Quantitative Evaluation of Aortic Insufficiency by Continuous Wave Doppler Echocardiography

ARTHUR J. LABOVITZ, MD, FACC, ROBERT P. FERRARA, MD, MORTON J. KERN, MD, FACC, ROBERT J. BRYG, MD, DENISE G. MROSEK, GEORGE A. WILLIAMS, MD, FACC
St. Louis, Missouri

To assess the usefulness of continuous wave Doppler echocardiography in the evaluation of aortic insufficiency, the aortic regurgitant flow velocity pattern obtained with continuous wave Doppler examination was compared with the results of aortography and conventional pulsed Doppler techniques in 25 individuals with aortic insufficiency. The diastolic deceleration slope as measured from the continuous wave tracing was significantly different among subgroups of patients with mild (1.6 ± 0.5 m/s²), moderate (2.7 ± 0.5 m/s²) and severe (4.7 ± 1.5 m/s²) aortic insufficiency as determined from aortography. Deceleration slopes greater than 2 m/s² separated individuals with moderate and severe insufficiency from those with mild insufficiency.

Similar findings were seen when comparing the pressure half-time method of diastolic velocity decay with pulsed Doppler echocardiography. These methods employ primarily either a flow mapping technique in which the extent of the regurgitant jet is mapped back from the aortic valve plane into the left ventricle or, more recently, the determination of regurgitant volume and regurgitant fraction from the calculated difference between aortic valve forward flow and the flow at a remote site (11–13). Continuous wave Doppler echocardiography differs from pulsed Doppler echocardiography in its ability to resolve high velocities by sacrificing range resolution. Utilizing the relation between velocity and pressure, the enhanced ability of continuous wave Doppler echocardiography to measure high velocities provides a means for calculating instantaneous pressure differences between the aorta and the left ventricle at end-diastole. End-diastolic velocities correlated poorly (r = 0.28) with catheter-measured end-diastolic pressure difference between the aorta and the left ventricle. These findings demonstrate that the aortic regurgitant flow pattern by continuous wave Doppler echocardiography may be useful in quantitating the degree of aortic insufficiency by assessing the rate with which aortic and left ventricular pressures equilibrate during diastole.

(J Am Coll Cardiol 1986;8:1341–7)

Methods

Study patients. The study group consisted of 25 patients (13 women and 12 men) with a mean age of 59.2 years (range 31 to 81). There were 13 patients with isolated aortic regurgitation, 7 with significant valvular aortic stenosis and 5 with a prosthetic aortic valve, of which two were dysfunctional. There were six patients with associated mitral regurgitation, seven with associated mitral stenosis and seven with coronary artery disease. The mean left ventricular ejection fraction was 50.2% (range 17 to 85%). Nine patients had a left ventricular ejection fraction of less than 45%.
Five patients were in New York Heart Association (NYHA) functional class II, 13 in functional class III and seven in functional class IV. Medications included digitals in 18 patients, diuretic drugs in 19 patients and vasodilators in 7 patients. Doppler examination was performed within 24 hours of cardiac catheterization in 15 patients, within 1 week in 5 patients and within 4 weeks in 5 patients.

**Doppler examinations.** Doppler examinations were performed utilizing a phased array echocardiographic-Doppler system (IREX IIIB or Meridian). Blood flow velocities were displayed graphically by mean of spectral analysis and recorded at paper speeds of 50 to 100 mm/s. Two types of transducers were used in these studies. One was a combined transducer in which the Doppler functions are integrated with two-dimensional imaging by means of a time-sharing relay; the other was a dedicated independent transducer (Pedof) used for Doppler signal only. Continuous wave Doppler recordings were obtained from the cardiac apex either from the apical five chamber or long-axis view with an effort made to record flow velocities in a parallel fashion. Aortic insufficiency was defined by Doppler signal as early diastolic flow reversal of at least 2 m/s. When present, aortic insufficiency was quantitated by a flow mapping technique from the cardiac apex in the pulsed Doppler mode. Insufficiency was graded as mild if present from the valve plane to 2 cm into the left ventricle, as moderate if present from 2 cm above the valve plane to the papillary muscle level and as severe if present from the papillary muscle level to the cardiac apex.

