Quantitative Assessment of the Hemodynamic Consequences of Aortic Regurgitation by Means of Continuous Wave Doppler Recordings

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The purpose of this study was to evaluate the ability of continuous wave Doppler ultrasound recordings to reflect the magnitude and hemodynamic effects of aortic regurgitation. Forty-five patients with angiographically proved aortic regurgitation had Doppler studies performed within 24 hours of cardiac catheterization. High quality spectral recordings of the regurgitant jet were obtained in 31 patients, whereas 14 patients exhibited dropout of high velocity signals precluding measurement of maximal velocities. The slope of the peak to end-diastolic velocity decrease measured by Doppler examination was compared with the decay in the aortic to left ventricular diastolic pressure gradient by catheterization and was found to correlate well (r = 0.86). The Doppler velocity decay slope was generally higher in patients with angiographically severe rather than mild or moderate aortic regurgitation, but considerable overlap was present among groups. However, a diastolic velocity decay slope of greater than 3 m/s² was seen only in those patients with advanced (3 or 4+) aortic regurgitation.

Left ventricular end-diastolic pressure was estimated from the Doppler recordings by subtracting the end-diastolic pressure gradient obtained by the modified Bernoulli equation from the cuff diastolic blood pressure. A correlation was observed (r = 0.84) between Doppler and catheterization left ventricular end-diastolic pressure in the 31 patients with high quality spectral data, although the SEE was substantial (5.5 mm Hg). These data demonstrate that continuous wave Doppler recordings of the regurgitant jet can be useful in assessing the angiographic severity and hemodynamics of aortic regurgitation.

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Methods

Study patients. The study population comprised 45 consecutive patients in whom aortic regurgitation was documented by supravalvular aortography. Each patient under-
went a Doppler echocardiographic study within 24 hours of cardiac catheterization. There were 35 men and 10 women with a mean age of 46 years (range 17 to 75). Atrial fibrillation was present in six patients; the remainder had sinus rhythm. The origin of aortic regurgitation was rheumatic heart disease in 13 patients, congenital valve abnormalities in 10, degenerative aortic valve disease in 10 and aortic dissection in 1. No definite origin could be determined in 11 patients. Reasons for cardiac catheterization included evaluation of aortic regurgitation, aortic stenosis, mitral stenosis and coronary artery disease.

**Catheterization.** Supravalvular aortography was performed in standard fashion using a variety of catheters positioned just above the aortic cusps. An iodinated radiopaque contrast agent (Renografin-76) was power-injected at a rate of 20 cc/s for 2 seconds. Angiographic images were obtained in the right anterior oblique projection and filmed at 60 frames/s with a 35 mm cine camera and a 6 inch (15.24 cm) image intensifier. In all instances, catheter position and opacification of the aortic root were judged to be adequate. Severity of aortic regurgitation was assessed on a scale of 1+ to 4+ according to previously published criteria (10). The distribution of angiographic aortic regurgitation was as follows: 1+ in 13 patients, 2+ in 13 patients, 3+ in 12 patients, and 4+ in 7 patients.

Simultaneous aortic and left ventricular pressure tracings were obtained with dual high fidelity micromanometer-tipped catheters (Millar) in 15 patients. Fluid-filled catheter systems were used in the remaining 30 patients. All pressure tracings were recorded on a hard copy printout with a simultaneous single lead electrocardiogram (ECG). Left ventricular end-diastolic pressure was measured at the onset of the QRS complex, the same point in the cardiac cycle utilized for Doppler measurements.

**Doppler echocardiography.** All Doppler studies were performed by experienced operators with commercially available machines. Patients were examined in the left lateral decubitus position using standard imaging windows that included parasternal long and short axes, apical five chamber and suprasternal views. Pulsed Doppler study was performed with a 2.5 MHz imaging transducer with full spectral and audio outputs. The left ventricular outflow tract was interrogated by placing the pulsed Doppler sample volume just beneath the plane of the aortic valve leaflets. The presence of aortic regurgitation was confirmed by detecting retrograde diastolic flow with a marked dispersion of the spectral signal and a maximal velocity of at least 1 m/s. After identification of aortic regurgitation by pulsed Doppler study, continuous wave Doppler recording was performed using either the same transducer or a 2.0 MHz dual-crystal, non-imaging transducer capable of accurately recording velocities of up to 6 m/s without aliasing. The maximal diastolic velocity was carefully identified by adjusting the orientation of the interrogating beam guided by the auditory and visual Doppler outputs. The optimal Doppler recording of the aortic regurgitant jet was obtained through the apical window in all but two patients in whom the suprasternal window was superior.

