Prediction of the severity of left ventricular outflow tract obstruction by quantitative two-dimensional echocardiographic Doppler studies

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ABSTRACT In this study we explored the use of continuous wave Doppler echocardiography guided by simultaneous two-dimensional echocardiographic imaging as a method for noninvasively estimating pressure gradients in patients with discrete forms of left ventricular outflow tract obstruction. We studied 16 children, ages 6 months to 17 years, with valvular aortic stenosis (n = 12) or with discrete subaortic stenosis (n = 4) and compared maximal Doppler velocities in the aorta with pressure gradients obtained at cardiac catheterization. Examinations could be performed from the suprasternal notch view or from the apical left ventricular outflow tract view with equal accuracy for the study of flow in the left ventricular outflow tract, and results were comparable in both views. With a simplified Bernoulli relationship (gradient = 4 \times \text{maximal velocity}^2), results suggested that Doppler echocardiography could be used to predict the severity of obstruction in our patients with a correlation coefficient of \( r = 0.94 \) (SEE \( \pm 7.5 \) mm Hg) between Doppler-estimated gradients and gradients obtained at catheterization. The method appears promising for initial evaluation and for serial management of patients with discrete forms of left ventricular outflow tract obstruction.


THE CLINICAL DIAGNOSIS of aortic stenosis in children is usually not difficult. However, clinical estimation of severity of left ventricular outflow tract obstruction is sometimes difficult.1

Because several forms of left ventricular outflow tract obstruction in childhood can follow a progressive course in the absence of clinical changes,2 a method for noninvasive estimation of severity would be very useful. Noninvasive diagnostic methods such as echocardiography and especially two-dimensional echocardiography performed during exercise3 are of some value in detecting patients at risk for significant aortic stenosis but do not quantify the severity of aortic stenosis.

Several echocardiographic studies4–7 have suggested M mode and two-dimensional echocardiographic methods to quantify the degree of obstruction of the left ventricular outflow tract at both valvular and subvalvular levels, but none of these methods has proved to be highly accurate, especially in patients after surgery. However, in preliminary studies Doppler echocardiography has been shown to be a promising technique for quantifying the severity of stenotic valvular lesions.8–12 With the simplified Bernoulli equation, both Holen et al.9 and Hatle et al.10–12 showed that a Doppler echocardiographic method could be used to relate peak flow velocities (measured in the jet distal to stenotic mitral or aortic valve orifices) to transvalvular gradients (measured at cardiac catheterization).

The purpose of this prospective study was to assess the capability and accuracy of a two-dimensional echocardiographic Doppler method to predict the severity of discrete subvalvular or valvular aortic stenosis in children by providing a noninvasively derived estimate of hemodynamic gradient measured in patients at rest.

Methods

Sixteen children ages 6 months to 17 years (mean age 3.4 years) were included in this study (table 1); all had clinically suspected obstruction of the left ventricular outflow tract. Twelve had obstruction at the valvular level and four had discrete subaortic stenosis. Two patients had undergone previous aortic valvulotomy and had mild aortic insufficiency, and one had undergone previous resection of a subvalvular membrane. One patient with subvalvular obstruction was studied before and after the operation. No patient in this study had both valvular...
and subvalvular disease, and none of the patients had significant aortic insufficiency before or after the operation.

All patients underwent cardiac catheterization within 24 hr of the ultrasonic study and five were studied during catheterization. Cardiac catheterization was performed after standard light sedation with meperidine (Demerol), chlorpromazine (Thorazine), and pentobarbital. At catheterization, peak systolic pressure gradients measured in patients at rest were recorded on pull-back across the aortic valve or subvalvular membrane with fluid-filled end-hole catheters. When necessary, catheters were filled with blood for damping purposes to produce a clearer peak-pressure trace. Cardiac output was determined in only 10 of the patients at catheterization and was within normal limits in all.

**Ultrasonic method.** Ultrasonic examinations were performed with the patients in a quiet resting state and in a supine position. For the suprasternal notch examination, patients had their shoulders elevated on a pillow so that their heads were angled backward to aid in access to the suprasternal notch and especially to the ascending aorta.

The instrument we used was a 2.5 MHz phased array two-dimensional echocardiographic Doppler system (PEDOF) that provided both pulsed and continuous Doppler capability (Irex-IIIIB). Doppler sampling was performed at 2 MHz interrogation frequency. Both two-dimensional echocardiographic images and Doppler flow curves were obtained with the same transducer array. In this system only the direction of the central image line in the sector could be interrogated for either pulsed or continuous Doppler sampling. To a depth of 6 cm in the pulsed mode, the maximal unambiguously detectable velocity was 160 cm/sec (the pulsed Doppler sample volume size was 7 mm long and 7 mm wide at 4 to 6 cm depth), but once located, a stenotic jet could be sampled in the continuous Doppler mode with or without simultaneous imaging up to a maximum velocity of 800 cm/sec.