**Cardiac catheterization.** Cardiac catheterization was performed in a routine manner using either the brachial or femoral artery approach. Left ventricular and aortic pressures were obtained through fluid-filled catheters (Bentley-Tranec model 60 to 800 physiologic pressure transducers) simultaneously or within two cardiac cycles by pullback across the aortic valve. Ascending aortography was performed in a 45° left anterior oblique projection with injection of 40 to 55 cc of Renografin-76 over 2 seconds. Angiographic aortic regurgitation was diagnosed from the aortic root angiogram, and severity of regurgitation was judged qualitatively as the degree and duration of contrast material appearing in the left ventricle during diastole. Mild angiographic aortic regurgitation was defined as minimal dye in the left ventricle clearing with each systole, moderate as slower clearance of dye from the ventricle with aortic opacification greater than ventricular and severe as rapid opacification of the ventricle with slow clearance and equal or greater density of dye in the left ventricle than in the aorta (9,14). To assess inter- and intraobserver variability, the degree of insufficiency present at aortography was graded twice by one observer and again by a second observer in all patients.

**Analysis of data.** From the spectral recording by continuous wave Doppler study, measurements of the slope of deceleration in meters per square seconds, pressure halftime in seconds, and end-diastolic velocity in meters per second were recorded (Fig. 1). The slope of diastolic deceleration was determined as the slope of a straight line drawn between the peak velocity and end-diastolic velocity. The pressure halftime was derived as previously described (15,16) directly from the spectral trace as the time required for the transvalvular pressure gradient to be halved. This measurement was not necessarily included in the line of the slope of deceleration. All values recorded were the average of three consecutive beats. Two observers independently performed measurements of deceleration slope and pressure halftime on 17 patients to assess interobserver variability. Measurements were performed twice by one observer in 12 subjects to assess intraobserver variability.

**Statistical analysis.** Student t tests were applied where appropriate. Continuous wave Doppler variables of deceleration slope as well as pressure halftime versus pulsed Doppler and catheterization variables were performed utilizing Spearman’s rank correlation coefficient. Values are expressed as the mean ± 1 SD.

**Results**

**Continuous wave Doppler recording versus cardiac catheterization.** Deceleration slope. There were nine patients with angiographically graded mild, nine with moderate and seven with severe aortic insufficiency. There was a high correlation (r = 0.93) between the grade of aortic insufficiency by angiography and the velocity deceleration slope as measured by continuous wave Doppler recording (that is, the more severe the insufficiency, the greater the slope). There was a significant difference among the deceleration slopes in individuals with mild (1.6 ± 0.5 m/s²), moderate (2.7 ± 0.5 m/s²) and severe (4.7 ± 1.5 m/s) aortic insufficiency (Fig. 2). A slope of 2 m/s² clearly separated individuals with moderate and severe insufficiency from those with mild insufficiency (p < 0.001).

**Pressure halftime.** There was an inverse correlation between the pressure halftime and the severity of aortic insufficiency as graded by angiography (r = −0.73) (Fig. 3). The more severe the insufficiency, the shorter the pressure halftime seen with increasing severity of aortic insufficiency. While the separation was not as dramatic as that of the deceleration slope, individuals with mild aortic insufficiency had a significantly longer pressure halftime than did those with moderate to severe insufficiency (432 ± 118 versus 284 ± 114 m/s, p < 0.01).

**End-diastolic velocity.** End-diastolic velocity as measured by continuous wave Doppler recording ranged from 0.6 to 3.2 m/s. These velocities were highest in those with mild aortic insufficiency (2.03 ± 0.89) when compared with individuals with angiographically graded moderate (1.42 ± 0.79) and severe (1.34 ± 0.88) insufficiency. These dif-
Figure 1. Continuous wave Doppler tracings from (A) a patient with mild aortic insufficiency and (B) a patient with severe aortic insufficiency. Note that the slope is greater and the pressure half-time is shorter in the patient with more severe aortic insufficiency, indicating a more rapid equilibration between left ventricular and aortic diastolic pressures.