Continuous wave spectral data were recorded on a hard copy printout (50 or 100 mm/s paper speed) with a simultaneous single lead electrocardiogram. All subsequent measurements were performed from the outer envelope of the continuous wave Doppler spectral recording. Peak diastolic velocity and end-diastolic velocity at the onset of the QRS complex were determined from beats that exhibited optimal definition of the spectral envelope. Three beats were measured for patients who had sinus rhythm and 7 to 10 beats were analyzed for patients with atrial fibrillation. Doppler velocity measurements were converted to pressure gradients by means of the modified Bernoulli equation as $PG = 4 (VEL)^2$, where $PG =$ pressure gradient in mm Hg and $VEL =$ maximal velocity of the jet in m/s.

**Comparison of Doppler and catheter pressure decay.** To determine whether Doppler diastolic decay slope accurately reflects pressure changes observed at cardiac catheterization, we evaluated 15 patients in whom simultaneous aortic and left ventricular high fidelity micromanometer-tipped pressure recordings were performed (Fig. 1). The contour of the pressure pulses from three consecutive beats were traced on a digitizing tablet and the data entered into

![Figure 1. Simultaneous aortic and left ventricular Millar pressure recordings from a patient with aortic regurgitation in this study. Peak pressure gradient (P1) in early diastole is 67 mm Hg, corresponding to a velocity (V1) of 4.1 m/s. End-diastolic pressure gradient (P2) measured at the onset of the QRS complex is 51 mm Hg corresponding to a velocity (V2) of 3.5 m/s. Predicted Doppler decay slope is $V1 - V2/time = 0.6 m/s/0.36 s = 1.4 m/s^2$. Decay slope by continuous wave Doppler measurement was 1.0 in this patient.](image-url)
a microcomputer. The computer then identified the largest simultaneous diastolic pressure drop, whereas the end-diastolic gradient was taken at the onset of the QRS complex. The peak diastolic and end-diastolic pressure gradients (PG) were measured and converted to velocity (VEL) by rearranging the modified Bernoulli equation as $\text{VEL} = \sqrt{\text{PG}/4}$.

The time between these two points was measured and the slope of the velocity decay determined from catheter data as peak diastolic velocity minus end-diastolic velocity over time. Using the same microcomputer and digitizing tablet, the peak and end-diastolic (at the onset of the QRS complex) velocities of the Doppler regurgitant signal were identified and marked with a cursor. The slope of the line connecting these two points was then computed in m/s² (Fig. 2). This value, termed the diastolic decay slope, was determined as the average of at least three separate beats for each patient. Catheterization- and Doppler-derived slopes were compared to assess whether the Doppler diastolic decay slope accurately reflected the pressure changes recorded at cardiac catheterization.

**Comparison of decay slope with angiographic grade.**

To determine the relation of Doppler measurements to angiographic quantification of aortic regurgitation, the diastolic decay slope of the aortic regurgitant jet was compared with the angiographic grade of the lesion. Individual values for diastolic decay slope were then grouped for subsets of patients with mild (1 +), moderate (2 +) and severe (3 to 4 +) aortic regurgitation and values for each subgroup were compared by Student’s $t$ test for group data.

