DIAGNOSTIC METHODS

AORTIC REGURGITATION

Noninvasive evaluation of aortic regurgitation by continuous-wave Doppler echocardiography

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ABSTRACT Continuous-wave Doppler echocardiography was used to examine the aortic regurgitant flow velocity pattern in 32 patients with aortic regurgitation (AR) and 10 patients without AR. The aortic regurgitant flow velocity pattern, characterized by a rapid rise in flow velocity immediately after closure of the aortic valve, high peak flow velocity, and a gradual deceleration until the next aortic valve opening, were successfully obtained in 30 of the 32 patients with AR (sensitivity 94%, specificity 100%). The velocity decline was greater in patients with severe AR; thus, the slope of the velocity decline (deceleration) and the time to decline to half the peak velocity (half-time index) were measured from the flow velocity pattern. The deceleration became greater and the half-time index shortened in accordance with angiographic grading of AR (p < .01). The deceleration and the half-time index also correlated well with the aortic regurgitant fraction (r = .79, p < .01; r = -.89, p < .01). Because the half-time index could be measured easily and independently of Doppler incident angle, it seemed a simple and accurate index of assessing the severity of AR. Thus continuous-wave Doppler echocardiography permitted the noninvasive evaluation of AR.


THE RECENT ADVENT of continuous-wave Doppler echocardiography has made it possible to measure high flow velocities that cannot be measured with conventional pulsed Doppler echocardiography.1 Thus high blood flow velocity across the stenotic valve can now be obtained noninvasively for the determination of the pressure gradient across the stenotic valve and stenotic valve orifice area by means of the simplified Bernoulli equation.2-4 The usefulness of continuous-wave Doppler echocardiography in evaluating valvular stenosis has been confirmed in many studies.2-5 Recently, several investigators1, 9, 10 described that characteristic regurgitant flow velocity patterns, which could not be measured with pulsed Doppler echocardiography because of aliasing effects of high velocities, could be measured with continuous-wave Doppler echocardiography. However, the feasibility of this method for evaluating valvular regurgitation has never been studied.

In this study, we used continuous-wave Doppler echocardiography for noninvasive evaluation of aortic regurgitation (AR). Patterns of aortic regurgitant flow velocity across the aortic valve were analyzed to develop an index that could be used for assessing the severity of AR.

Methods
Patient selection. The study population consisted of 32 patients with AR (22 men and 10 women, ages 37 to 71 years, mean 54) and 10 patients without AR (eight men and two women, ages 42 to 64 years, mean 55). All patients underwent diagnostic cardiac catheterization, and the presence of AR was confirmed or ruled out by aortic root angiography. Twenty-six patients had pure AR and six had combined aortic stenosis and regurgitation; 10 patients had associated mitral stenosis and 11 patients had associated mitral regurgitation. Twenty-seven were in sinus rhythm and the remainder had atrial fibrillation.

Doppler examination was performed 18 to 24 hr before cardiac catheterization in 31 patients, within 1 week in six patients, and within 4 weeks in five patients. The clinical condition of the patients did not change in the interim.

Doppler examination. The Doppler examinations were performed with a duplex Doppler echocardiograph (Toshiba SDS-21B with SSH-40A) equipped with a 2.4 MHz phased-array transducer. Measurements were performed in the continuous-wave Doppler mode. The beam direction of the transmitted ultrasound was fixed and displayed as a bright dotted line in the two-dimensional echocardiographic image (figure 1). The beam direction of the received ultrasound was movable and displayed as a bright solid line in the two-dimensional echocardiographic...
image. In continuous-wave Doppler sampling, no specific depth gate is established, and all velocities along the lines are processed for velocity determination. Doppler signals derived from structures were minimized by a high-pass filter, and all signals were analyzed in real time by fast-Fourier transform. Doppler flow velocity pattern, simultaneous lead II electrocardiogram, and phonocardiogram were displayed on a monitor and recorded on videotape or on a strip-chart recorder at a paper speed of 50 to 100 mm/sec. The directions of the Doppler beams could be verified frequently during the examination by briefly switching to the imaging mode.

