Pulsed Doppler Echocardiographic Study of Mitral Stenosis

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SUMMARY The value of pulsed Doppler echocardiography in the assessment of mitral stenosis was studied in a consecutive series of 175 patients before right- and left-heart catheterization. All Doppler recordings were interpreted independently by two observers. Twenty patients had repeat studies to demonstrate the reproducibility of the method. Adequate recordings were obtained in 156 patients. A normal flow pattern was observed in all 41 patients in sinus rhythm without a mitral valve gradient but in none of the 51 patients in sinus rhythm with a mitral gradient. In atrial fibrillation the normal pattern was identified in all three patients with no mitral gradient but in none of the 61 with a gradient. Three patterns of mitral valve flow could be distinguished that corresponded to mild, moderate and severe stenosis. The mitral valve gradient in the 36 patients with pattern I was 6.1 ± 1.7 mm Hg (sd) (range 3–10 mm Hg); in 54 patients with pattern II it was 12.0 ± 2.5 mm Hg (range 8–18 mm Hg) (p < 0.001 vs I); in 22 patients with pattern III it was 22.0 ± 6.6 mm Hg (range 18–27 mm Hg) (p < 0.001 vs II). Overlap was observed in only four patients, all of whom had a gradient between 8–10 mm Hg. Mitral valve area was 2.14 ± 0.58 cm² in pattern I, 1.17 ± 0.33 cm² in pattern II and 0.67 ± 0.26 cm² in pattern III (p < 0.001 between all groups). The presence of associated mitral regurgitation in 39 patients and aortic valve disease in 32 patients did not affect the Doppler assessment of mitral stenosis. Thus, pulsed Doppler echocardiography can accurately detect the presence of mitral stenosis and assess its severity.

THE NONINVASIVE STUDY of mitral valvular disease has been greatly enhanced by ultrasound techniques. M-mode echocardiography allows recognition of the stenotic valve and bidimensional echocardiography permits an estimation of mitral valve area. Mitral valve flow can be recorded by Doppler echocardiography and preliminary results suggest that this technique can provide an estimate of the severity of mitral stenosis.

The limitations of standard echocardiography in the quantification of mitral stenosis have been recognized and the usefulness of the bidimensional approach is being evaluated. Pulsed Doppler techniques theoretically provide an alternative approach to this problem. In this study we extended previous work from our laboratory to assess prospectively in a large number of patients undergoing cardiac catheterization the accuracy of Doppler echocardiography in detecting and defining the severity of mitral stenosis.

Methods

Patient Selection

A Doppler study of the mitral valve was attempted on the day before right and left cardiac catheterization in 175 consecutive patients with suspected congenital or valvular heart disease investigated at our institution between September 1977 and August 1978. Nineteen patients in whom a low signal-to-noise ratio precluded the recording of mitral valve flow were excluded from the study. In the remaining 156 patients, a comparison of the Doppler and hemodynamic data was possible. Twelve patients had had mitral valve replacement by a Carpentier-Edwards xenograft. Cardiac catheterization revealed the presence of a mitral valve gradient in 112 patients. Mitral stenosis was associated with significant mitral regurgitation in 39 and 32 had aortic valvular disease. Among the 44 patients without mitral stenosis six had coronary artery disease, eight aortic valve disease, nine atrial septal defect, four ventricular septal defect, six isolated mitral regurgitation, one pulmonary valve stenosis and 10 normal right- and left-heart catheterization. Mean age was 43 years (range 18–65 years). In one patient we obtained simultaneous Doppler and intracardiac pressure gradient recordings.

Doppler Apparatus and Doppler Output

The directional range-gated Doppler instrument has been described elsewhere. The unit used in this study transmits ultrasound at a frequency of 4 MHz, with a pulse repetition rate of 5–10 kHz. The transcutaneous depth of exploration ranges from 3–14 cm. The duration of the emitted pulse is adjusted between 2–4 μsec and the crystal is allowed to receive for 100–200 μsec. The size of the sample volume is determined by the delay in the receiver and by the duration of the ultrasound burst. A high-pass filter with a cutoff frequency of 600 Hz eliminates low-frequency signals originating from cardiac wall motion.
According to the Doppler principle, the unit measures the speed of moving structures that reflect ultrasound. The frequency shift (ΔF) between the emitted and reflected ultrasound is proportional to the emitted frequency (F), to the velocity (V) of moving structures within the sample volume and to the angle (θ) between the ultrasound beam and the moving structures according to the formula

\[ ΔF = \frac{2 \cdot V \cdot F \cdot \cos θ}{C} \]

where C is a constant representing the speed of ultrasound in the medium.

