Continuous-wave Doppler echocardiographic assessment of severity of calcific aortic stenosis: a simultaneous Doppler-catheter correlative study in 100 adult patients

PHILIP J. CURRIE, M.B.B.S., F.R.A.C.P., JAMES B. SEWARD, M.D., GUY S. REEDER, M.D., RONALD E. VLIETSTRA, MB.CH.B, DENNIS R. BRESNAHAN, M.D., JOHN F. BRESNAHAN, M.D., HUGH C. SMITH, M.D., DONALD J. HAGLER, M.D., AND A. JAMIL TAJIK, M.D.

ABSTRACT Studies of the correlation of aortic valve gradient determined by continuous-wave Doppler echocardiography and that determined at catheterization have, to date, involved young patients and nonsimultaneous measurements. We therefore obtained simultaneous Doppler echocardiographic and catheter measurements of pressure gradient in 100 consecutive adults (mean age 69, range 50 to 89 years). In 63 patients pressure measurements were obtained with dual-catheter techniques and in 37 they were obtained by withdrawal of the catheter from the left ventricle to the ascending aorta. Forty-six of these patients also underwent an outpatient Doppler study 7 days or less before catheterization. The simultaneous pressure waveforms and Doppler spectral velocity profiles were digitized at 10 msec intervals and maximum, mean, and instantaneous gradients (mm Hg) were derived for each. The correlation between the Doppler-determined gradient and the simultaneously measured maximum catheter gradient was r = .92 (SEE = 15 mm Hg), that between the Doppler-determined and mean catheter gradient was r = .93 (SEE = 10 mm Hg), and that between the Doppler and peak-to-peak catheter gradient was r = .91 (SEE = 14). The correlation between the nonsimultaneously Doppler-determined gradient and the maximum gradient measured by catheter was not as strong (r = .79, SEE = 24). The continuous-wave Doppler echocardiographic velocity profile represents the instantaneous transaortic pressure gradient throughout the cardiac cycle. The best correlation with continuous-wave Doppler–determined gradient was obtained with maximum and mean gradients measured by catheter. Continuous-wave Doppler echocardiography can be used to reliably predict the pressure gradient in adults with calcific aortic stenosis.
Circulation 71, No. 6, 1162–1169, 1985.

THE CLINICAL EVALUATION of severity of aortic valvular stenosis is difficult, especially in elderly patients in whom significant aortic stenosis may be underestimated.[1,2] Two-dimensional echocardiography has been helpful in the noninvasive evaluation of these patients, but is less reliable in the patient with a heavily calcified, immobile aortic valve.[3,4] The development of continuous-wave Doppler echocardiography has enabled pressure gradients to be estimated across stenotic cardiac lesions.[5-11] This technique has been applied to patients with aortic valvular stenosis and the results have been correlated with nonsimultaneously obtained catheter pressure gradients in small groups of patients.[8-13] To date, the utility of continuous-wave Doppler echocardiography in the noninvasive determination of a wide range of gradients in adults with calcific aortic stenosis has not been validated by simultaneous measurement of pressure gradient with a catheter.

We therefore prospectively studied 100 consecutive patients over the age of 50 years who had suspected calcific aortic valve stenosis at the time of cardiac catheterization to assess the accuracy of the continuous-wave Doppler technique.

Methods

Patient population. The study population consisted of 100 consecutive patients (age ≥50 years) in whom simultaneous Doppler echocardiographic and catheter pressure measurements were obtained during cardiac catheterization for evaluation of aortic valve stenosis. The study period was 6 months. There

From the Division of Cardiovascular Diseases and Internal Medicine and the Division of Pediatric Cardiology, Mayo Clinic, Rochester, MN.
Dr. Currie was supported by an Overseas Clinical Fellowship of the National Heart Foundation of Australia.
Address for correspondence: Dr. Philip J. Currie, Mayo Clinic, 200 First St. SW, Rochester, MN 55905.
Received Jan. 15, 1985; accepted Feb. 21, 1985.

were 55 men and 45 women with a mean age 69 years (range 50 to 89 years). Ninety patients were in sinus rhythm, nine were in atrial fibrillation, and in one rhythm was paced. No patient was excluded from entry into the study on the basis of quality of results of the Doppler echocardiographic examination.

