jet will depend on the flow rate as long as the initial velocity at the orifice is constant.\textsuperscript{7,8} Thus, the velocity decrease for regurgitant jets across SJ valves, MH valves, and circular orifices should be the same as long as driving pressure and flow rate are the same. Therefore, one might presume that the aliasing distance, the distance at which the velocity passes the Nyquist limit, should be the same for all three. However, the aliasing distance differed substantially between the two valves and the circular orifices. SJ valves showed low-velocity jets with aliasing only close to the valve. Similar characteristics have previously been reported for normal regurgitant jets in Björk-Shiley valves.\textsuperscript{1} In MH valves, however, the large central jet demonstrated aliasing up to 5.5 cm from the orifice. Although the majority of regurgitation originated from the circumference in MH valves, the very small peripheral jets demonstrated only low velocities without aliasing. Viscosity may play a more important role in these very small gaps and tunnels with a number of small jets and flow near chamber walls. This may cause a faster decrease in jet velocity for regurgitant flow from the circumference in both valve types and the pivot points in SJ valves.

The central high-velocity jet in MH valves represents a unique situation caused by the particular design of this valve. The MH valve has been designed to provide a sliding disk motion that allows disk excursion out of the valve housing. This enables flow between disk and housing to wash out platelet agglomerates and maximizes the opening angle of the disk. To allow full disk excursion, the disk occluder has a central hole, and a strut inserted through this orifice guides the disk motion. This strut may conceivably cause the surrounding regurgitant flow originating from the central hole to converge to a high-velocity jet because of the Coanda effect, although the precise mechanism is not understood at present.

Limitations

The use of the continuity equation to calculate orifice areas may result in inaccuracies in estimating areas in the complex regurgitant orifices of prosthetic valves, which consist of multiple small gaps and tunnels. However, these numbers are intended as a model for comparison of regurgitant areas with circular orifices at identical flow rates and driving pressures. Furthermore, the in vitro model used in this study cannot precisely duplicate the complex flow dynamics of a mitral prosthesis implanted in a patient. Therefore, these results should be applied clinically with some caution. For example, micro bubbles, which are difficult to avoid completely in in vitro models, may create larger jet sizes than those occurring in vivo.\textsuperscript{23} This, however, should not influence the relative differences in jet size between the valves and the circular orifices and should be of little importance for the velocity analysis. The attenuation of Doppler is minimized in an in vitro setting and may allow imaging of larger jets and more jets than is possible in vivo. In addition, the size and compliance of the left atrium are known to influence jet size\textsuperscript{5,6} and may differ in our model from clinical situations.

Finally, the aliasing distance depends on the Nyquist limit, which was selected arbitrarily in this study. Different settings for the Nyquist limit would change the absolute jet aliasing distances and may also

**Figure 8.** Regurgitation across the closed St. Jude valve (29 mm) visualized by dye injection into the simulated ventricle. Two views corresponding to Doppler imaging planes of 0° (left panel) and 90° (right panel) are shown. Note that regurgitation occurring anterior and posterior to the actual Doppler image plane is superimposed.
change the magnitude of difference between valves and circular orifices. However, significant differences would remain between the valves and the simple orifices, and the order (longest aliasing distances for circular orifices and shortest for SJ valves) would remain the same. Although the instrument settings used in this study represent typical adjustments for transesophageal studies, it should be noted that slightly higher velocities can be imaged without aliasing. However, higher Nyquist limits would only result in less or no aliasing in SJ valves and a decreased but still significant aliasing in MH valves.

Clinical Implications

Although the advent of transesophageal Doppler echocardiography has resulted in dramatically improved views of prosthetic valve regurgitation, it also necessitates thorough understanding of the complex regurgitant jet morphologies that occur in mechanical prosthetic valves. The in vitro images obtained in this study are analogous to the ones obtained with the transesophageal approach in a clinical setting, because valvular regurgitation is viewed through the regurgitant receiving chamber without interference by any valve structures. Under these conditions, large regurgitant jets may be seen by color Doppler even though regurgitant flow across normal closed SJ and MH valves is minimal. The summed area and the velocity decay of regurgitant jets in SJ valves, MH valves, and circular orifices of similar regurgitant orifice size differ markedly, even with identical driving pressures and flow volume. Therefore, color Doppler experience derived from studies dealing with simple regurgitant orifices may not apply to prosthetic regurgitant jets. Furthermore, the color Doppler appearance of prosthetic valve regurgitation may be misleading, particularly when jets from different valve types are used to try to compare differences in the actual magnitude of regurgitation. In normal SJ valves, multiple low-velocity jets are seen with only short aliasing distances. In normal MH valves, a large central jet is seen with aliasing that extends far into the atrium and peripheral jets without aliasing (assuming a Nyquist velocity of 0.53 m/sec or greater). The large central jet may suggest that there is more regurgitation in MH valves than in SJ valves, although actual flow rates and driving pressures are similar.

Most importantly, MH valves should not be removed solely on the basis of a central regurgitant jet with a long aliasing distance. Peripheral jets in MH and all jets in SJ valves should be considered normal as long as no or only minimal aliasing is present. In contrast, peripheral jets with significant aliasing may represent strong evidence of pathological regurgitation.

References


**KEY WORDS** • mechanical heart valves • normal regurgitation • color Doppler
Color Doppler regurgitant characteristics of normal mechanical mitral valve prostheses in vitro.
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