Each patient was asked to rest in a supine position or in a left lateral decubitus position and to breathe in a relaxed way during Doppler examination. The transducer was placed on the cardiac apex and angulated medially to depict the left ventricular outflow tract and the ascending aorta in a left anterior oblique equivalent view. The crossing point of transmitted and received ultrasound beam lines was advanced to the level of the aortic orifice. The transducer was tilted slowly until the highest Doppler frequency shifts could be obtained with the aid of the audio signals. In four patients, additional recordings were obtained with the transducer in the lower left sternal border.

**Data analysis.** The envelope of the flow velocity pattern in diastole, i.e., instantaneous maximal velocity, was used for quantitative analysis. The highest discernible frequencies were traced by hand, and three indexes were determined with continuous-wave Doppler echocardiographic measurements: (1) peak flow velocity, (2) deceleration, and (3) half-time index. Peak velocity was calculated from the Doppler equation as

\[
\text{velocity} = c \cdot \Delta F/2 \cdot f_0 \cdot \cos \theta
\]

where \(c\) = sound velocity in tissue or 1540 m/sec, \(\Delta F\) = Doppler shift frequency, \(f_0\) = carrier frequency, and \(\theta\) = Doppler incident angle. \(\theta\) was assumed to be zero in this study (cos \(\theta = 1.0\)) because the direction of aortic regurgitation flow could not be predicted from the anatomy of the surrounding structures. The deceleration was determined as the slope of a straight line drawn between the peak velocity and the shoulder at end-diastole. Half-time index was defined as the interval between the peak velocity and one-half of the peak velocity with reference to the straight line drawn in determining the deceleration. All measurements from flow velocity patterns are presented as the average of at least five cardiac cycles.

Peak velocity and half-time index were determined in seven patients by one observer on two occasions (intraobserver variability). Another observer independently performed the determination for the same seven patients (interobserver variability). All observers were blinded to each other’s results and to the results of catheterization. Peak velocity correlated well between intraobserver and interobserver determinations, with a correlation coefficient of .99 and mean absolute differences between observations (expressed as a percentage of the first observer’s first observation) of 2.6% (intraobserver) and 5.8% (interobserver). Good correlations were also obtained for half-time index, with a correlation coefficient of .99 and mean absolute differences between observations of 2.8% (intraobserver) and 6.4% (interobserver).

**Cardiac catheterization.** All patients underwent cardiac catheterization. Aortic root angiography was performed with injection of 50 to 60 ml of meglumine/sodium diatrizoate (Urografin). The degree of AR was graded independently from the echocardiographic findings on a three-point scale from angiography as follows: (1) mild (nine patients), minimal dye in the upper part of the left ventricle clearing in the next systole; (2) moderate (13 patients), dye in the left ventricle not clearing in the next systole, with slow opacification of the left ventricle, which remained fainter than that of the aorta; (3) severe (10 patients), dye producing a rapid opacification of the left ventricle equal to or denser than that of the aorta.

In addition to semiquantitative angiographic grading, AR was quantitated by aortic regurgitant fraction, which was determined during cardiac catheterization. Since the regurgitant output is the difference of the total cardiac output and the effective cardiac output, the regurgitant fraction is calculated as the difference divided by the total cardiac output. In this study, the effective forward cardiac output was measured with the indicator dilution procedure. The total cardiac output was measured with left ventriculography and standard area-length methods.\(^{11, 12}\)

**Statistical analysis.** All values were expressed as mean ± SD. Significance of differences between the mean values of peak flow velocity, decelerations, and half-time index in patients with and without AR were assessed with analysis of variance and a multiple comparison method. The diagnostic value of aortic regurgitant peak flow velocity was assessed by calculating sensitivity and specificity. Doppler indexes were also compared with the regurgitant fraction by linear regression analyses.
Results

Flow velocity patterns in the left ventricular outflow tract. A representative recording of flow velocity in the left ventricular outflow tract obtained in a patient without AR is shown in figure 1. In all 10 patients without AR, the flow velocity pattern in diastole had only slow velocity components. In 30 of 32 patients with AR, the aortic regurgitant flow velocity patterns were successfully recorded by continuous-wave Doppler echocardiography (figures 2 and 3). The two patients with AR in whom aortic regurgitant flow velocity patterns were not successfully recorded by continuous-wave Doppler echocardiography had mild AR as proved by aortic root angiography. The pattern of aortic regurgitant flow was characterized by a rapid rise in flow velocity to a peak level just after the aortic valve closure, followed in turn by a slow linear deceleration until the next aortic valve opening.