Continuous-wave Doppler echocardiographic technique. The continuous-wave Doppler echocardiographic examination was performed with an IREX model 3B system (IREX Systems, Ramsay, NJ) with the use of a 2.0 MHz nonimaging transducer (Pedof, Vingmed A/S). Occasionally a 2.5 MHz two-dimensional imaging/Doppler transducer was used for orientation. All the Doppler examinations during cardiac catheterization were performed by the same examiner (P. J. C.). Recording of the aortic valve systolic velocity was systematically attempted from suprasternal, right parasternal, apical, and subcostal transducer positions, with multiple sampling sites at each position. Each patient was rotated into a right lateral decubitus position for right parasternal interrogation and into a left lateral decubitus position for apical interrogation.

Continuous-wave Doppler recordings were considered optimal only after systematic examination to locate the signal of highest audible frequency, maximal velocity, and most clearly defined spectral velocity envelope. Optimal signals were assumed to be in a near-parallel orientation to the direction of maximal blood flow across the stenosis. No correction was used to compensate for any presumed angle between the ultrasound beam and direction of maximum systolic jet. The Doppler-determined estimate of systolic pressure gradient across the aortic valve was calculated by the modified Bernoulli equation[5, 9] as follows: GRAD $= 4v^2$, where GRAD = maximum pressure gradient (in mm Hg) and v^2 = maximum velocity squared (in m/sec).

Interobserver variability in the maximum Doppler-determined velocity estimation at catheterization was assessed by review of the tracings from all 100 patients by three independent, trained echocardiographic observers who had no knowledge of other data. The tracings were graded according to technical quality as follows: 1 = inadequate; 2 = fair; 3 = satisfactory; 4 = good.

In addition to the simultaneous Doppler-catheter pressure measurements, 46 patients also underwent a nonsimultaneous Doppler echocardiographic study within 7 days of catheterization. This was performed during a comprehensive two-dimensional echocardiographic examination done on an outpatient basis; an average of 4 days separated the two Doppler studies.

Cardiac catheterization. Intravenous diazepam (2.5 to 15 mg) was used for sedation during catheterization. Fluid-filled catheters (No. 7F or 8F) connected to strain-gauge pressure transducers (Gould P23Id, Oxnard, CA) were used for pressure measurement. The frequency response of the catheter recording systems was linear up to 12 to 15 Hz. The systolic aortic pressure gradient was measured by one of the following three techniques. In 37 patients, catheter pullback from the left ventricle across the aortic valve was performed. Subsequently, the left ventricular pressure waveforms recorded immediately before the pullback were superimposed over the ascending aortic waveforms immediately after the withdrawal. These tracings were aligned for R wave of the electrocardiogram and respiratory phase. In the other 63 patients, dual catheters were used for pressure recordings. Of these 63 patients, 33 underwent transseptal catheterization, while in 30 simultaneous left ventricular and ascending aortic pressure measurements were obtained with one catheter retrogradely across the aortic valve and one in ascending aorta. Four of the nine patients with atrial fibrillation underwent a dual-catheter procedure. In the remaining five, care was taken to match electrocardiographic RR intervals of the left ventricular and aortic pressure tracings.

The pressures were recorded on a calibrated multichannel direct-writing polygraph and onto the calibrated IREX 7 inch strip-chart recorder, via a direct-current coupler, simultaneously with the Doppler spectral signal and the electrocardiogram (figure 1, *A*).

