In symptomatic severe aortic regurgitation, left ventricular diastolic pressure increases rapidly, often exceeding left atrial pressure in late diastole. This characteristic hemodynamic change should be reflected in the Doppler mitral inflow velocity, which is the direct result of the diastolic pressure difference between the left ventricle and left atrium. Mitral inflow velocity was obtained by pulsed wave Doppler echocardiography in 11 patients (6 men, 5 women; mean age 53 years) with severe symptomatic aortic regurgitation and compared with normal values from 11 sex- and age-matched control subjects.

The following Doppler variables were determined: velocity of early filling wave (E), velocity of late filling wave due to atrial contraction (A), E to A ratio (E/A), deceleration time and pressure half-time. In severe aortic regurgitation, E and E/A (1.13 m/s and 3.3, respectively) were significantly higher (p < 0.001) than normal (0.60 m/s and 1.5, respectively). Deceleration time and pressure half-time (117 and 34 ms, respectively) were significantly shorter (p < 0.001) than normal (203 and 59 ms, respectively). Late filling wave velocity (A) was not statistically different in the two groups, although it tended to be lower in the patient group (0.39 versus 0.50 m/s). Diastolic mitral regurgitation was present in eight patients (73%). M-mode echocardiography of the mitral valve, performed in 10 patients, showed that only 3 (30%) had premature mitral valve closure.

In symptomatic severe aortic regurgitation, the Doppler mitral inflow velocity pattern is characteristic, with increased early filling wave velocity (E) and early to late filling wave ratio (E/A) and decreased deceleration time of the E wave. This Doppler pattern appears to be more sensitive than premature closure of the mitral valve for detecting hemodynamically significant aortic regurgitation.

Methods

Study patients. This study is based on 11 patients (6 men, 5 women; mean age 53 years; range 26 to 77) with severe aortic regurgitation who underwent a comprehensive echocardiographic examination between October 1986 and September 1987 at a Mayo Clinic-affiliated hospital. All were in sinus rhythm without first degree atrioventricular (AV) block. With the exception of one patient who had a fatal cardiac arrest, all underwent aortic valve replacement within 35 days (range 1 to 35) after the echocardiographic study. Repeat two-dimensional Doppler echocardiographic examinations were performed after aortic valve replacement in four patients.

Severe aortic regurgitation was documented in eight patients by Doppler color flow imaging. Aortography was performed in five patients and showed severe aortic regur-
Table 1. Clinical Characteristics of 11 Study Patients*

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Sex/Age (yr)</th>
<th>Blood Pressure (mm Hg)</th>
<th>LVEF (%)</th>
<th>AR on Aortogram</th>
<th>Cause of AR</th>
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<tr>
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<td>60</td>
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<td>Aortic valve debidement</td>
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<tr>
<td>2</td>
<td>M/26</td>
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<td>ND</td>
<td>Prosthesis malfunction</td>
</tr>
<tr>
<td>3</td>
<td>F/68</td>
<td>132/40</td>
<td>55</td>
<td>ND</td>
<td>Endocarditis</td>
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<tr>
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<td>54</td>
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<td>Anuloaortic ectasia</td>
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<td>F/59</td>
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<td>Severe</td>
<td>Prosthesis malfunction</td>
</tr>
<tr>
<td>7</td>
<td>M/31</td>
<td>120/44</td>
<td>56</td>
<td>ND</td>
<td>Endocarditis (prosthesis): ring abscess</td>
</tr>
<tr>
<td>8</td>
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<td>50</td>
<td>Severe</td>
<td>Aortic root dilation; aortitis</td>
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<tr>
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<td>Aortic dissection</td>
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<td>F/47</td>
<td>140/50</td>
<td>56</td>
<td>ND</td>
<td>Prosthesis malfunction</td>
</tr>
</tbody>
</table>

*Subsequent treatment was aortic valve replacement in all except Patient 5, who died before operation. AR = aortic regurgitation; F = female; LVEF = left ventricular ejection fraction; M = male; ND = not done.

gitation (grade 4) in all according to the criteria of Sellers et al. (8). Aortic valve and root abnormalities responsible for the severe aortic regurgitation were identified in 10 patients at the time of aortic valve replacement (Table 1). Eleven sex- and age-matched control subjects were selected from a pool of normal subjects studied to establish normal Doppler values in our laboratory. All control subjects had normal findings on cardiac examination and two-dimensional echocardiography.