Differences, however, did not achieve statistical significance. There was a weak correlation \( r = 0.28 \) between the Doppler-calculated end-diastolic pressure difference (pressure difference = \( 4V^2 \)) and the directly determined aortic diastolic and left ventricular diastolic pressure difference.

**Pulsed Doppler versus continuous wave Doppler technique.** Using standard pulsed Doppler mapping technique from the cardiac apex, 13 patients were judged as having mild, 8 moderate and 4 severe aortic insufficiency. There was a good correlation \( r = 0.85 \) between the deceleration slope measured by continuous wave Doppler technique and the grade of insufficiency as assessed by pulsed Doppler technique, with increasing deceleration slope seen with increasing severity of insufficiency. An inverse correlation was also seen comparing the pressure half-time from the continuous wave Doppler study versus the grade of insufficiency by pulsed Doppler technique \( r = 0.81 \), with shorter pressure half-times noted with increasing severity of aortic insufficiency.

**Cardiac catheterization versus pulsed Doppler technique** (Fig. 4). There was good correlation between the grade of aortic insufficiency as assessed by cardiac catheterization versus pulsed Doppler technique \( r = 0.86 \). In general, there was a trend for pulsed Doppler technique to underestimate the degree of insufficiency. Four patients judged as having mild insufficiency by pulsed Doppler technique...
Figure 2. Comparison of the deceleration slopes as measured from the continuous wave Doppler tracing and severity of aortic insufficiency as graded from aortography in 25 cases. There was a good correlation ($r = 0.93$) between the catheterization grade and deceleration slope, with the more severe cases exhibiting the greatest slope. Mild versus moderate ($p < 0.001$), moderate versus severe ($p < 0.01$) and mild versus severe ($p < 0.001$).

were found to have moderate insufficiency by cardiac catheterization. Likewise, two individuals found to have moderate insufficiency by pulsed Doppler technique were graded as having severe insufficiency at cardiac catheterization. There was agreement by both techniques in the remaining 19 patients. The presence or absence of mitral stenosis did not affect this correlation.

Inter- and intraobserver variability. Doppler measurements. The mean percent difference between observers in the measurement of deceleration slope was $6 \pm 5.3\%$; the largest absolute difference was $0.5$ m/s$^2$. Interobserver difference in measured pressure half-time was $6.4 \pm 6.4\%$, the largest absolute difference being $80$ ms. The intraobserver difference for slope and pressure half-time was $7.8 \pm 4.8$ and $8.1 \pm 9\%$, respectively. The largest difference in slope measurements by one observer for two observations was $0.25$ m/s and; for pressure half-time the largest difference was $90$ ms.

Catheterization measurements. Intra- and interobserver variability as to the degree of insufficiency as judged by aortography was minimal. Observer A downgraded a severe lesion to moderate in one patient and a moderate lesion to mild in one patient. Observer B disagreed with observer A in two cases. In one patient, insufficiency rated as mild was judged moderate and in another, insufficiency judged as moderate by observer A was rated mild.

Discussion

Several reports (1-9) have documented the high sensitivity of both pulsed and continuous wave Doppler echocardiography in the detection of aortic insufficiency in native and prosthetic heart valves. In the pulsed mode, spectral analysis of the velocity in the left ventricular outflow tract reveals a characteristic signal appearance that includes a high velocity signal, usually exceeding the Nyquist limitation, that exhibits signal aliasing throughout diastole. In
the continuous wave mode, Doppler spectral recordings of tranvalvular aortic flow are equally characteristic, exhibiting high velocity flow reversal in early diastole (usually exceeding 2 m/s) that gradually decreases throughout diastole.