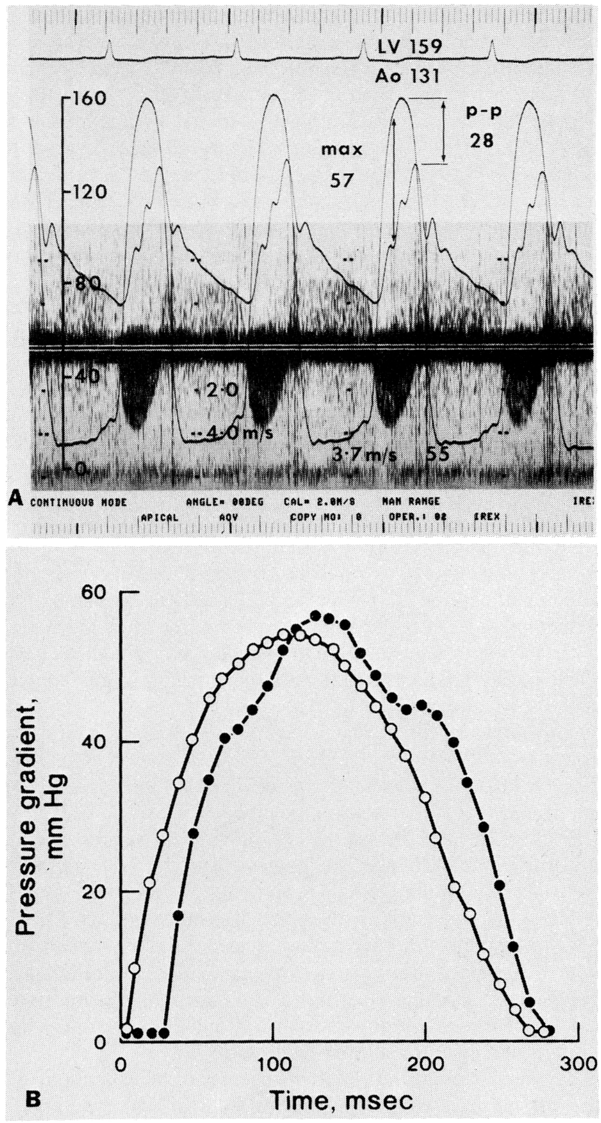

FIGURE 1. *A*, Simultaneous Doppler-catheter pressure recordings in a patient with moderate aortic stenosis. The pressure gradient was measured with a dual-catheter technique with catheters in the left ventricle (LV) and aortic root (Ao). The maximum catheter gradient (max) was 57 mm Hg and peak-to-peak gradient (p-p) was 28 mm Hg. The simultaneous Doppler echocardiogram was recorded from the apical transducer position with a maximum velocity of 3.7 m/sec and maximal Doppler gradient of 55 mm Hg. *B*, Digitization of the Doppler spectral velocity envelope and LV + Ao pressure waveforms of the third beat from *A*. The phase delay of the catheter gradient (closed dots) compared with the Doppler-derived gradient (open dots) is related to the fluid-filled catheter system. The mean catheter gradient (area under the curve) was 39 mm Hg and was comparable to the mean Doppler-derived gradient of 37 mm Hg. Note the irregularity in contour of the catheter gradient curve, which is related to the irregularities in the ascending aortic pressure waveform in *A*.

Determination of cardiac output was performed before angiography with the indocyanine green dye dilution technique. Aortic incompetence was assessed by aortic root angiography in 22 patients. The degree of mitral valve incompetence was assessed qualitatively and left ventricular ejection fraction was calculated from biplane left ventricular angiograms.

Pressure gradient analysis. The simultaneously recorded Doppler spectral profile and left ventricular and ascending aortic pressure waveforms were digitized at 10 msec intervals with instantaneous Doppler echocardiographic and catheter pressure gradients being calculated at each interval (figure 1, *B*). Mean Doppler-determined gradients were derived by application of the modified Bernoulli equation at every 10 msec interval to calculate the instantaneous Doppler-determined gradients during systole. The maximum gradient measured by catheter was the maximum instantaneous pressure gradient between the left ventricle and ascending aorta and the maximum Doppler echocardiographic gradient was derived from the maximum velocity. The peak-to-peak systolic catheter gradient represented the difference between the peak left ventricular systolic pressure and the peak systolic ascending aortic pressure and as shown in figure 1, *A*, these peak pressures are not synchronous.

The continuous-wave Doppler echocardiographic systolic ejection time (DOPET) and the time from onset of the systolic Doppler spectral envelope to maximum velocity (TTP) were determined. The ratio of these Doppler measurements (TTP/DOPET) was calculated to determine its accuracy in assessing the severity of aortic stenosis.[9]

Learning experience analysis. To assess the importance of a learning effect, the 100 patients were equally divided into three sequential subgroups according to study number. Features analyzed included the correlation of Doppler-determined and catheter pressure gradients and the technical quality of the Doppler spectral envelope.

Statistical methods. Data are expressed as mean ± SD. The correlation of Doppler-determined gradients with pressure gradients measured by catheter was assessed by linear regression analysis using a least squares method.

Comparisons of simultaneous Doppler echocardiographic measurements with nonsimultaneous Doppler measurements were made with the paired Student t test.