The range-gating system allows definition of a sample volume with known size and depth displayed on the A- and M-mode echocardiogram. The Doppler shift of frequency within this sample volume is analyzed through a zero-crossing detector. The derived analog velocity signal is visualized on the oscilloscope and transcribed on a Gould Brush model 2400 forced-ink recorder.

The derived velocity flow curve represents the average of all velocities of blood cells within the sample volume. The tracing indicates flow direction (toward or away from the transducer) and the presence or absence of turbulence. The Doppler shift is audible and the audio signal provides useful information about the quality of blood flow. For example, a laminar flow sounds soft and regular and its velocity profile is neat and fine on the recorded tracings. A turbulent flow has a rough, more intense pitch with sounds of irregular intensity. The tracing is not smooth and has indentations corresponding to sudden variations in the velocity of moving elements. The velocity profile tracing omits important information about the width of the spectrum of reflected ultrasound; however, its graphic representation provides objective data about the pattern of flow. Mitral stenosis was evaluated in this study using only the information contained on the tracings, which were recorded at a paper speed of 50 cm/sec.

Doppler Studies

Patients were examined in the supine left lateral position. After careful palpation of the apical impulse, the transducer was placed in the intercostal space at the cardiac apex and oriented posteriorly, superiorly and to the right along the axis of the left ventricular inflow tract. A- and M-mode echocardiography permitted rapid recognition of the anterior mitral leaflet and location of the sample volume in the left atrium at the level of the mitral annulus, just behind the valve leaflets in their systolic position. A 5-kHz pulse repetition rate was used. By slightly changing the angle of the transducer and the depth of the sample volume the operator could avoid recording the motion of the valve leaflets that could cause errors in the interpretation of the tracings. The valvular motion is readily apparent on the audio signal, and one can avoid recording it with a little experience. Selection of the highest amplitude flow curves facilitated the interpretation of the tracings. By convention, a flow running toward the transducer inscribed a curve above the electronic zero baseline, and a flow running in the opposite direction was recorded below the baseline. The systolic and diastolic flow timing was recognized on the tracing by simultaneously recording lead II of the ECG.

The interpretation of tracings was based on our experience from a preliminary study in which three distinctly abnormal flow curves correlated with different degrees of mitral stenosis. All Doppler flow patterns were analyzed before cardiac catheterization. The tracings were then reviewed and interpreted blindly by an independent observer. The reproducibility of the flow pattern in the same patient was also studied by performing a Doppler study on three different days in 20 patients. Half of these 60 studies were performed by one examiner and the other half by a second.

Cardiac Catheterization Studies

Cardiac catheterization was performed in a fasting state after premedication with 10 mg oral diazepam. Pulmonary wedge, left ventricular and aortic pressures were recorded with #8F catheters connected to P23Db Statham strain gauges on an Honeywell fiberoptic recorder at a paper speed of 100 cm/sec and a scale of 4 mm Hg/cm. Mitral valve gradient was planimetered over 10 consecutive cardiac cycles and a mean gradient was calculated. Cardiac output was obtained by the Fick or dye-dilution method. Mitral valve area was calculated by the formula of Gorlin and Gorlin when significant mitral valve regurgitation was absent. Mitral regurgitation was assessed by left ventriculography and graded as mild when a small regurgitant flow with incomplete opacification of the left atrium was present and as significant when complete opacification of the left atrium occurred. Heart rate at the time of cardiac catheterization was similar to heart rate at the time of the Doppler study, with a maximal variation of 10 beats/min between the two examinations. Blood pressure was also comparable in each patient at the time of the two studies. Statistical analyses were done using the t test. Values are expressed as mean ± SD.