Quantitative analysis of Doppler flow velocity patterns and angiographic findings. The detailed observations of the quantitative analysis of Doppler recordings are summarized in table 1. No significant difference in heart rate was observed between the 10 patients without AR and the 30 patients with AR in whom Doppler recordings of aortic regurgitant flow were successfully obtained (68 ± 7 vs 68 ± 11 beats/min). Diastolic peak flow velocity recorded in the left ventricular outflow tract with continuous-wave Doppler echocardiography was significantly greater in patients with AR than in patients without AR (3.9 ± 0.6 vs 0.5 ± 0.2 m/sec; p < .01). When the peak flow velocity was greater than 1.8 m/sec, the probability of AR was 100% (figure 4). Sensitivity was 94%, specificity was 100%, and diagnostic accuracy was 95%. The peak velocity of aortic regurgitant flow, however, had no correlations with the grading of AR.

As the degree of AR became severer, deceleration of the aortic regurgitant flow velocity became greater and
the half-time index became lower (figures 5 and 6). The deceleration in patients with moderate AR was significantly greater than that in patients with mild AR (2.2 ± 0.4 vs 1.5 ± 0.5 m/sec²; p < .01). The deceleration in patients with severe AR (4.0 ± 1.0 m/sec²) was significantly greater than that in patients with moderate AR (p < .01). The half-time index was significantly lower in patients with moderate AR than in patients with mild AR (0.89 ± 0.14 vs 1.22 ± 0.24 sec; p < .01) and was significantly lower in patients with severe AR (0.52 ± 0.08 sec) than in patients with moderate AR (p < .01). Concurrent aortic stenosis, mitral stenosis, or mitral regurgitation did not seem to affect the value of any Doppler indexes.

Comparisons of Doppler indexes and aortic regurgitant fraction. The Doppler indexes—deceleration and half-time index—were compared with aortic regurgitant fraction in 20 patients without mitral regurgitation (figures 7 and 8), since the concurrent mitral regurgitation produced overestimation of total cardiac output and hence overestimation of regurgitant fraction. Aortic

<p>| TABLE 1 |
| Summary of quantitative analysis of Doppler recordings in 40 patients in whom Doppler recordings were successfully obtained in the left ventricular outflow tract |</p>
<table>
<thead>
<tr>
<th></th>
<th>No AR</th>
<th>Mild AR</th>
<th>Moderate AR</th>
<th>Severe AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>10</td>
<td>7</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>55 ± 7</td>
<td>61 ± 8</td>
<td>51 ± 10</td>
<td>55 ± 7</td>
</tr>
<tr>
<td>Sex</td>
<td>8 M, 2 F</td>
<td>5 M, 2 F</td>
<td>9 M, 4 F</td>
<td>7 M, 3 F</td>
</tr>
<tr>
<td>Heart rate (bpm)</td>
<td>68 ± 7</td>
<td>76 ± 13</td>
<td>64 ± 9</td>
<td>68 ± 7</td>
</tr>
<tr>
<td>Peak velocity (m/sec)</td>
<td>0.5 ± 0.2</td>
<td>3.6 ± 0.8</td>
<td>3.9 ± 0.5</td>
<td>4.0 ± 0.5</td>
</tr>
<tr>
<td>Deceleration (m/sec²)</td>
<td>NE</td>
<td>1.5 ± 0.5</td>
<td>2.2 ± 0.4</td>
<td>4.0 ± 1.0</td>
</tr>
<tr>
<td>Half-time index (sec)</td>
<td>NE</td>
<td>1.22 ± 0.24</td>
<td>0.89 ± 0.14</td>
<td>0.52 ± 0.08</td>
</tr>
</tbody>
</table>

Values are mean ± SD.
NE = not evaluated.
^p < .01 vs no AR; ^p < .01 vs mild AR; ^p < .01 vs moderate AR.

