Noninvasive Assessment and Differentiation of Left Ventricular Outflow Obstruction with Doppler Ultrasound

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SUMMARY Blood flow velocities in the left ventricle and the ascending aorta were recorded noninvasively with Doppler ultrasound. The ultrasound beam was aligned as much as possible to the direction of velocity, using the frequency shift in the audio signal as a guide to obtain velocities as close as possible to those present. From the maximal velocity recorded by continuous-wave Doppler, a peak pressure drop was calculated in 24 patients with aortic valve stenosis and nine with fixed subaortic stenosis. Fourteen patients with aortic stenosis and three with fixed subaortic stenosis were catheterized in these patients, the correlation between calculated pressure drops and those obtained by pressure recording was good ($r = 0.85$).

The pressure drop can be underestimated by underestimating velocity, but cannot be overestimated. With pulsed Doppler, the level of obstruction can be determined.

WE HAVE REPORTED that the pressure drop from the left ventricle to the aorta can be calculated if maximal velocity in the aortic jet is obtained noninvasively by Doppler ultrasound. Especially in children and young adults, the aortic jet was easily recorded from the suprasternal notch and the first or second right intercostal space. The ultrasound beam could usually be aligned with the aortic jet so that a maximal velocity with calculated pressure drop close to that measured during catheterization could be obtained. Continuous-wave (CW) Doppler can be used to record the high velocities present in the aortic jet in aortic valve stenosis (2–6 m/sec), but gives no information about where along the sound beam the high velocities occur. With pulsed Doppler, velocities are recorded in a small area a certain distance from the transducer and can be localized, but high velocities cannot be measured. The maximal velocities that can be recorded by pulsed Doppler are limited by the pulse repetition rate of the instrument used. By pulsing the ultrasonic beam, ambiguity is introduced both in the range resolution and in the quantitation of the frequency shift of the Doppler signal. Ambiguity in range resolution is rarely a problem, because echoes from longer distances are attenuated, but to avoid ambiguity in quantitation of the frequency shift, the velocities recorded must be within limits determined by the product of the distance and the velocity (range-velocity product).

By using both CW and pulsed Doppler, the level of obstruction can be located and the velocity pattern in valvular and fixed subvalvular stenosis can be described.

Patients and Methods

Group 1 consisted of 24 patients, ages 4–32 years (mean 14.6 years) who had aortic valve stenosis. Left-heart catheterization was done in 14 patients. In 10 patients the diagnosis was based on clinical findings and two-dimensional echocardiography that showed a doming valve with reduced opening.

Group 2 consisted of nine patients, ages 3–53 years, who had fixed subvalvular stenosis. Three of them were catheterized and two underwent operation. (One was seen both before and after operation, the other only postoperatively.) In the six remaining patients the diagnosis was confirmed by two-dimensional echocardiography showing a membrane located 1–1.5 cm below the aortic valve. Five patients, ages 16–20 years, had high-output states. Right-heart catheterization was done in three. One patient had undergone closure of a persistent ductus arteriosus 10 years previously at the age of 7 years. The others had no history of heart disease. Right- and left-heart catheterizations were done percutaneously from a femoral vein and artery; a catheter with sideholes was used in the left ventricle. Cardiac output was determined by the Fick method. Pressure was measured with an Elema Shoenander transducer (type EMT 35) and recorded on a Mingograph 81 recorder.