Results

Mitral Flow Patterns

The mitral flow patterns are illustrated in figure 1. In patients with sinus rhythm, the normal pattern (0) is characterized by a smooth bifid flow curve. The first peak starts with the opening of the mitral valve and corresponds to rapid ventricular filling during the first third of diastole. The second peak is of smaller amplitude, occurs in the last third of diastole at the time of the A wave of the mitral valve leaflets and corresponds to the atrial contraction wave. Pattern 1, observed in mild mitral stenosis, also has a bifid flow but differs from the normal flow pattern because the late diastolic peak is higher in amplitude than the first
peak. Pattern II, in moderate mitral stenosis, is turbulent and characterized by a monophasic flow curve peaking in mid or late diastole. It is irregular and dome-shaped in appearance. Pattern III, observed in severe stenosis, is very turbulent with a slow, steadily ascending flow. At end-diastole, at the time of the QRS complex, a sharp descent occurs.

In atrial fibrillation, the absence of atrial contraction and the variation in cardiac cycle length alter the classification. Patients without stenosis have a smooth sounding flow that transcribes on paper as a regular velocity curve. In long diastoles, flow ends before the QRS complex; in short diastoles, pattern III is never observed. Pattern I in atrial fibrillation is characterized by turbulence on the audio signal causing jagged velocity flow curve. The flow is sustained to end-diastole of long cardiac cycles, and in short diastolic cycles a pattern III is observed (fig. 2). With moderate and severe stenosis, the flow curve during long diastoles is the same as in sinus rhythm (fig. 1).

Reproducibility of the Method

The tracings were interpreted independently by two observers and in all but one patient the two interpretations agreed. Review of the tracing in this patient revealed that the misinterpretation was caused by an artifact related to motion of a mitral leaflet interfering with the flow curve.

The mitral valve flow pattern was reproducible from day to day in the 20 patients who had Doppler examinations on different days. Half the Doppler studies in these patients were done by one examiner and half by another examiner. There were no interobserver differences in the classification of the Doppler pattern in these patients.

Diagnosis of Mitral Valve Stenosis

Of the 41 patients in sinus rhythm in whom the Doppler examination showed a normal flow pattern, i.e., a biphid flow curve with a dominant early diastolic wave, none had a mitral valve gradient. However, none of the 51 patients with a mitral valve gradient at cardiac catheterization and in sinus rhythm had this normal flow pattern.

In the three patients with atrial fibrillation without a mitral valve gradient, flow ended before the QRS complex of the ECG in long diastoles and a pattern III was never observed. All 61 patients with mitral valve gradients and atrial fibrillation had cardiac cycles that showed pattern III.
Figure 2. Mitral valve flow pattern in the presence of atrial fibrillation and mild mitral stenosis. Pattern III is observed after a short cardiac cycle (fifth RR interval), and during long cardiac cycles (third RR interval) flow ends at end-diastole or earlier. This pattern is characteristic of mild stenosis in atrial fibrillation. With no stenosis, flow ends before end-diastole of the long cardiac cycle and a pattern III is not observed in short diastolic cycles. Patterns II and III are the same as in sinus rhythm (fig. 1). $V$ = velocity; $O$ = zero flow, electronic baseline.

Assessment of the Severity of the Mitral Stenosis

Figures 3 and 4 illustrate the correlation between the Doppler flow pattern and the hemodynamic data. Pattern I was noted in 36 patients, and in all the gradient was below 10 mm Hg (mean 6.1 ± 1.7 mm Hg [SD]). Mitral valve area calculated for the 25 patients with this pattern and without significant mitral regurgitation was 2.14 ± 0.58 cm².

Pattern II was seen in 54 patients and was associated with gradients between 8–18 mm Hg. Mean gradient was 12 ± 2.5. Mitral valve area calculated in 31 patients was 1.17 ± 0.33 cm².

Pattern III was observed in 22 patients and all had gradients above 18 mm Hg (mean 22 ± 2.6 mm Hg). Mitral valve area calculated in 17 patients with this pattern was 0.67 ± 0.26 cm².

The differences in mitral valve gradient and area

Figure 3. Correlation between the Doppler pattern and mitral valve gradient. Forty-four patients had a normal flow pattern (O) and in none of these was a mitral valve gradient observed at cardiac catheterization. Pattern I was observed in 36 patients and in all, the gradient was below 10 mm Hg (mean 6.1 ± 1.7 mm Hg). Pattern II seen in 54 patients was associated with gradients between 8–18 mm Hg (mean 12 ± 2.5 mm Hg). Pattern III was observed in 22 patients and in all the gradient was above 18 mm Hg. The overlap between Doppler patterns was minimal.
between Doppler pattern I and II and between pattern II and III were all significant (p < 0.001). Only four patients with pattern I overlapped with pattern II; all of them had gradients between 8–10 mm Hg. Overlap was more frequent when Doppler patterns were correlated with mitral valve area (fig. 4).