In the continuous mode no specific depth gate was established, and all velocities along the central line of sight were processed for velocity determination.

Doppler outputs from this system were available as an audio signal, a spectral output sampled every 20 msec with spectral analysis performed by CHIRP Z algorithm, and an analog display of the mean and maximal detected velocities displayed in meters per second; that is, the instrument calculated velocity from frequency shift based on the standard relationship between kilohertz shift in frequency and velocity defined in the Doppler equation:

\[ V = \frac{(\Delta F \times V_s)}{(2F_0 \times \cos \theta)} \]

where \( \Delta F \) = frequency shift, \( V_s \) = velocity of sound, \( F_0 = 2 \) mHz interrogation frequency, and \( \theta \) = the angle between sampling direction and flow. The analog outputs required manual gain manipulation and adjustment to maximize the velocities recorded while a recognizable waveform was maintained in which the maximal analog velocity waveform, always displayed upward, and the mean analog waveform, displayed in the direction of flow (up if toward the transducer, down if away from it), returned toward each other and close to the baseline (figure 1) in diastole. During the examination, maximal velocities were obtained by finding the high-pitched whistling signal of the stenotic jet under audio and by two-dimensional imaging guidance; then the 600 Hz filter was used to minimize the contribution of the lower velocities. The two-dimensional images, spectral and analog Doppler outputs, and the simultaneous lead II electrocardiogram were recorded on videotape and/or hard copy at a paper speed of 50 to 100 mm/sec.

Ultrasonic examination began with two-dimensional imaging of the left ventricular outflow tract, aortic valve, and ascending aorta from an apical long-axis view or anteriorly angled four-chamber view; then the ascending aorta and right pulmonary artery were visualized from the suprasternal long-axis view \(^\text{13}\) by angling as far anteriorly as possible toward the aortic valve. After a pulsed Doppler survey of the above sites, continuous Doppler sampling was performed across the center of the aorta and the domed aortic valve leaflets or the subaortic membrane, in line with the apparent orifice, in those views for which an adequate line of site with a sampling angle less than 45 degrees could be obtained along with an adequate Doppler record. If available, aortic velocities were recorded for both views.

The maximal velocity was found and recorded by changing the position of the Doppler sample line within the aorta until the highest frequency audio signals were identified and the highest maximal systemic velocity was recorded. An angle cursor was set along the sample line that showed the presumed direction of flow (figures 2A and 2B). After the angle cursor was set, the correction of velocities for the angle between assumed direction of flow and the direction of Doppler sampling was performed automatically by the system as a division of velocities by the cosine of the angle of incidence, which produced a corresponding change of the calibrations. We presumed that this angle

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**FIGURE 1.** Analog record shows ascending aortic traces in a patient with mild aortic stenosis. The calibration dots for both the spectral trace (bottom) and the analog maximal traces (top) and mean velocity traces (inside the maximal velocity trace) are each 1 m/sec and the spectral and analog velocities show good agreement. The analog velocities return to the zero line in diastole. The black arrow denotes the selected spectral maximum velocity.
velocity and the spectral peak were within 10% of each other, they were averaged; if the analog peak underestimated the spectral value by more than 10%, the analog trace was ignored (figure 3).

Spectra were obtained with standard gray scale allocation selected to provide a relatively linear and almost bistable output. This allowed detection of the peak velocity, even if it were not the only velocity represented significantly within the signal. This, plus a low-reject setting in the spectrum, produced some tailing off of the spectral signal with spectral noise shown above the peak, as seen in figures 2A and 3, but did not preclude finding the peak velocity, which was significantly darker than the noise beyond it. Figures 1 to 4 have a black arrow to denote the spectral maxima selected after review of the entire study.

Data analysis. Maximal velocities were measured by two record readers, each unaware of the results of catheterization. Values were averaged because results were always within 10% of each other. The peak systolic flow velocities from 2 to 3 consecutive beats were recorded and converted to transvalvular gradients with the proposed simplified Bernoulli equation:

\[ VG = 4V^2 \]

where \( VG \) in mm Hg = valvular gradient; \( V \) = peak Doppler velocity in m/sec.

Control group. Our patient group was compared with a control group of 92 normal children (ages 1 to 14 years) who had

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**FIGURE 2A.** Sampling of the ascending aorta from the suprasternal notch in a direction almost parallel to flow is shown in a patient with mild aortic stenosis. Calibration for the lower spectral trace is 2 m/sec; calibration for the upper traces is 1 m/sec. A white line shows the angle correction applied retrospectively on review of the data, and the black arrow shows the spectral maximum velocity (see text for details).