The pressure drop within the left ventricle or across the aortic valve was recorded during withdrawal of the catheter from the left ventricle to the aorta, and the peak pressure drop was measured over three to five beats. Left ventricular angiography was done with the patient in the right anterior oblique position. Pressure and ultrasonic recordings were done simultaneously in four patients; in the others, the ultrasonic examination was usually done the day before catheterization. The ultrasonic examination was done with a Doppler instrument (Pedof, Vingmed A/S) that can be used in either a pulsed or a continuous mode. It is described in detail elsewhere. The ultrasonic frequency is 2 MHz. In the pulsed mode, velocities are recorded in a cylindrical volume that is 7 mm in diameter and 7.5 mm long; with repetition rates of 9.8 and 6.7 kHz, velocities up to 1.75 m/sec can be recorded within 7 cm, and up to 1 m/sec within 12 cm. The sample volume used in pulsed Doppler can be moved in 1–2-mm steps along the ultrasound beam. In the continuous mode, velocities are recorded all along the sound beam; there is no range resolution, but...
velocities up to 6 m/sec can be measured. The apparatus has a mean and a maximal frequency estimator, and the velocity curves can be recorded on an ordinary paper recorder together with the amplitude of the Doppler signal, ECG and phonocardiogram. The mean velocity estimator is directional. Flow toward the transducer is recorded as positive and flow away from the transducer is recorded as negative. The maximal velocity estimator is nondirectional. An audio signal contains the frequency shifts obtained from the velocities in the sample volume (pulsed Doppler) or along the sound beam (CW Doppler).

With the frequency shift and the angle (φ) between velocity and ultrasound beam, velocity can be calculated according to the Doppler equation:

\[ V_2 = \frac{c}{2f_0 \cos \phi} \]

where \( V_2 \) is velocity, \( f_0 \) the transmitted ultrasonic frequency, \( f_\phi \) the frequency shift and \( c \) the velocity of sound in blood. The angle cannot be satisfactorily measured for blood flow within the heart and the aorta. The highest frequency shift will be recorded at an angle of zero between ultrasound beam and velocity. The audio signal can therefore be used to find the direction where the frequency shift is highest, i.e., where the angle is smallest. Disregarding this angle in the equation with angles less than 20° (cos 20° = 0.94) will underestimate velocity less than 6%, whereas with larger angles the velocity indicated by the frequency shift will be significantly underestimated. As described earlier, maximal velocity across an obstruction can be used to calculate the pressure drop across the obstruction from the formula \( P_1 - P_2 = 4 \cdot V^2 \), where \( V \) is maximal velocity in the jet.

Pressure drops calculated from maximal velocity were almost identical to simultaneous pressure recording in mitral and aortic valve stenosis, provided a small angle to the jet could be obtained. With larger angles, both velocity and pressure drop will be underestimated.

When recording from the jet with CW Doppler at a substantial angle, high frequencies from the jet and the lower frequencies from beside the jet will be recorded. With decreasing angle, the frequency shift from the jet velocity will become higher, but the amount of low frequencies present in the audio signal will decrease. Thus, a position may be obtained where high frequencies are heard almost exclusively in a tonelike audio signal, despite the use of CW Doppler where velocities all along the beam are recorded. In figure 1, recording from position A, the ultrasound beam will traverse the jet at greater length and the audio signal will contain more high and fewer low frequencies than from position B or C. Lack of low frequencies in the audio signal when recording from the jet therefore indicates an optimal position. In patients with very high velocities (5.5–6 m/sec), the audio signal may then become barely audible with only the highest frequencies present.

The amount of low frequencies present in the audio signal is well heard, and with spectral analysis of the Doppler signal it can be shown directly in the recording. With the present recording system the “mean” velocity recorded will be lower the more low frequencies are present in addition to the high ones. Beside the jet only low frequencies are recorded, but with high intensity.

Velocity in the ascending aorta was recorded from the suprasternal notch or the first or second right intercostal space with the transducer directed toward the aortic valve area using the continuous mode. When a harsh sound with low frequencies of high intensity was found, the transducer was moved and angled until the much higher frequency sound from velocities in the aortic jet was found. In the position where the highest frequencies could be heard, mean and maximal velocity were recorded together with the amplitude of the Doppler signal, ECG and phonocardiogram. With maximal velocities greater than 2.2–2.4 m/sec in the ascending aorta, a peak pressure drop was calculated from the maximal velocity recorded using the formula described.