**Estimation of left ventricular end-diastolic pressure.**

An analysis was carried out to determine if Doppler recordings could be used to obtain an estimate of left ventricular end-diastolic pressure. The maximal end-diastolic velocity of the aortic regurgitant jet was determined from the continuous wave spectral output as the highest velocity recorded at the onset of the QRS complex (Fig. 2). The end-diastolic gradient was computed from this measurement by the modified Bernoulli equation. Diastolic blood pressure was obtained at the time of the Doppler examination by sphygmomanometry. A single brachial artery cuff pressure was measured in either arm by a physician. Phase V of the Korotkoff sounds was taken as the diastolic blood pressure according to previously published criteria (11). In the setting of severe aortic regurgitation, phase V can sometimes occur at extremely low pressures, a circumstance in which phase IV more closely approximates intraarterial diastolic pressure (12). This situation did not occur in any of the patients in this study. Doppler-derived left ventricular end-diastolic pressure (LVEDP) was then calculated according to the following formula:

$$\text{LVEDP} = \text{DBP} - \text{PG},$$

where DBP is the diastolic aortic blood pressure and PG is the end-diastolic pressure gradient between aorta and left ventricle estimated by Doppler recording.

**Analysis of data.** Interobserver and intraobserver variability for Doppler estimates of left ventricular end-diastolic pressure and diastolic decay slope were assessed more than a month after the initial readings. This analysis did not address the temporal variability of left ventricular end-diastolic pressure or the potential differences due to recording technique in sequential Doppler examinations. Doppler hard copy tracings were analyzed independently by two observers who were unaware of the catheter data. The correlation

![Figure 2.](image-url)
coefficient for Doppler readings by different observers was 0.86 for left ventricular end-diastolic pressure and 0.86 for diastolic decay slope. The correlation coefficient for Doppler analysis by the same observer 1 month later was 0.93 for left ventricular end-diastolic pressure and 0.89 for diastolic decay slope.

Results

Suitability of Doppler studies for accurate measurements. Visual inspection of the Doppler spectral recordings revealed that patients in this study could be divided into two distinct groups. In one group continuous wave Doppler examinations yielded spectral envelopes of the jet that were well defined and complete throughout diastole. Recordings of this nature were obtained in 31 (69%) of the 45 patients. The Doppler studies in the remaining 14 patients exhibited dropout of high velocity signals yielding a tracing of incomplete outline and precluding measurement of maximal velocity or diastolic decay slope (Fig. 3). All 19 patients with 3+ or greater aortic insufficiency had sufficiently well defined Doppler spectral data to obtain measurements. In contrast, however, only 5 of 13 patients with 1+ and 7 of 13 patients with 2+ aortic regurgitation had Doppler studies that were suitable for quantification. Attempts to correlate Doppler with catheterization data employing results from all 45 patients were unsuccessful because of the inability to make accurate measurements in patients with ill defined Doppler tracings. Therefore, analysis was carried out only in the 31 patients with well defined jet recordings. The mean diastolic blood pressure was 61.9 mm Hg at catheterization and 60.7 mm Hg during the Doppler examination. Mean heart rate was 78.2 and 75.2 during catheterization and Doppler studies, respectively.

Relation of pressure and velocity decay. Comparison of the diastolic decay slopes obtained by Doppler and catheterization measurements was performed in 15 patients with high fidelity pressure tracings. The diastolic decay slope of the Doppler velocity profile accurately predicted the dissipation of the aortic to left ventricular pressure gradient measured at the time of catheterization ($r = 0.86$). Linear regression analysis between these two values yielded a regression line close to unity ($y = 1.13x - 0.33$) and a SEE of 0.49 m/s$^2$.

Relation of diastolic decay slope to angiographic grade of regurgitation and left ventricular end-diastolic pressure. The relation between the diastolic decay slope of the regurgitant jet and the angiographic grade of aortic regurgitation is shown in Figure 4. The slope of decay in patients with severe (3 to 4+) aortic regurgitation was greater than in those patients with mild or moderate (1 to 2+) regurgitation ($3.12 \pm 1.05$ versus $1.89 \pm 0.54$, $p < 0.01$). Although considerable overlap existed between groups, a decay slope of greater than 3 m/s$^2$ was observed only in those patients with grade 3 to 4+ aortic regurgitation. In contrast, the slope of the velocity decay of the aortic regurgitant jet did not correlate closely with the left ventricular end-diastolic pressure measured at catheterization ($r = 0.30$, SEE = 1.03, $y = 0.03x + 2.06$).