Variation in accuracy of Doppler-determined pressure gradient as a result of differing quality of recordings and experience with the method was assessed by comparing the differences between the Doppler-determined and catheter pressure gradients in the three subgroups by one-way analysis of variance and the Newman-Keuls multiple-range test.

Effects of cardiac index, left ventricular ejection fraction, and the presence of coronary artery disease on the accuracy of Doppler-determined gradients were assessed by linear regression analysis of the differences between Doppler-determined and catheter pressure gradients with each of these parameters.

Results

Continuous-wave Doppler recordings. The maximum velocity of the transaortic systolic flow ranged from 1.8 to 6.1 m/sec (mean 3.8 ± 1.1 m/sec). The transducer position yielding the maximum velocity was apical in 47, suprasternal in 25, right parasternal in 14, and subcostal in 14 patients. The quality of recordings as graded by the independent observers was good in 40 (40%) patients, satisfactory in 44 (44%), and fair in 16 (16%). The Doppler recordings were considered usable in all 100 patients. The interobserver variability in the maximum Doppler-determined gradient recorded at catheterization had a mean coefficient of variation of 6% and a range of 0 to 24%.

Correlation of simultaneous Doppler-catheter pressure gradients. The maximum Doppler-derived gradients ranged from 13 to 147 mm Hg (mean 62 ± 36 mm Hg) and the simultaneous maximum pressure gradients measured by catheter ranged from 2 to 180 mm Hg (mean 71 ± 38 mm Hg). The correlation between maximum Doppler-determined gradient and the simultaneously obtained maximum catheter gradient was

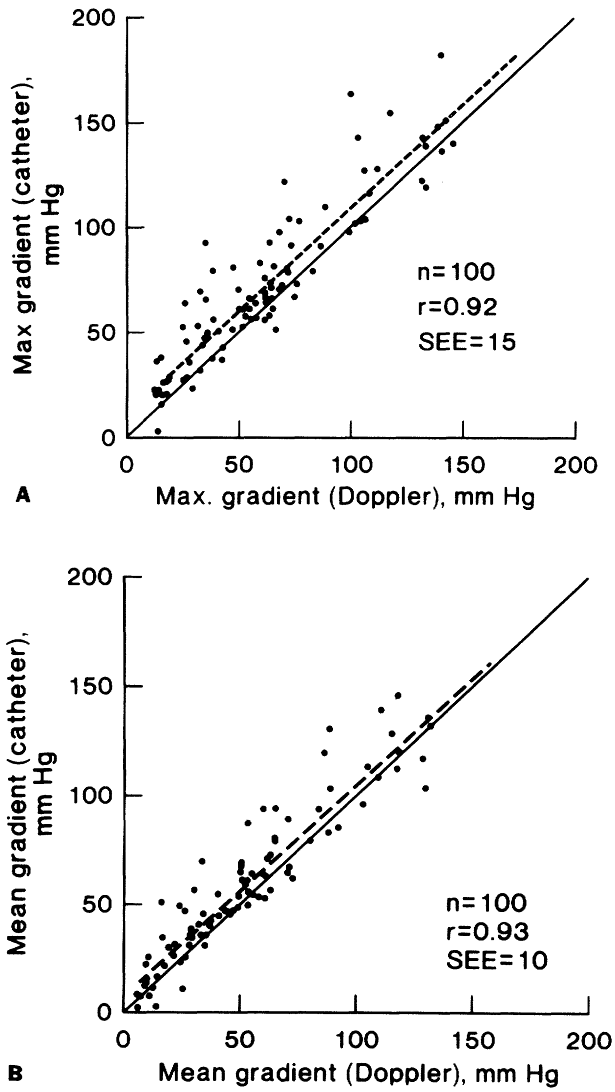

FIGURE 2. *A*, Correlation of simultaneous maximal Doppler-determined and catheter pressure gradients in the 100 patients. The regression equation is catheter gradient = 10.3 + 0.97 × Doppler-determined gradient. The dotted line represents the regression line and the solid line the line of identity. *B*, Correlation of simultaneous mean Doppler-derived and catheter pressure gradients in the 100 patients. The regression equation is catheter gradient = 5.2 + 0.98 × Doppler-determined gradient. The dotted line represents the regression line and the solid line the line of identity.