The transducer was then placed at or slightly medial to the apical area to record velocities in the left ventricle. In systole, velocity is away from the transducer.

**Figure 1.** Recording from the aortic jet with continuous wave (CW) Doppler from the optimal position A, mainly high frequencies will be present in the audio signal. From positions B and C, the high frequencies from the jet will be a little lower and many low frequencies from beside the jet will be heard. An audio signal with high frequencies and lack of low frequencies indicates a small angle to the jet. Change from position A to B is reflected in the curves as a greater reduction in mean than in maximal velocity, because more of the low velocities besides the jet are recorded.
toward the aorta, and in diastole, velocity of mitral flow is toward the transducer and biphasic in sinus rhythm. These velocities can be recorded from low in the left ventricle and followed upward and backward to the aortic and mitral valves. The sounds of valve movements are sharp and short and are easily separated from the blood velocities on the sound and on the recorded amplitude curve. We recorded the valve movements and the velocity of blood flow and used the distance from the transducer to determine where changes occurred when abnormal velocities were found. Simultaneous M-mode echocardiography was not used for localization of the area of measurement.

From the apex, CW Doppler was used to find the position and direction where the highest velocity away from the transducer in systole could be recorded. Pulsed Doppler was then used to follow the velocity of flow from low in the left ventricle up toward the aortic valve and beyond the valve by moving the sample volume stepwise 0.5 cm at a time. High maximal velocities cannot be recorded by pulsed ultrasound; however, because systolic velocities in the left ventricle in normal subjects are usually less than 1 m/sec, increases in velocity can still be detected. If a marked increase in velocity was found, we noted whether it occurred in the left ventricle or above the aortic valve.

Using pulsed Doppler introduces ambiguity in quantitation of the frequency shift with distortions of the recorded curves if frequencies exceeding the limit for the pulsed Doppler system used are present. By using CW Doppler when velocities exceeding this limit were present, misinterpretations due to such distortions could be avoided. Figure 2 shows an example of distortion of the pulsed Doppler curve that occurs when the pulsed mode is used in the presence of high velocities. With the pulsed mode a maximal velocity (nondirectional) at the limit for the method is shown, and mean velocity shows negative velocities in mid-systole. Switching to the continuous mode shows that velocity is positive throughout systole and maximal velocity is high. The “negative” velocities in the pulsed mode represent an artifact that occurs when maximal velocity exceeds the limit for the method. In the presence of high velocities, repeated positive/negative shifts can be seen during systole. Ambiguity in range resolution may also occur using pulsed Doppler. With the pulse repetition rates used in this instrument such ambiguity was occasionally noted when recording a strong signal distant from the transducer. Aortic valve movements at 11 cm depth (pulse repetition rate 6.7 kHz) could sometimes also be recorded at 3 cm from the transducer (pulse repetition rate 9.8 kHz). When one is aware that this phenomenon may occur, the distance between the real and the spurious echo is large enough to avoid difficulties in interpretation or localization of this signal.

**Results**

Maximal velocity curves from the left ventricle and into the aorta in a normal child are shown in figure 3. During recording from the apex, at 7 cm from the transducer just below the aortic valve, the valve closure was first heard. It was better heard and recorded at 8 cm, and at 9 cm the opening movement of the valve was more prominent than the closure. A slight increase in maximal velocity is usually recorded at a level where both the opening and closing movement of the valve are well heard and recorded.

Adults usually have a maximal velocity around 0.7 m/sec in the left ventricle, while children and adolescents have values of 0.7–1.2 m/sec. From the suprasternal notch in the ascending aorta, higher maximal velocities are recorded, usually 1–1.70 m/sec, and are highest in the youngest age groups. In patients with increased cardiac output, higher maximal velocities, up to 2.40 m/sec, have been recorded. These data are based on pulsed and CW Doppler recordings in more than 800 patients and normal subjects (unpublished data).