Echocardiography. A Hewlett-Packard cardiac ultrasonography unit was used for the comprehensive M-mode/two-dimensional/Doppler/color flow imaging echocardiographic examination. A combined 2.5 MHz phased array and pulsed wave Doppler transducer and a nonimaging continuous wave Doppler probe were used. Examination was performed with the patient in the left lateral decubitus position. Mitral inflow velocity was obtained by pulsed wave Doppler examination from the apical view by placing the sample volume between the tips of mitral leaflets (Fig. 1). Velocity signals were recorded on a strip chart at 50 mm/s.

The following variables were analyzed: 1) velocity of early filling wave (E); 2) velocity of late filling wave due to atrial contraction (A); 3) ratio of E to A (E/A); and 4) deceleration time and pressure half-time of the E wave. Deceleration time was measured as the interval from the peak of E to the point where the deceleration curve reaches the baseline. Pressure half-time was defined as the interval required for the peak transmitral gradient to decrease to half its peak value. It was measured on the Doppler mitral inflow velocity tracing as the interval from peak E velocity to the time when the velocity was equal to the peak velocity divided by the square root of 2 (9). Moving the sample volume slightly to the atrial side of the mitral orifice provided a search to document mitral regurgitation during late diastole. The continuous wave Doppler pattern of the aortic valve was obtained from the apical position by using a nonimaging probe to measure pressure half-time of the aortic regurgitation signal (10).

Severity of aortic regurgitation was assessed by comparing the width of the regurgitation jet in the color flow image with the diameter of the left ventricular outflow tract (11). Aortic regurgitation was judged to be severe when its jet width was greater than two-thirds of the outflow tract diameter on the parasternal long-axis view.

The M-mode echocardiogram of the mitral valve was obtained by placing an M-mode cursor through the central portion of the mitral valve in a parasternal short-axis view under guidance by two-dimensional echocardiography. It was used to determine whether mitral valve closure was premature (complete coaptation of the anterior and posterior mitral valve leaflets at or before the initial inscription of the QRS complex). Left ventricular ejection fraction was calculated by the method of Quinones et al. (12).

Analysis. For each patient and normal control subject, Doppler velocity signals from three cardiac cycles were analyzed to obtain a mean value for each variable. Doppler values were expressed as mean ± standard deviation. Comparisons of mean values for study and control groups were performed by Student's paired t test.
Figure 2. Upper, Continuous wave Doppler signal of aortic regurgitation in the same patient on two examinations 3 days apart, demonstrating progressive shortening of pressure half-time. Either value alone indicates severe aortic regurgitation. Lower left, Continuous wave Doppler signal of the mitral valve, showing the timing of systolic (thin arrow) and diastolic (before QRS onset) (thick arrow) mitral regurgitation. Lower right, Pulsed wave Doppler signal of mitral flow, with short deceleration time of the E wave and diastolic mitral regurgitation (thick arrow). M = mitral valve closure.

Results

Clinical characteristics of the study patients (Table 1). All were in New York Heart Association functional class III or IV. Mean left ventricular ejection fraction was 57% (range 47 to 70). The cause of the aortic regurgitation was aortic prosthesis malfunction in four patients, aortic root dilation in two, endocarditis in three, aortic dissection in one and postoperative aortic valve decalcification procedure in one. The aortic valve was replaced in all patients except one who had cardiac arrest in the hospital a day before the planned operation.