Comparison of Doppler and catheterization values of left ventricular end-diastolic pressure. Values for left ventricular end-diastolic pressure measured at the time of result...
Discussion

The ability of Doppler measurements to predict transvalvular pressure gradients by the modified Bernoulli equation has been well established (13–20). Although generally used to evaluate valvular stenosis, knowledge of the transvalvular gradient can also allow noninvasive estimation of intracardiac pressures in the presence of a regurgitant lesion. Previous studies have demonstrated that right ventricular and pulmonary artery systolic pressures can be accurately determined in patients with tricuspid regurgitation from the continuous wave Doppler recording of the jet across the tricuspid valve (21–24). These data indicate that assessment of the gradient between the aorta and left ventricle in aortic regurgitation has the potential to provide data regarding the severity of the lesion as well as left ventricular end-diastolic pressure.

Validity of Doppler velocity measurements to assess aorta to left ventricle pressure gradient. From the theoretical vantage point, the velocity of the aortic regurgitant jet should be a function of the instantaneous pressure drop between the aorta and left ventricle in diastole. However, few data have been previously available to validate this relation. The results of this study indicate that the rate of disappearance of the pressure drop at catheterization delimited by micromanometer-tipped transducers and the rate of decay of the velocity of the aortic jet by Doppler correlate closely. Thus, these data establish the validity of utilizing velocity measurements from the aortic regurgitant jet to assess the time course of changes in pressure gradient between aorta and left ventricle.

Decay slope: relation between jet acceleration and angiographic grade of regurgitation. It has been suggested that the slope of the deceleration from peak diastolic to end-diastolic velocity is proportional to the angiographic grade of aortic regurgitation (25,26). This relation is based on the fact that the magnitude of regurgitation is a major determinant of the time course of the pressure drop between the aorta and left ventricle during diastole. Thus, in the setting of mild regurgitation a high diastolic pressure will be maintained in the aorta whereas the pressure in the left ventricle will be low. The net result will be maintenance of the pressure drop and therefore the jet velocity throughout diastole in patients with mild lesions. Conversely, with severe grades of aortic insufficiency, the pressure in the aorta will fall progressively during diastole, the pressure in the left ventricle will rise proportionally during this period and predicted a left ventricular end-diastolic pressure of >15 mm Hg, the catheterization measurement was of this magnitude in 16 of 21 cases. Thus, the sensitivity and specificity of Doppler measurement in detecting left ventricular end-diastolic pressure of >15 mm Hg was 76 and 90%, respectively.
the pressure drop between these chambers will be reduced substantially. Because velocity is a function of the pressure drop, a rapid diastolic decay slope of the aortic regurgitant jet would occur in patients with a large regurgitant volume. These data demonstrate that a general relation exists between jet deceleration and angiographic grade of regurgitation. Although substantial overlap exists, the slope of the velocity decay is significantly greater in patients with 3+ to 4+ aortic regurgitation than in those with lesions of milder magnitude. Further, a diastolic velocity decay slope equal to or greater than 3 m/s² was observed only in patients with severe (grades 3+ or 4+) aortic regurgitation.

Limitations in the ability of the Doppler velocity decay slope to predict the angiographic severity of aortic regurgitation should not be surprising, in as much as these measurements may reflect different hemodynamic characteristics. Angiographic severity is primarily determined by the regurgitant volume. However, the pressure drop across the aortic valve, as manifested by velocity, is also dependent on the compliance of the ventricle, loading conditions and other associated valvular lesions. Patients with a mild degree of aortic regurgitation but a stiff ventricle may have a rapid velocity deceleration, whereas patients with severe regurgitation but a highly compliant ventricle may maintain a sizable pressure drop and high velocity throughout diastole. Furthermore, the use of a semiquantitative grading scale to assess the severity of aortic regurgitation has known limitations (27) and may account for some of the overlap observed in Figure 4. Accordingly, this study revealed only a general correlation between diastolic decay slope and the angiographic severity of aortic regurgitation.