**Aortic Valve Stenosis**

Figure 4 shows recorded maximal velocities in the left ventricle and aorta in patient 9, a 17-year-old with aortic valve stenosis. The highest velocity was recorded from the first right intercostal space. With pulsed Doppler from the apex a significant increase in

**FIGURE 2.** An example of distortion of the mean velocity that occurs when the pulsed mode is used in the presence of high velocities. Pulsed Doppler from the aortic jet shows maximal velocity at the limit for the method while mean velocity is negative in mid-systole. Switching to continuous wave (CW) Doppler shows that higher velocities are present and positive throughout systole.
velocity was found at the valve area, but higher up than the slight increase noted in normal subjects. It was not noted until the opening movement of the valve was clearly better recorded than the closure. This higher localization of increase in velocity in aortic valve stenosis is supposed to be due to a doming valve, and makes the differentiation from subvalvular increase in velocity easier. Similar results were found in the other patients with aortic valve stenosis, who were young and had mobile valves. Increased velocity below the aortic valve was not recorded in any of these.

The recorded maximal velocities with calculated pressure drops are compared with catheterization data in table 1. In these young patients, the aortic jet was easy to find. Comparison of the pressure drop calculated from the ultrasonic recording with that at catheterization ($r = 0.85$) indicates that a small angle to the jet was obtained in these patients. The highest velocity was in all recorded from above, usually from the first right intercostal space. In a few patients with isolated aortic valve stenosis, high velocities can be recorded with CW Doppler from the apex or the left sternal border, but pulsed Doppler can then show that the increased velocity is only found above the aortic valve.

### Fixed Subvalvular Aortic Stenosis

All the patients with subvalvular stenosis had the highest velocities recorded from above with CW Doppler, as in valvular stenosis. Maximal velocities were obtained from the same directions and the velocity curves were similar. However, with the pulsed Doppler recorded from the apex up toward the aortic valve, a different pattern was noted. In subvalvular stenosis a marked increase in velocity was recorded in the left ventricular outflow tract just below the aortic valve. The increase was usually noted at the level where aortic valve closure was first heard; below this level normal velocities were recorded. The sample volume had to be moved 1–2 cm higher to record aortic valve opening as well as the closure, indicating that the obstruction was located 1–2 cm below the valve. At this higher level a marked systolic fluttering of the aortic valve was easily heard. The pattern of increase
TABLE 1. Maximal Velocities and Calculated Pressure Drops Compared with Recorded Pressure Drop

<table>
<thead>
<tr>
<th>Pt</th>
<th>Age (years)</th>
<th>Maximal velocity recorded by CW Doppler (m/sec)</th>
<th>Peak pressure drop (mm Hg)</th>
<th>Maximal velocity recorded in the left ventricle by pulsed Doppler (m/sec)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Apex</td>
<td>Above</td>
<td>Ultrasonic recording</td>
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<tr>
<td>Aortic valve stenosis</td>
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<td></td>
<td></td>
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<tr>
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<td>4.32</td>
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<td>1.12</td>
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<td>1.10</td>
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<td>14*</td>
<td>32</td>
<td>0.96</td>
<td>4.82</td>
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<tr>
<td>Fixed subvalvular stenosis</td>
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<td>11</td>
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<td>5.54</td>
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The highest velocity in all but one patient was recorded from the suprasternal notch or the first or second intercostal space. The correlation between calculated and recorded pressure drop in aortic valve stenosis was 0.85.

*Simultaneous measurements.
†Postoperative measurements.
Abbreviation: CW = continuous wave.

in velocity located 1-2 cm below the valve was found in all these patients and the distance corresponded to the distance from the membrane/ring to the aortic valve found at surgery or on two-dimensional echocardiograms.