FIGURE 4. Peak velocity of the aortic regurgitant flow in patients with and without AR. The mean value is indicated (horizontal long bar) with SDs for each group. There is a significant increase of the value in patients with AR compared with patients without AR (p < .01); however, there is no significant difference among the subgroups of AR patients divided according to the angiographic grading. Open symbols, Pure AR; closed symbols, combined aortic stenosis; circles and triangles, the absence and presence of concomitant mitral stenosis, respectively.

FIGURE 5. Deceleration of the aortic regurgitant flow was compared with the angiographic grading in 30 patients with AR in whom continuous-wave Doppler recordings of aortic regurgitant flow were successfully obtained. The mean value is indicated (horizontal long bar) with SDs for each group. Symbols are as in figure 4.
FIGURE 6. Half-time index was compared with the angiographic grading in 30 patients with AR in whom continuous-wave Doppler recordings of the aortic regurgitant flow were successfully obtained. The mean value is indicated (horizontal long bar) with SDs for each group. Symbols are as in figure 4.

regurgitant fraction correlated well with deceleration ($r = .79, p < .01$) and with half-time index ($r = -.89, p < .01$). Associated aortic stenosis and/or mitral stenosis did not seem to interfere the quantitation of AR.

Discussion

In this study, we analyzed aortic regurgitant flow velocity patterns to evaluate AR. The aortic regurgitant flow velocity pattern, recorded with continuous-wave Doppler echocardiography, showed a characteristic contour as reported before$^{1-9,10}$ and was quite different from that recorded with pulsed Doppler echocardiography. High velocities of the aortic regurgitant flow cannot be measured with pulsed Doppler echocardiography because of aliasing effects; the characteristic broad frequency spectral pattern of aortic regurgitant flow by pulsed Doppler echocardiography is produced concomitantly by the turbulence around the aortic regurgitant jet and aliasing effects of the high velocities.

Characteristic aortic regurgitant flow velocity patterns were successfully obtained in 30 of 32 patients with AR by continuous-wave Doppler echocardiography, and the peak flow velocity seemed to be useful in differentiating patients with AR and patients without AR. Although pulsed Doppler echocardiography might have been considered the most valuable noninvasive technique for detecting AR,$^{13,14}$ the sensitivity and specificity of detecting AR by continuous-wave Doppler echocardiography were comparable to those by pulsed Doppler echocardiography.$^{13-16}$ The two patients with AR in whom aortic regurgitant flow velocity pattern could not be detected had mild AR. All the patients with moderate or severe AR were successfully evaluated with continuous-wave Doppler echocardiography. This method seemed to be as useful in detecting AR as pulsed Doppler echocardiography.
Although the peak velocity of aortic regurgitant flow was useful in detecting AR, it did not correlate with the grading of AR. As AR became severer, the aortic regurgitant flow velocity pattern showed remarkable changes in the deceleration phase rather than in the peak velocity. The aortic regurgitant flow velocity decelerated more rapidly as AR became severer. The aortic regurgitant flow velocity is determined by the pressure difference between the aorta and the left ventricle (Bernoulli principle); therefore, the rapid deceleration in the aortic regurgitant flow velocity in patients with severe AR may be attributed to the rapid pressure decrease in the aorta and rapid pressure increase in the left ventricle.

We determined two indexes from the aortic regurgitant flow velocity pattern: deceleration and half-time index. Close observation showed that the velocity decrease in aortic regurgitant flow was not necessarily linear but curvilinear. Although one might think that actual half-time might improve the evaluation of AR, we could not measure the actual half-time because it was longer than the diastolic filling period in all but one patient in this study. Thus we determined both indexes on the imaginary straight line drawn between the peak velocity and the shoulder at end-diastole.