Other investigators (28) proposed the use of pressure half-time of the continuous wave Doppler profile of the regurgitant jet to assess the severity of aortic insufficiency. Pressure half-time of the regurgitant jet was also measured in this study and found to be lower with increasing grades of aortic regurgitation. However, substantial overlap among groups was present, similar to that observed with decay slope. Further, correcting for diastolic blood pressure did not enhance the ability of the decay slope to predict angiographic severity of aortic regurgitation.

Left ventricular end-diastolic pressure. The ability of Doppler measurements to predict left ventricular end-diastolic pressure in patients with aortic regurgitation has been previously suggested (29). This study lends support to that contention. In 31 patients in whom a well defined jet envelope was obtained, Doppler-derived estimates of left ventricular end-diastolic pressure generally correlated with catheter-measured values. Of greatest significance, the specificity of Doppler measurements in predicting a left ventricular end-diastolic pressure of >15 mm Hg was 90%.

Several important considerations regarding the estimation of left ventricular end-diastolic pressure by Doppler study merit emphasis. Although the correlation coefficient between Doppler and catheterization values was quite acceptable, the SEE of 5.5 mm Hg was substantial, particularly with regard to the range of measurements encountered clinically. In addition, the precision with which diastolic blood pressure can be measured by cuff sphygmomanometer may be limited, particularly in patients with advanced aortic regurgitation. Finally, although the inter- and intraobserver variability was minimal, the temporal reproducibility of Doppler left ventricular end-diastolic pressure estimates in individual patients remains to be established. Thus, the potential clinical value of this method in detecting serial or exercise-induced changes in left ventricular end-diastolic pressure must remain speculative.

Limitations. Clearly, inability to acquire an optimal spectral envelope in all patients represents the major limitation of the methods described. Acceptable spectral data were obtained in only 69% of the 45 patients with aortic regurgitation in this study. In contrast, high quality tracings were acquired in 96% of patients with tricuspid regurgitation in whom right ventricular systolic pressure was evaluated by Doppler measurement (21). A potential explanation for this discrepancy is that the tricuspid valve is large and often anatomically normal in patients with tricuspid regurgitation. Thus, the regurgitant jet generally follows its presumed direction of flow, facilitating the Doppler examination. On the other hand, the aortic valve in aortic regurgitation is often fibrotic or calcified, or both. This may lead to eccentricity of the regurgitant jet such that it is tangential to the interrogating Doppler beam as applied from standard acoustic windows. Failure to properly locate and interrogate the center of the regurgitant jet may lead to dropout of high velocity signals and underestimation of the maximal velocity. The resulting value for left ventricular end-diastolic pressure will be falsely elevated, because it is derived by subtracting the pressure gradient from the diastolic cuff pressure. The failure to adequately detect the spectral envelope of the regurgitant jet may in itself be a predictor of mild to moderate aortic insufficiency, because all patients in this study with 3+ or greater aortic insufficiency had high quality spectral data.

Our specific study is also limited by the fact that cardiac catheterization and Doppler recordings were not acquired simultaneously. However, mean diastolic blood pressure and mean heart rate did not differ significantly between catheterization and Doppler examinations. In addition, no patient in the study underwent any hemodynamic manipulation (that is, angiography, vasodilators) between the time of the catheterization and Doppler studies.

Conclusion. This study demonstrates that continuous wave Doppler recordings of the aortic regurgitant jet can yield information regarding the hemodynamic consequences of this lesion in many patients. Recordings suitable for such analysis are available in approximately two-thirds of patients with aortic regurgitation. The slope of the velocity decline...
of the spectral envelope of the regurgitant jet accurately reflects pressure changes observed at catheterization and correlates generally with the angiographic severity of aortic regurgitation. A velocity decay slope of greater than 3 m/s? nearly always predicts greater than 3 + aortic regurgitation. A general estimation of left ventricular end-diastolic pressure can be obtained noninvasively by continuous wave Doppler examination for most patients with greater than I + aortic regurgitation. The technique requires a defined spectral envelope with unambiguous recording of high velocity signals. These findings may be clinically useful in the evaluation and follow-up of patients with aortic regurgitation.

References