Figure 5 shows a Doppler recording before and after operation in patient 16. Before operation, the maximal velocity recorded in the ascending aorta gave a calculated peak pressure drop of 56 mm Hg. After operation a residual peak pressure drop of 25 mm Hg was calculated. Both these measurements were confirmed by pressure recording. Pulsed Doppler record-

**Figure 5.** Subvalvular aortic stenosis in patient 16, a 16-year-old boy. The highest velocity was recorded from above both before and after removal of a subvalvular membrane. Reduction in the maximal velocity recorded indicated reduction of peak pressure drop from 56 to 25 mm Hg. A localized increase in velocity at 7.5 cm was noted 1.5 cm below valve level. Mo = mitral valve opening; Ac = aortic valve closure; Ao = aortic valve opening.
ing from the apex showed that the increase in velocity occurred 1.5 cm below the aortic valve level. The pressure drop across the subvalvular obstruction calculated from maximal velocity recorded in the ascending aorta with CW Doppler in the other patients in this group ranged from 10-57 mm Hg (mean 34 mm Hg). The increase in maximal velocity below the aortic valve recorded with pulsed Doppler was from 0.71-0.96 m/sec below the obstruction to 1.45 to more than 1.75 m/sec, and the direction of the increased maximal velocity was toward the aortic valve. Aortic regurgitation was present in seven of the nine patients.

High Cardiac Output

In the five patients with high cardiac output, maximal velocities recorded in the left ventricle were 1.14-1.75 m/sec (mean 1.34 m/sec) and in the ascending aorta 1.87-2.42 m/sec (mean 2.04 m/sec). The cardiac outputs in three of them were 10, 13 and 17 l/min. A gradual increase in velocity up through the left ventricle was recorded in these, in contrast to the localized increase found in patients with obstructive lesions, where the increase was found over a distance of 0.5 cm or less.

Discussion

Site of Obstruction

The presence of an obstruction to flow was diagnosed when a localized and marked increase in velocity was found. The level could be determined by pulsed ultrasound. The patients with fixed outflow obstruction showed similar velocity curves in the ascending aorta, but showed an increase in velocity at a high valve level in valvular stenosis and below the valve in subvalvular stenosis.

Degree of Obstruction

In aortic valve stenosis the peak pressure drop calculated from the velocity recording was quite close to that obtained by pressure recording (table 1). Therefore, calculation of the pressure drop from maximal velocity in aortic valve stenosis can be done using the same formula as in mitral stenosis. It also indicates that a small angle to the aortic jet was obtained in these young patients. This is in contrast to older patients with aortic valve stenosis, in whom a small angle to the jet could be obtained in only about 50%, and in some, the jet could not be recorded at all.1 The main reason for these difficulties in older patients is probably more deformed and calcified valves with more variations in the direction of the jet. Larger angles to the jet in these subjects are suggested by an audio signal containing many low frequencies of high intensity in addition to the higher frequencies from the jet.

The aortic jet was easy to locate in the younger patients. Recording from the jet should be tried from several positions to obtain as small an angle as possible, and one should always bear in mind the possibility of underestimating the pressure drop by recording from a too large angle to the jet. The real pressure drop may be higher, but will never be less than that calculated from the maximal velocity recorded. Higher pressure drop by ultrasound, as well as lower, may be seen when nonsimultaneous measurements are compared, as in most patients in table 1, because changes in cardiac output and peripheral vascular resistance may have changed the pressure drop between the two occasions. Timing of the peak velocity in systole can also be useful because severe stenosis is associated with late peak velocity.1 Our results indicate that a small angle to the jet can be obtained in fixed subaortic stenosis, as in valvular stenosis, but too few of the cases were catheterized to determine whether this can be done regularly. The quality of the audio signal in the continuous mode, however, indicated that the angle is small in patients with fixed subaortic stenosis.