The mitral gradients associated with each pattern were similar when either sinus rhythm or atrial fibrillation was present (table 1). With pattern I, the 16 patients in sinus rhythm had a gradient of $5.5 \pm 1.2$ mm Hg and the 20 patients in atrial fibrillation a gradient of $6.6 \pm 1.8$ mm Hg (NS). With pattern II, gradients were, respectively, $12 \pm 2.8$ in the 22 patients in sinus rhythm and $11.9 \pm 2.7$ in the 32 patients with atrial fibrillation (NS). The gradient was $21.8 \pm 2.5$ in the 13 patients with pattern III and sinus rhythm and $22.2 \pm 2.2$ in the nine patients with this pattern and atrial fibrillation (NS). The only patient who had simultaneous Doppler and intracardiac pressure recordings went from a Doppler pattern II during long cardiac cycles, with a hemodynamic gradient of $13 \text{ mm Hg}$, to a pattern III during short cardiac cycles, with a gradient of $19 \text{ mm Hg}$.

The presence of mitral regurgitation did not change the relation between the Doppler pattern and the gradients, which were, respectively, $6.4 \pm 1.7, 12.5 \pm 3.7$ and $21.4 \pm 2.8 \text{ mm Hg}$ with patterns I, II and III. The correlation was also unaffected in the 32 patients with coexisting aortic valve disease. Mean gradients were, respectively, $6.2 \pm 2.4, 12.5 \pm 2.6$ and $22.7 \pm 2.5 \text{ mm Hg}$. These values were not significantly different from those in patients with isolated mitral stenosis (table 1).

**Application to the Carpentier-Edwards Porcine Xenograft**

Twelve patients in this study had had mitral valve replacement by a Carpentier-Edwards prosthesis. Six were in atrial fibrillation and six in sinus rhythm. All had pattern I and all gradients were 4.5–8 mm Hg (mean $5.2 \pm 1.6 \text{ mm Hg}$).

**Discussion**

Previous reports have shown that mitral valve flow can be studied by pulsed Doppler echocardiography and that the severity of mitral stenosis can be appreciated by the pattern of the wave form obtained. The present study provides additional information in the analysis of these velocity flow curves and represents a more definitive study performed prospectively in a large series of patients. A good-quality flow recording adequate for diagnostic purposes was obtained in 89% of 175 consecutive patients who underwent cardiac catheterization.

**Diagnosis of Mitral Stenosis**

In patients in sinus rhythm, the Doppler flow pattern easily identified patients with or without mitral stenosis. Thus, loss of the biphasic flow pattern or the presence of a filling wave in late diastole larger than the early diastolic wave indicated the presence of mitral stenosis. Mitral stenosis never occurred in patients who did not have these abnormalities. These observations are in agreement with intracardiac Doppler studies obtained by transseptal left-heart catheterization.

In the presence of atrial fibrillation, different diagnostic criteria are necessary because atrial contraction does not occur. The presence of turbulence in the recording and of a grade 3 Doppler pattern during

**Table 1. Relationships Between the Doppler Pattern and the Mitral Valve Gradient**

<table>
<thead>
<tr>
<th>Doppler pattern</th>
<th>All patients</th>
<th>Sinus rhythm</th>
<th>Atrial fibrillation</th>
<th>Mitral regurgitation</th>
<th>Aortic valve disease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>MVG</td>
<td>n</td>
<td>MVG</td>
<td>n</td>
</tr>
<tr>
<td>I</td>
<td>36</td>
<td>6.1 ± 1.7</td>
<td>16</td>
<td>5.5 ± 1.2</td>
<td>20</td>
</tr>
<tr>
<td>II</td>
<td>54</td>
<td>12 ± 2.5</td>
<td>22</td>
<td>12 ± 2.8</td>
<td>32</td>
</tr>
<tr>
<td>III</td>
<td>22</td>
<td>21.9 ± 2.6</td>
<td>13</td>
<td>21.8 ± 2.6</td>
<td>9</td>
</tr>
</tbody>
</table>

Abbreviations: n = number of patients; MVG = mean mitral valve gradient (mean ± sd).
short diastoles or after several short cardiac cycles was indicative of mitral stenosis. Pattern III was not found with atrial fibrillation in the absence of a mitral gradient. The behavior of Doppler flow curves in atrial fibrillation is consistent with the hemodynamic observation in mitral stenosis that the mitral valve gradient increases with shorter diastolic filling periods.