Deceleration became greater as AR became severer; however, there were some overlaps between mild and moderate AR and between moderate and severe AR, and correlation between deceleration and the aortic regurgitant fraction was poor. This may be explained by possible errors in the measurement of the aortic flow velocity. The direction of the aortic regurgitant jet is not predictable from the anatomy of surrounding structures, thus we did not correct the velocity for the Doppler incident angle. In some patients, the Doppler beam might not have been aligned parallel to the aortic regurgitant jet despite the fact, that we set the Doppler beam direction to obtain the highest Doppler frequency shifts with the aid of the audio signals. Thus we determined the half-time index in addition to deceleration. The half-time index should not be subject to the Doppler incident angle as long as the aortic regurgitant flow vector does not change during diastole, because the half-time index is not a function of velocity but of time, whereas deceleration is a function of both velocity and time. The half-time index shortened as AR became severer; however, there were still some overlaps between mild and moderate AR and between moderate and severe AR, which may be explained partly by possible changes in the Doppler incident angle against the jet as the heart altered its shape in diastole. In addition, the velocity decrease in the aortic regurgitant flow may have been influenced by various factors other than the degree of AR, such as stroke volume, compliance of the aorta, systemic vascular resistance, and compliance of the left ventricle. Further studies are indicated to assess the role of these factors. However, the half-time index correlated well with the angiographic grading and with the regurgitant fraction, and it seemed sufficient for quantitating AR.

Aortic root angiography is the most frequently used technique for patient evaluation in routine clinical practice, and its value has also been clearly shown. However, the angiographic grading is influenced by catheter position, rate and volume of contrast medium injection, left ventricular size, and the presence of mitral regurgitation. Therefore, we further compared the Doppler indexes with the regurgitant fraction measured during cardiac catheterization.

Pulsed Doppler flow mapping has been demonstrated to be quite useful in evaluating the degree of AR, since the distribution of diastolic disturbed flow in the left ventricle represents the distribution of aortic regurgitant flow. However, in the presence of mitral stenosis, it is often difficult to distinguish the broad frequency spectral pattern of AR and mitral stenosis even with real-time spectral analysis. On the other hand, the aortic regurgitant flow velocity pattern by continuous-wave Doppler echocardiography should be influenced very little by the combined mitral valve diseases, and we could determine the Doppler indexes regardless of concomitant mitral valve diseases. However, in the recording of aortic regurgitant flow velocity patterns by continuous-wave Doppler echocardiography in patients with associated mitral stenosis, another serious problem might arise in some cases: transmitial flow velocity can be mistaken for the aortic regurgitant flow velocity pattern because these patterns are similar. In such patients it is therefore necessary to verify that the recorded pattern is not of the transmitial flow but of the aortic regurgitant flow. In patients in sinus rhythm we could easily differentiate these patterns based on the presence or absence of secondary acceleration in late diastole caused by atrial contraction. Even in patients with atrial fibrillation we could distinguish these patterns based on the peak velocity and the time lag of the onset of the flow velocity pattern behind the second heart sound. Thus we solved the problem of the transmitial flow velocity pattern being mistaken for the aortic regurgitant flow velocity pattern in patients with concomitant mitral valve diseases by closely observing (1) the Doppler beam direction, (2) the shape of the flow velocity pattern, (3) the peak flow velocity, and (4) the time lag of the onset of
the flow velocity pattern behind the second heart sound. Many of our patients had concurrent aortic stenosis and mitral stenosis or mitral regurgitation. No associated valvular lesions interfered with evaluation of AR.

Our results demonstrate that continuous-wave Doppler echocardiography allows the noninvasive diagnosis and evaluation of AR. In addition to the high diagnostic accuracy in detecting AR, this method provides estimates of the degree of AR. The use of continuous-wave Doppler echocardiography in the evaluation of AR represents another extension of its capabilities.

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Noninvasive evaluation of aortic regurgitation by continuous-wave Doppler echocardiography.
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