Continuous wave Doppler echocardiography and color flow imaging. A satisfactory continuous wave Doppler signal of aortic regurgitation was obtained in 10 patients (Fig. 2). The diastolic pressure half-time of this signal ranged from 121 to 300 ms (mean 182). Color flow imaging showed severe aortic regurgitation in eight patients (73%), but an eccentric jet prevented a satisfactory assessment of aortic regurgitation severity in three patients. Aortic root angiography showed severe aortic regurgitation in five patients, including the three patients with suboptimal color flow imaging.

Mitral inflow velocity by Doppler measurement. A typical mitral inflow velocity pattern from one of our patients with severe aortic regurgitation is shown in Figure 2. Doppler data from all 11 patients and the normal control subjects are summarized in Table 2. The E velocity was significantly (p < 0.001) higher than normal, but the A velocity was not significantly different from (although it tended to be lower than) normal. The E/A ratio was significantly (p < 0.001) higher than that of the normal control subjects. Deceleration time and pressure half-time were shortened significantly (p < 0.001) and, except for one patient (Case 11), there was no overlap in these time intervals among patients with aortic regurgitation and normal control subjects.

Echocardiography was repeated in four patients after aortic valve replacement (3 to 8 days postoperatively). The Doppler pattern of the mitral inflow velocity had become normal in two patients (Cases 1 and 3) (Fig. 3) and continued to be abnormal in two (Cases 7 and 9). However, Patient 7 who had a large aortic ring abscess cavity due to endocarditis was found to have persistent aortic regurgitation after aortic valve replacement, and Patient 9 had perioperative myocardial infarction.

Comparison of diastolic mitral regurgitation and premature mitral valve closure. Diastolic mitral regurgitation was present in eight patients (73%); the mean deceleration time in these patients was 105 ms (range 82 to 130) and was shorter than that in the three patients without diastolic mitral regurgitation (mean 148 ms; range 138 to 160). Mitral valve closure was documented in 10 patients by M-mode echocardiography; only 3 (30%) of these patients had premature mitral valve closure relative to the onset of the QRS complex.

Discussion

Pridie et al. (13) were the first to recognize premature closure of the mitral valve on M-mode echocardiograms from patients with severe aortic regurgitation. It subsequently was reported (3,4) that the premature mitral valve closure was a result of a marked increase in left ventricular diastolic pressure to greater than left atrial pressure. Left ventricular diastolic pressure occasionally equals or even exceeds aortic diastolic pressure, causing the aortic valve to open during diastole (5-7). Therefore, M-mode echocardiographic evidence of premature mitral valve closure or diastolic aortic valve opening is a mechanical manifestation of hemodynamic changes in the left ventricle in relation to left atrial and aortic diastolic pressures, respectively.

Mitrail inflow deceleration time and pressure half-time. With its capability to determine transvalvular pressure gradients reliably (14), Doppler echocardiography can measure the rate of pressure equilibration across the cardiac valves (9). In this study, we observed that deceleration time and pressure half-time of the transmitral pressure gradient derived from Doppler mitral inflow velocity are shortened in symptomatic patients with severe aortic regurgitation, probably because of the rapid increase in left ventricular diastolic pressure. It has also been reported (10) that the shortened
### Table 2. Summary of Doppler Echocardiographic Data in 11 Patients

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Heart Rate (beats/min)</th>
<th>E Wave (m/s)</th>
<th>A Wave (m/s)</th>
<th>E/A</th>
<th>DT (ms)</th>
<th>PHT (ms)</th>
<th>Diastolic MR</th>
<th>PHT of AR Signal (ms)</th>
<th>QRS to MVC (ms)</th>
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</tr>
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<td>83 ± 12</td>
<td>1.13* ± 0.18</td>
<td>0.39 ± 0.17</td>
<td>3.3* ± 1.5</td>
<td>117* ± 22</td>
<td>34* ± 6</td>
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</table>

* All values are expressed as mean ± standard deviation (SD).