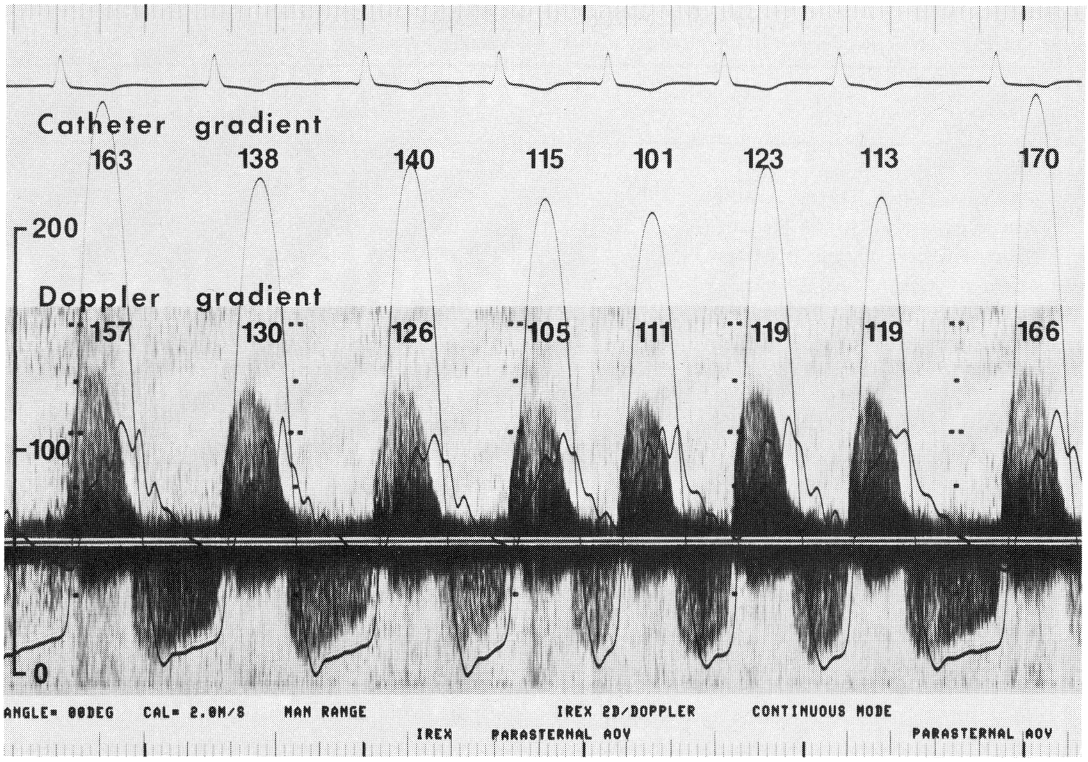

FIGURE 3. Simultaneous Doppler-catheter pressure measurements with a dual-catheter technique showing the beat-to-beat comparison in a patient with atrial fibrillation and severe aortic stenosis. The catheter and Doppler-derived gradients are maximum systolic gradients. The Doppler echocardiogram was recorded with the transducer in the right parasternal position. Note that aortic regurgitation was also detected.

highly significant (r = .92, SEE = 15) (figure 2, *A*).

The peak-to-peak gradient measured by catheter ranged from 0 to 133 mm Hg (mean 46 ± 33 mm Hg), which was significantly lower than either the maximum catheter gradient or maximum Doppler-determined gradient ($p < .001$). There was a correlation between the maximum Doppler echocardiographic gradient and the peak-to-peak gradient (r = .91, SEE = 14 mm Hg).

The mean Doppler-determined gradient ranged from 5 to 101 mm Hg (mean 41 ± 25 mm Hg) and the mean pressure gradient measured with the catheter ranged from 0 to 112 mm Hg (mean 45 ± 26 mm Hg). These correlated closely (r = .92, SEE = 10 mm Hg) (figure 2, *B*).

There was good beat-to-beat comparison between the Doppler- and catheter-measured pressure gradients in individual patients, even those with irregular heart rhythm, as illustrated in figure 3.

Correlation of TTP/DOPET with pressure gradient. TTP/DOPET ranged from 0.10 to 0.54 (mean 0.36 ± 0.09). This ratio correlated poorly with both the maximum pressure gradient (r = .39) and the peak-to-peak gradient measured by catheter (r = .30).