Using the above criteria, all patients with mitral stenosis were detected and all patients without stenosis were correctly identified even when associated mitral regurgitation or aortic valvular disease was present. These criteria might have been less specific if a large number of patients with a wide spectrum of heart disease had been studied; however, none of the 34 patients with other types of heart disease or the 10 normals studied were misdiagnosed. In addition, all of the data acquired by Doppler echocardiography were not used in this study. We did not use the audible signal of the Doppler shift of frequency and based our diagnosis only on the recorded signal, which omits much of the data in the audio signal. Turbulence with mitral stenosis is well perceived by the ear as high-frequency sounds and spectral analysis of the audio signal using a rapid Fourier transformation could improve the diagnostic capabilities of Doppler echocardiography.

Assessment of Severity of Mitral Stenosis

The study of flow patterns provided an accurate, semiquantitative assessment of the severity of mitral stenosis. The overlap in gradient among the three patterns observed was always between 8–10 mm Hg and thus did not appear important enough to impair the clinical utility of the test.

The correlation between Doppler patterns was better with mitral valve gradient than with mitral valve area. This is expected since flow velocity (V) is more directly related to gradient (MVG) than to area (MVA) according to the formulas V = MVF/MVA, MVG = MVF/\sqrt{V}MVG, and V = \sqrt{V}MG. With a steady flow through an orifice Torricelli's law predicts that the pressure gradient is closely related to the velocity through the orifice when the Reynolds number is large enough and the viscous losses of energy negligible compared with the losses of kinetic energy: \(\Delta P = \frac{1}{2} \epsilon V^2 \text{max}^2\) (\(\Delta P = \text{pressure gradient}, \epsilon = \text{mass density of fluid}, \text{and } V \text{max} = \text{maximum fluid velocity}\). Holen et al.\(^5\) and Hatle et al.\(^6\) used the Doppler shift to calculate the maximum velocity of the mitral flow and showed that indeed this parameter correlated very well with pressure drop through the stenotic mitral valve.

Heart rate influences mitral valve gradient because tachycardia shortens filling time, compromising ventricular flow across the mitral valve. Atrial fibrillation allows study of the dynamic beat-to-beat variation in mean gradient and in Doppler pattern. Thus, the Doppler pattern changes to a higher grade when short cardiac cycles are selected. This was clearly evident in the one patient that had Doppler recordings at the time of cardiac catheterization.

The Doppler flow patterns observed in this study can be related directly to the hemodynamic abnormalities that occur in mitral stenosis. Thus, in mild stenosis initial filling of the left ventricle is reduced and left atrial volume is increased. Since the force of contraction of the left atrium is related to left atrial pressure at the onset of contraction,\(^21\) this will lead to an increased driving pressure during atrial systole, and thus an increased blood flow velocity. Therefore, the Doppler study will show a relatively tall end-diastolic wave in sinus rhythm, indicating that mitral blood flow velocity is higher during atrial contraction than during passive left ventricular filling.

With more severe degrees of stenosis, the velocity flow curve is monophasic, dome-shaped in moderate stenosis, and ascending throughout diastole in severe stenosis. In the presence of an anatomic obstruction, the rate of flow is reduced and thus volume acceleration of blood flow through the mitral valve is expected to be slow. If the gradient is sustained, acceleration will also be sustained to end-diastole. Acceleration varies inversely with the degree of stenosis and can be appreciated as the slope of the Doppler flow curve. Thus, the characteristics of the flow patterns observed in this study can be explained by known hemodynamic principles.

Significant mitral regurgitation does not affect the predictive value of the Doppler pattern. Similarly, the presence of aortic stenosis or regurgitation did not influence the relation between the Doppler pattern and mitral valve gradient. This represents an advantage of the Doppler approach compared with standard echocardiography for the noninvasive evaluation of mitral stenosis.

Doppler echocardiography may also be superior to standard echocardiography in patients with mitral bioprostheses. The Doppler echocardiographic study is facilitated in these patients by the echo-producing stents of the valve; however, quality decreases because of difficulty in eliminating valvular noises. The role of Doppler echocardiography in patients with prosthetic mitral valves must be evaluated in a larger series of patients, including those with valvular dysfunction.

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