### Normal Control Subjects

<table>
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<tr>
<th>Subject No.</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Heart Rate (beats/min)</th>
<th>E Wave (m/s)</th>
<th>A Wave (m/s)</th>
<th>E/A</th>
<th>DT (ms)</th>
<th>PHT (ms)</th>
<th>Diastolic MR</th>
<th>PHT of AR Signal (ms)</th>
<th>QRS to MVC (ms)</th>
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<tr>
<td><strong>Mean ± SD</strong></td>
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*p < 0.001 for difference from mean of sex- and age-matched control subjects. A = late filling wave velocity due to atrial contraction; DT = deceleration time; E = rapid early filling wave velocity; E/A = E to A ratio; MR = mitral regurgitation; PHT = pressure half-time; QRS to MVC = onset of QRS (on the electrocardiogram) to the time of mitral valve closure (<0 indicates premature closure of mitral valve); other abbreviations as in Table 1.

The changes in the Doppler mitral flow velocity pattern in severe aortic regurgitation may create a diagnostic pitfall in determining the severity of mitral stenosis by using the transmitral pressure half-time. Hatle et al. (9) showed that mitral valve area can be reliably estimated as the quotient of 220 divided by the Doppler-derived mitral pressure half-time. Hence, mitral inflow velocity, which is easier to obtain, can serve as another variable in evaluating the hemodynamic consequence of aortic regurgitation.

The discrepancy between these two studies may be related to the difference in the severity of aortic regurgitation and left ventricular compliance. A large regurgitant volume pressure half-time (<400 ms) of the aortic regurgitation velocity signal has a predictive value for detecting severe regurgitation. It was shortened in all 10 of our patients in whom the aortic regurgitation signal could be obtained. However, the complete aortic regurgitation Doppler envelope may not always be feasible (as in Case 10) because of an eccentric regurgitation jet. Hence, mitral inflow velocity, which is easier to obtain, can serve as another variable in evaluating the hemodynamic consequence of aortic regurgitation.

The changes in the Doppler mitral flow velocity pattern in severe aortic regurgitation may create a diagnostic pitfall in determining the severity of mitral stenosis by using the transmitral pressure half-time. Hatle et al. (9) showed that mitral valve area can be reliably estimated as the quotient of 220 divided by the Doppler-derived mitral pressure half-time. The pressure half-time for a given mitral valve area was found to be independent of atrial fibrillation and mitral regurgitation (15). Although transmitral pressure half-time was shortened significantly in our patients with severe aortic regurgitation, a previous study (16) showed that mitral valve area calculated by the pressure half-time method correlates well with that from cardiac catheterization, even in the presence of significant aortic regurgitation. However, the patients in that study had chronic compensated aortic regurgitation (grade 2 to 4) rather than symptomatic severe aortic regurgitation as in the present study, and those investigators (16) cautioned that the pressure half-time method may not be accurate in the setting of acute aortic regurgitation. More recently, Nakatani et al. (17) reported that the pressure half-time method significantly overestimated mitral valve area in eight patients with moderate to severe (grade 3 to 4) chronic aortic regurgitation.
operation.

bles (increased E, decreased A and increased E/A) charac-

teristic of restrictive ventricular filling were opposite to what

was expected with increased heart rate.

Premature mitral valve closure versus Doppler mitral
inflow velocity. In our study, premature closure of the mitral
valve was seen in only 3 (30%) of the 10 patients with
symptomatic aortic regurgitation. Seven of 17 patients with
severe aortic regurgitation in the study by Botvinick et al. (4)
did not have premature closure of the mitral valve. There-
fore, it appears that the Doppler mitral inflow velocity of
restrictive ventricular filling pattern is more sensitive in
predicting the rapid increase in left ventricular diastolic
pressure associated with severe aortic regurgitation. Prema-
ture mitral valve closure is also not specific for increased left
ventricular diastolic pressure because it occurs in patients
with first degree AV block, which unmasks atrial relaxation.
However, mitral deceleration time or pressure half-time
should be normal in patients with first degree AV block and
normal left ventricular diastolic pressure.