Effect of experience (learning experience). The 100 consecutive patients were divided into three equal sequential subgroups according to their study number (group 1, first 33 patients; group 2, second 33 patients; group 3, final 34 patients studied). The correlations of maximum Doppler-determined gradient with maximal and peak-to-peak pressure gradients measured by catheter and the correlations between mean gradients by the two methods are shown in table 1 for the three subgroups. There was improvement in the correlations with increased experience with the method. Comparison in the three subgroups of differences between the Doppler-derived and catheter-measured pressure gradients showed that improvement in accuracy was most apparent between the time group 1 and the two other groups were studied ($p < .05$). There was no significant change in accuracy between study of groups 2 and 3. The quality of the spectral envelopes also improved progressively in the three subgroups of patients.

Effect of cardiac index, left ventricular function, or associated coronary artery disease. The cardiac index measured in 95 patients ranged from 0.7 to 5.3 liters/min/m^2 (mean 2.5 ± 0.6 liters/min/m^2). Angiographic biplane left ventricular ejection fraction was calculated for 89 patients and ranged from 14% to 89% (mean 57 ± 17%). Selective coronary angiography was per-

TABLE 1
Learning experience: comparison in the three sequential patient subgroups

	Group 1 (n = 33)	Group 2 (n = 33)	Group 3 (n = 34)
Correlation (r value/SEE)			
Max. catheter–max. Doppler gradient	.88/19	.91/13	.96/12
Peak-to-peak–max. Doppler gradient	.86/17	.92/11	.95/12
Mean catheter–mean Doppler gradient	.88/13	.92/9	.97/7
Comparison of mean differences between Doppler and catheter gradients (mm Hg)			
Max. catheter–max. Doppler gradient	14±19	6±12	5±12
Peak-to-peak–max. Doppler gradient	−11±19	−18±11	−21±13
Mean catheter–mean Doppler gradient	8±12	3±8	2±7
Quality of Doppler Spectral Envelope (n)			
Fair	7	4	5
Satisfactory	16	14	14
Good	10	15	15

formed in 97 patients with significant coronary artery disease (≥50% stenosis) being detected in 59 (61%) patients. There were no significant effects of the level of cardiac index, the degree of left ventricular dysfunction, or the presence or severity of associated coronary disease on the accuracy of Doppler-measured pressure gradients.

Effect of quality of Doppler spectral profiles. There was a significant effect of the quality of Doppler spectral profiles on the accuracy of Doppler-measured pressure gradients. Accuracy of Doppler echocardiographic gradient measurements was significantly better for patients with good tracings than in those for whom they were of satisfactory or fair quality ($p < .05$).

Relationship of maximum and peak-to-peak gradients in patients with aortic stenosis. The maximum instantaneous catheter gradient was always higher than the peak-to-peak gradient over a wide range of severity of aortic stenosis (figure 4), with a close correlation between the maximum and peak-to-peak gradients (r = .95, SEE = 11 mm Hg) (figure 5). The linear regression equation relating these gradients was