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**FIGURE 2B.** Suprasternal notch sampling in a patient with moderately severe aortic stenosis is obtained with a sampling angle of 42 degrees as shown by the cursor and the angle determined in the lower alpha numerics of the Doppler trace. Calibrations are as in figure 2A. The black arrow shows the spectral maximum velocity.
peak systolic aortic velocities of 88.1 ± 3.6 cm/sec (SE) recorded in the ascending aorta from the suprasternal long-axis view, and 93.3 ± 6.4 cm/sec when recorded from the apical long-axis view after correction for sampling angle. The control group records provided a comparison with those records of the children with left ventricular outflow tract obstruction.

**Statistical methods.** Correlation coefficients for linear regression and power function regression relationships were calculated by a comparison of maximal Doppler velocity and derived Doppler gradients with actual gradients obtained at cardiac catheterization.

**Results**

All patients had successful Doppler examinations for recording of transaortic maximal jet velocity. In six patients, both apical (figure 4) and suprasternal views could be obtained and results were within 10% of each other for maximal velocity. In these patients, the average value from the two views was used and is shown in table 1. In the other 10 patients, only suprasternal views were available. All sampling angles were less than 45 degrees, and in 13 patients the sampling angle was 30 degrees or less. In patients with obstruction at the valvular level, various degrees of thickening and abnormal valve motion with doming were detected by two-dimensional echocardiography. In all patients with subvalvular obstruction, a membrane or residual postoperative deformity was visualized. Results for Doppler sampling are listed in table 1.

All Doppler aortic flow curves in the patients with aortic stenosis demonstrated significant spectral broadening. Also, the aortic flow velocities recorded in the patients (table 1) were increased compared with the normal peak systolic aortic velocities recorded in the control group. The peak Doppler flow velocities \( r = .91, \text{SEE} = 31.5 \text{ cm/sec} \) (figure 5), as well as the gradients calculated by the derived simplified Bernoulli equation \( r = .94, \text{SEE} = 7.5 \text{ mm Hg} \) (figure 6) correlated well with measured catheterization gradients, ranging from 20 to 155 mm Hg. Although the number of patients was small, there was no significant statistical difference in the accuracy of the method in the assessment of aortic stenosis vs subaortic stenosis, nor did the presence of mild aortic insufficiency (figure 7) preclude gradient prediction.

**Discussion**

In this study, we have demonstrated that the peak-pressure drop across the left ventricular outflow tract calculated by recording maximal systolic Doppler velocity was very close to the gradients measured by
TABLE 1

<table>
<thead>
<tr>
<th>Site of Patient obstruction</th>
<th>Maximal Doppler Catheter gradient</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>velocity (cm/sec)</td>
<td>gradient</td>
</tr>
<tr>
<td>1 Valvular</td>
<td>300&lt;sup&gt;A&lt;/sup&gt;</td>
<td>36</td>
</tr>
<tr>
<td>2 Subvalvular</td>
<td>480&lt;sup&gt;a&lt;/sup&gt;</td>
<td>92</td>
</tr>
<tr>
<td>3 Valvular</td>
<td>285&lt;sup&gt;b&lt;/sup&gt;</td>
<td>32</td>
</tr>
<tr>
<td>4 Valvular</td>
<td>380&lt;sup&gt;a&lt;/sup&gt;</td>
<td>58</td>
</tr>
<tr>
<td>5 Valvular</td>
<td>300&lt;sup&gt;b&lt;/sup&gt;</td>
<td>36</td>
</tr>
<tr>
<td>6 Valvular</td>
<td>400&lt;sup&gt;b&lt;/sup&gt;</td>
<td>64</td>
</tr>
<tr>
<td>7 Valvular</td>
<td>370&lt;sup&gt;a&lt;/sup&gt;</td>
<td>55</td>
</tr>
<tr>
<td>8 Subvalvular</td>
<td>340&lt;sup&gt;a&lt;/sup&gt;</td>
<td>46</td>
</tr>
<tr>
<td>9 Subvalvular</td>
<td>280&lt;sup&gt;b&lt;/sup&gt;</td>
<td>31</td>
</tr>
<tr>
<td>10 Valvular</td>
<td>500&lt;sup&gt;a&lt;/sup&gt;</td>
<td>100</td>
</tr>
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<td>11 Valvular</td>
<td>390&lt;sup&gt;a&lt;/sup&gt;</td>
<td>61</td>
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<tr>
<td>12 Subvalvular</td>
<td>190&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>13 Valvular</td>
<td>276&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>14 Valvular</td>
<td>250&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>15 Valvular</td>
<td>320&lt;sup&gt;b&lt;/sup&gt;</td>
<td>41</td>
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<tr>
<td>16 Valvular</td>
<td>330&lt;sup&gt;a&lt;/sup&gt;</td>
<td>44</td>
</tr>
<tr>
<td>Mean</td>
<td>336.9</td>
<td>±20.9</td>
</tr>
<tr>
<td>SE</td>
<td>47.8</td>
<td>±9.0</td>
</tr>
</tbody>
</table>

Catheter gradient = cardiac catheterization pull-back pressure gradient; AI = aortic insufficiency; Max vel = maximum velocity; Postop. = postoperative status for resection of an aortic coarctation.