Like the disappearance of the premature mitral valve
closure in severe aortic regurgitation after aortic valve
replacement (4), the mitral inflow velocity pattern of severe
aortic regurgitation returns to normal after aortic valve
replacement unless other superimposed conditions that re-
result in restrictive ventricular filling (such as restrictive car-
diomyopathy, severe left ventricular dysfunction or de-
creased left ventricular compliance) remain.

Limitations. Major limitations of this study are its small
number of patients and lack of hemodynamic correlation
with Doppler mitral inflow velocity patterns. However, the
changes in Doppler mitral inflow velocity in the 11 patients
with severe aortic regurgitation were consistent, and the
typical hemodynamics of severe aortic regurgitation have
been well documented by others (3,4). The patients in this
study were selected because they had symptomatic aortic
regurgitation of relatively short duration. Although our ini-
tial observation suggests that the Doppler mitral inflow
velocity pattern is potentially helpful in detecting hemody-
amically significant aortic regurgitation, a prospective
study involving a larger number of patients with aortic
regurgitation of various severities and durations is needed to
determine its clinical value.

Conclusions. As yet, there is no completely satisfactory
noninvasive method for evaluating the severity of aortic
regurgitation. Although Doppler color flow imaging and
determination of pressure half-time of aortic regurgitation by
continuous wave Doppler examination have been shown to
be helpful in the assessment of aortic regurgitation, optimal
recordings occasionally cannot be obtained. Mitral inflow
velocity is easy to document by pulsed wave Doppler
echocardiography, and the characteristic increased mitral
inflow velocity relative to late filling velocity we observed in
the patients with severe aortic regurgitation may prove to be
useful as an additional noninvasive hemodynamic variable in

Figure 3. Mitral inflow velocity patterns before (upper) and after
(lower) aortic valve replacement in Patient 3, who had aortic valve
endocarditis. Deceleration time was very shortened (85 ms), and the
E/A ratio was increased to 4.4 before aortic valve replacement.
These values were normal (225 ms and 1.1, respectively) after
operation.

may not always produce a significant increase in left ventric-
ular diastolic pressure or shortening of the mitral pressure
half-time if the left ventricle is chronically dilated and
compliant. On the other hand, the pressure half-time is
shortened in patients with decreased left ventricular compli-
ance and "restrictive" physiology (18). Therefore, we
should be aware of the multiple factors that influence the
mitral pressure half-time to avoid an overestimation of mitral
valve area.

E, A and E/A. When left ventricular end diastolic pres-
sure is markedly increased, late ventricular filling as a result
of atrial contraction (A) is diminished (19), resulting in
decreased A velocity. Although not statistically significant in
our study (probably because of the small number of
patients), A velocity in the patient group was smaller than
that in the normal control group (0.39 versus 0.50 m/s) and
was similar to the peak A velocity derived from 14 patients
with restrictive physiology reported by Appleton et al. (18).
After the impaired left atrial emptying at end-diastole, left
atrial volume and pressure continue to increase until the
opening of the mitral valve, producing a relatively high E
velocity. Consequently, the E/A ratio was significantly in-
creased in the patient group. These Doppler variables are
influenced by multiple factors such as the patient's age (20)
and heart rate (21). The heart rate in the patient group was
slightly higher than that in the normal control group (83
versus 66 beats/min), but the changes in the Doppler vari-
ables (increased E, decreased A and increased E/A) charac-

E/A ratio was increased to 4.4 before aortic valve replacement.

mitral valve closure is also not specific for increased left
ventricular diastolic pressure because it occurs in patients
with first degree AV block, which unmasks atrial relaxation.
However, mitral deceleration time or pressure half-time
should be normal in patients with first degree AV block and
normal left ventricular diastolic pressure.
the evaluation and management of patients with chronic or acute aortic regurgitation.

References