Assessing the degree of obstruction in aortic valve stenosis by ECG and phonocardiogram may fail because severe stenosis may be present with a normal ECG, despite early maximum of the systolic mur.6, 4 Estimation of left ventricular systolic pressure from the relation between left ventricular wall thickness and cavity dimension obtained by echocardiography have proved useful in both aortic valve stenosis7,10 and in fixed subvalvular obstruction.11 Reduced cusp separation shown with M-mode may be of some help in valvular stenosis, but is better shown with two-dimensional echocardiography.12 Recording jet velocities with CW Doppler seems easier, at least in the younger patients. This may be because the aortic jet has some length, while with echocardiography the beam must pass through the valve area at one certain level.

Attempts to assess the severity of aortic valve stenosis with pulsed Doppler only have been reported based on analysis of several features of pulsed Doppler recordings from the ascending aorta.13 Some of the features used as the degree and duration of negative velocities during systole, or slope of analog curve, may not represent turbulence, but instead represent curve distortions due to presence of velocities above the limit for the pulsed Doppler system, as shown in figure 2. The higher the velocities in the sample volume, the longer the period with false-negative velocities will be. If this is used as an indication of the degree of obstruction, the position of the sample volume and the angle to the velocity are critical and difficult to assess when the high frequencies from the jet are not present in the audio signal. Therefore, when high velocities are present, as in most obstructions, CW Doppler must be used to assess the degree of obstruction because pulsed Doppler used alone gives less information and can be misleading if the limits of this method and ambiguity of signals are not appreciated.

References

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Two-dimensional Echocardiographic Assessment of Electrocardiographic Criteria for Right Atrial Enlargement

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with the technical assistance of Eugene Beers, R.T., RDMS

SUMMARY Right atrial (RA) size was determined with two-dimensional echocardiography using the apical four-chamber view in 45 adult patients with various echocardiographic criteria for RA enlargement and in 25 normal controls. RA size varied from 11.4-24.0 cm² (mean 16.1 cm²) in controls. RA enlargement (≥ 25 cm²) was found in only two of 11 patients with P-pulmonale (predictive value [PV] = 18%) and one of five with prominent positive P-wave forces in lead V₃ (PV = 20%). However, RA enlargement was found in eight of eight patients with a qR pattern in lead V₁ in the absence of clinical indications of coronary artery disease (PV = 100%). RA enlargement was also found in 13 of 28 patients with a total QRS amplitude in lead V₁ of 6 mm or less and a threefold or greater ratio of total QRS amplitude in lead V₂ relative to that in V₁ (V₂/V₁ ≥ 3) (PV = 48%). A V₂/V₁ ratio of 4 or more detected 11 of 13 patients with RA enlargement, with six false-positive diagnoses (sensitivity = 85%, specificity = 60%, PV = 65%). The combination of total QRS amplitude in V₁ of 4 mm or less, together with a V₂/V₁ ratio of 5 or more, detected six of 11 with RA enlargement, with one false-positive diagnosis (sensitivity = 46%, specificity = 93%, PV = 86%). We conclude that ECG criteria for RA enlargement that primarily use increased P-wave amplitude have a limited PV. The qR pattern in lead V₁ appears to be extremely accurate in detecting RA enlargement. ECG criteria in leads V₁ and V₂ using decreased amplitude in leads V₁ and a V₂/V₁ ≥ 3 are of some value in detecting RA enlargement.

THE ABILITY of the ECG to detect right atrial enlargement has been the subject of many investigations.1-4 In these studies, methods of validating right atrial dimensions included radiographic, autopsy, and hemodynamic data. In the latter instances, cases for study were chosen because of the presence of congenital cardiac lesions known to be associated with systolic or diastolic overloading of the right atrium.5-8

Recently, two-dimensional echocardiography has been shown to be an accurate technique for determining right atrial size9 and has been used to detect right atrial enlargement in patients with either mitral stenosis or atrial septal defect.10 In this investigation we determined two-dimensional echocardiographic estimates of right atrial size in patients who had various echocardiographic criteria suggesting right atrial enlargement.

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