<sup>a</sup>Suprasternal interrogation only.
<sup>b</sup>Suprasternal plus apex view results averaged.

catheterization and that the method could be used to assess the severity of discrete forms of left ventricular outflow tract obstruction in children.

Noninvasive techniques such as M mode<sup>14, 15</sup> and two-dimensional echocardiography<sup>16, 17</sup> have provided diagnostic information about the site and overall severity of left ventricular outflow tract obstruction, but the attempts to quantify obstruction of the left ventricular outflow tract have had only fair accuracy for prediction of gradients.<sup>4-7</sup> Previous reports by Hatle et al.<sup>10, 12</sup> regarding quantification of left ventricular outflow tract obstruction by Doppler echocardiography, showed that good results could be achieved with both pulsed and continuous mode Doppler interrogation obtained with a "blind" nonimaging transducer from the suprasternal notch. However, technical difficulties arose in some patients, especially those with very thick aortic valves where the jet was eccentric and, consequently, difficult to find.

The Doppler system used in this study, particularly the capability of the device to visualize the ascending aorta and simultaneously perform Doppler interrogation by pulsed or continuous modes, provided a method for accurate quantitation of flow, even in the most severe stenotic lesions.

Pulsed Doppler interrogation, combined with two-dimensional echocardiographic imaging, permits very localized flow sampling, but the pulsing used to achieve range gating limits its capacity for detecting high velocities. The continuous mode technique has limitations in that it samples flow throughout the entire depth of the selected image line, but because the signal is not limited in the repetition rate of sampling, it appears capable of detecting very high velocities. From either the suprasternal notch or the apex, other velocities from areas of the heart within the beam that could interfere with aortic flow velocities were not recognizable in the signal, probably because they were much lower than aortic velocities, particularly in the most severe cases, and were also not parallel to the direction of sampling.

Our results suggest a tendency of the Doppler technique to underestimate the gradient measured across

![FIGURE 5](http://circ.ahajournals.org/)

Top. Linear correlation between pressure gradient measured at catheterization on the abscissa and Doppler-derived maximal velocity on the ordinate. Correlation coefficient (r) as well as the standard error of the estimate (SEE) for the regression analysis are shown. Bottom. Since the Bernoulli equation predicts a relationship between pressure gradient and the square of the maximal velocity, a power-function fit for this data yields an equivalent correlation coefficient as above, but leads to a lower SEE. The equation for this curve is maximal velocity = 61 × (gradient)<sup>1/2</sup>.
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In some patients, the maximal velocities were difficult to find, requiring changes in position of the Doppler sample volume size inside the ascending aorta, as well as changes in gain to obtain the highest frequency audio signal and the highest velocity spectral record. We did not encounter significant overestimation of valve gradient, which can occur in this method only if the sampling angle is overestimated. This difficulty with determination of sampling angle has been discussed in Methods and may mean that the technique will be easier to apply in children than in adults, who may have very deformed calcific aortic valves. Nonetheless, a preliminary experience reported in adults by Kwan et al.\textsuperscript{18} suggested considerable accuracy for the present technique.

Our study demonstrates that two-dimensional Doppler echocardiography, with continuous Doppler sampling, provides a valuable method for assessment of severity of left ventricular outflow tract obstruction in children with valvular and discrete subvalvular aortic stenosis. Since aortic stenosis is not uncommonly a progressive disease in children,\textsuperscript{1} this technique should be of importance not only in initial evaluation, but especially in serial management as well, as an aid to the timing of catheterization and surgery.

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FIGURE 6. Catheterization gradient on the abscissa compared with Doppler-estimated gradient on the ordinate shows a close linear correlation; \( r = \) correlation coefficient; \( \text{SEE} = \) standard error of the estimate for the regression relationship.

FIGURE 7. Doppler flow record obtained from the suprasternal notch in a patient with mild residual aortic stenosis after valvulotomy; mild aortic insufficiency is also present. Diastolic velocities are below the baseline on spectral and mean (the lower analog trace) traces and represent the regurgitant flow. Calibration is as in figure 2. The black arrow shows the maximum velocities used to calculate the gradient in this patient selected after review of the entire study.
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