Limitations of other techniques. The severity of aortic insufficiency is most commonly evaluated during cardiac catheterization by a qualitative assessment of the degree of insufficiency by aortic root injection with, in many cases, the calculation of aortic regurgitant volume and regurgitant fraction. However, practical considerations, not the least of which are cost and patient risk, often limit the use of this technique for following up patients with aortic insufficiency. Although several noninvasive methods (17-21) have been shown to provide prognostic information in individuals with aortic insufficiency, a more reliable noninvasive method of assessing the degree of insufficiency remains desirable.

The use of the pulsed Doppler flow mapping technique in relating the severity of regurgitation to the spatial distribution of the regurgitant jet has been evaluated extensively. This method employs carefully mapping back from the aortic valve plane into the left ventricle to determine the extent of the regurgitant jet. Arbitrary landmarks, distances or areas are employed to separate mild, moderate and severe degrees of insufficiency. Despite the widespread application of this technique, certain features have been identified that affect its usefulness and reliability. First and foremost is the dependence on technician experience and time constraints in order to accurately describe the extent of the regurgitant jet into the left ventricle. The angle of this jet may course over the anterior mitral leaflet or be directed more toward the interventricular septum. Additionally, in individuals with a prosthetic heart valve, the regurgitant jet may take a more eccentric pattern (7,8,10,22,23). Furthermore, the lack of standardization of landmarks or extent of area of regurgitant jet in describing the degrees of insufficiency limits interobserver consensus. Theoretically, there is the additional problem in the use of similar landmarks in both the dilated and the normal-sized ventricle. Clearly, the meaning of regurgitant jet that reaches the papillary muscle level in a normal-sized ventricle may differ from that of a regurgitant jet that reaches a papillary muscle in a markedly dilated hypokinetic ventricle. It has been suggested that the presence of associated mitral valve disease, most notably mitral stenosis, may add confusion to the interpretation of a high velocity diastolic jet in the left ventricle because this pattern may resemble that of aortic insufficiency in the pulsed Doppler mode. Careful attention to the timing of these events, however, will usually enable separation of the two (24).

More recently, pulsed Doppler echocardiography has been utilized to quantitate the degree of aortic regurgitation by calculating the regurgitant volume and regurgitant fraction. These methods entail the calculation of an aortic stroke volume as the product of the flow velocity integral obtained in the pulsed Doppler mode at the level of the aortic valve and the cross-sectional area of the aortic valve anulus. From this volume, a similarly calculated stroke volume from a remote area such as the pulmonary artery would be subtracted in order to derive the regurgitant volume. Although these methods appear promising in recent experimental studies, their potential lack of validity in the presence of a stenotic valve commonly seen in the adult with aortic insufficiency limits their practical usefulness.

Present study. In the present study, the conventional pulsed Doppler flow mapping technique showed a good correlation with angiographically graded aortic insufficiency. However, in 6 of the 25 cases there was underestimation of the degree of insufficiency as assessed by pulsed Doppler echocardiography when compared with aortography, despite a good overall correlation ($r = 0.86$). These results are consistent with those of previous investigators (1,3). The continuous wave Doppler technique in the quantitative evaluation of aortic insufficiency has not been extensively examined. The ability of continuous wave Doppler ultrasound to resolve the high velocities associated with an aortic regurgitant jet provide the basis for the present study. Because of the relation between velocity and pressure, the continuous wave method allows the assessment of the pressure difference between the aorta and left ventricle throughout diastole. Theoretically, if this information can be acquired in a relatively parallel fashion, continuous wave Doppler recording will provide accurate and reproducible information describing the relation of aortic and left ventricular pressures during diastole. The basic assumption is that in the more severe forms of aortic regurgitation, the diastolic aortic pressure falls rapidly while left ventricular filling pressures rise rapidly so that the gradient between the aorta and left ventricle declines at a faster rate. This hemodynamic relation would therefore translate to a steeper deceleration slope during diastole in individuals with more severe forms of aortic insufficiency.

The results of the present study support this concept in that there was a strong correlation between the angiographically determined degree of insufficiency and the deceleration slope. In fact, all individuals with a moderate to severe degree of insufficiency as graded from the aortic root injection had a deceleration slope greater than 2 m/s². This correlation was strong in all individuals including those with associated aortic stenosis as well as those with concomitant mitral valve disease and individuals with a low cardiac output and dilated left ventricle. Likewise, the pressure halftime, measured directly from the spectral tracings, showed a good correlation, with shorter pressure half-times being associated with more severe forms of insufficiency. This index was not quite as good a discriminator between the mild and more severe forms of insufficiency at least in part because it was more dependent on a very high quality tracing from which to make these measurements. This is supported
by a larger degree of interobserver variability in these measurements. Both the slope and pressure half-time measurements from the continuous wave tracing correlated well with the conventional pulsed Doppler grading of aortic insufficiency.

Theoretical limitations of these methods. Both the pressure half-time method and the less complex deceleration method rely on the observation that left ventricular diastolic pressure and aortic pressure more rapidly approach each other with increasing degrees of regurgitation. These methods treat the insufficient aortic valve as having a stenotic "regurgitant valve area" (5) whose size determines the insufficient flow and rate of pressure change. Quantifying this orifice by mapping with pulsed mode Doppler recording does correlate with angiographic estimates of aortic regurgitant severity (5). Quantification of the regurgitant valve area by deceleration or pressure half-time methods has certain theoretic limitations including the additive effects of afterload and left ventricular diastolic compliance. The pressure half-time method of orifice quantitation relies on passive flow from one chamber with a single outlet into another with a single inlet. Such a situation is true for isolated mitral stenosis, for which the pressure half-time method has been successfully applied. The aorta in aortic insufficiency, however, has a "double outlet," to the periphery and to the left ventricle. Aortic diastolic pressure decay is thus related to peripheral resistance as well as to aortic valve regurgitant severity. Theoretically, alterations in aortic afterload may play a role in the overlap of pressure half-time seen in the groups with mild and moderate regurgitant severity in Figure 3. In addition, an assumption is made that the information is being acquired in a parallel fashion. Obviously this is not always the case as demonstrated by the poor correlation of Doppler and invasive end-diastolic pressure difference where the angle to flow is of critical importance.

Limitations of the study. Aortic root angiography for the grading of aortic insufficiency, even when done carefully by experienced angiographers, has been known to over- and underestimate the severity of aortic regurgitation (25). While the use of calculated regurgitant fractions may have been helpful, even this method is subject to several limitations including that of the accuracy of both Fick and angiographically calculated outputs. Additionally, 10 studies were not performed within 24 hours of cardiac catheterization. This lack of simultaneous measurements may introduce some variability in the hemodynamic indexes despite apparent clinical stability. The lack of correlation between invasively and Doppler-derived end-diastolic pressure differences between the left ventricle and aorta is probably at least in part secondary to methodologic shortcomings including the lack of simultaneous Doppler and catheterization studies, the inclusion of "pullback" pressure measurements and the lack of control of the angle of incidence.

In addition, the state of hydration and its resultant influence on filling pressures were not necessarily equal at the time of each study. Finally, no attempt was made to assess the reproducibility of these measurements in serial studies. However, we have previously reported (10) on the reproducibility of similar Doppler measurements in serial studies in 22 clinically stable patients with a prosthetic heart valve and have demonstrated minimal variability between careful examinations, suggesting the clinical utility of monitoring such variables.

Conclusions. The use of continuous wave Doppler recording in the assessment of the severity of aortic insufficiency compares well with the quantitative assessment derived from aortic root injection. These results appear to be as useful as those obtained with the conventional pulsed Doppler flow mapping technique. Both methods should probably be employed when evaluating an individual to assess noninvasively the degree of aortic regurgitation.

We gratefully acknowledge the assistance of Susan Buenger in the preparation of this manuscript.

References
12. Touche T, Prasquier R, Nitenberg A, de Zuttere D, Gourgon R. Assessment and follow-up of patients with aortic regurgitation by an