$$\text{Peak-to-peak gradient} = 0.84 \times \text{maximum gradient} - 13.7$$

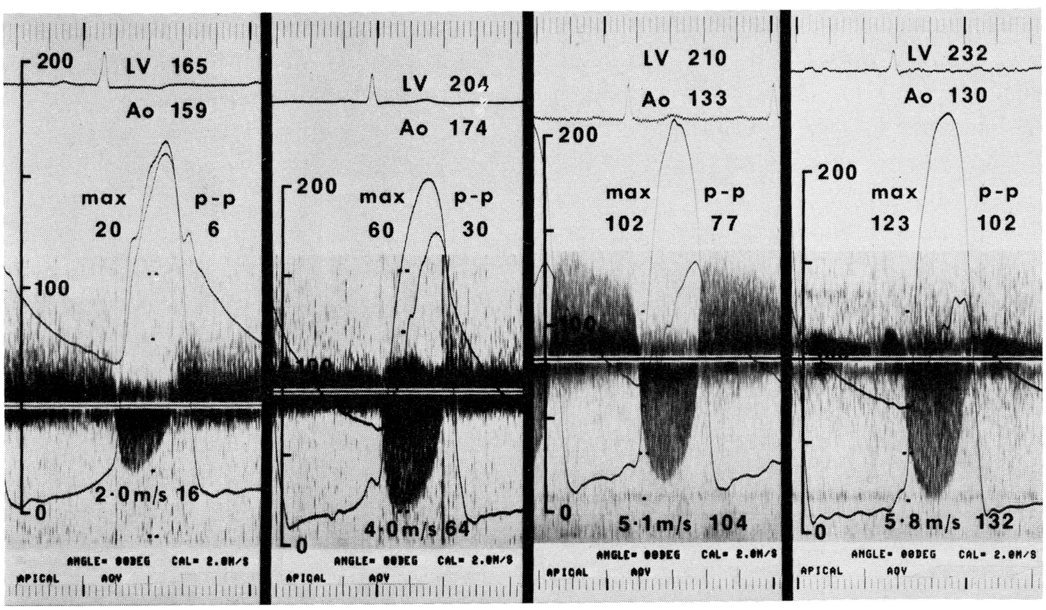

FIGURE 4. A composite of simultaneous Doppler-catheter pressure measurements in four patients with variable severity of aortic stenosis in whom dual-catheter left ventricular (LV) and ascending aortic (Ao) pressure measurements were obtained. The maximum catheter (max) gradient is greater than the peak-to-peak (p-p) catheter gradient at each level of stenosis. The maximum Doppler-derived gradients accurately measure the simultaneously recorded maximum catheter gradient, but overestimate the peak-to-peak catheter gradient. The Doppler calibration markers are 2 m/sec apart.

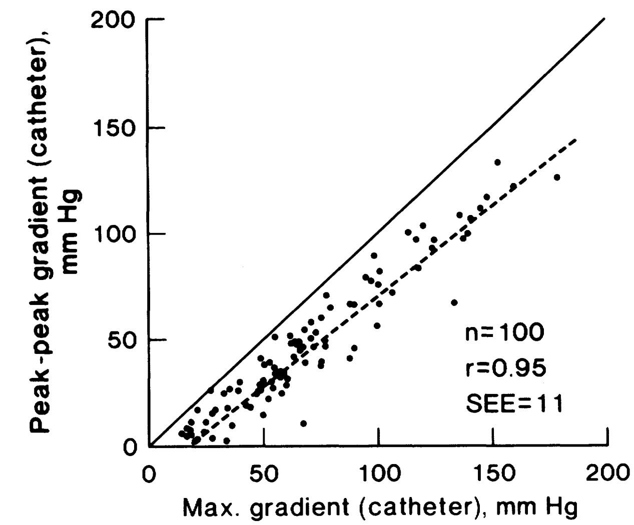

FIGURE 5. Correlation of the maximum catheter pressure gradient with the peak-to-peak catheter gradient in the 100 patients. The regression equation is peak-to-peak gradient = 0.84 × max gradient − 13.7. The dotted line represents the regression line and the solid line the line of identity.

To estimate the peak-to-peak catheter gradient from the maximum Doppler-derived gradient, this regression equation was applied in the last 67 patients. There was close correlation between the estimated peak-to-peak gradient derived from the Doppler profile and the catheter-measured peak-to-peak gradient (r = .94, SEE = 11 mm Hg). However, on an individual basis, these results were less reliable.

Outpatient Doppler measurements. In the 46 patients in whom two Doppler studies were obtained, the outpatient Doppler-determined velocities ranged from 1.6 to 5.8 m/sec (mean 3.4 ± 1.0 m/sec) and the maximum Doppler-derived velocities at catheterization ranged from 1.8 to 6.1 m/sec (mean 3.8 ± 1.2 m/sec). The Doppler-determined outpatient gradients ranged from 10 to 136 mm Hg (mean 51 ± 27 mm Hg) and those at catheterization ranged from 13 to 147 mm Hg (mean 62 ± 38 mm Hg); the maximum gradient measured by catheter ranged from 20 to 180 mm Hg (mean 68 ± 38 mm Hg). The outpatient Doppler-determined gradients were significantly lower than those measured at catheterization ($p < .001$). The correlation between the Doppler-derived maximum gradient in outpatients and maximum catheter gradient was represented by r = .79 and SEE = 24 mm Hg. This was significantly lower than the simultaneous maximum Doppler-catheter gradient correlation in these same 46 patients (r = .95, SEE = 12 mm Hg).

Discussion

This study documents that continuous-wave Doppler echocardiography can be used to reliably and noninvasively measure the systolic pressure gradient in adults with valvular aortic stenosis. As might be expected, the correlation and accuracy are highest for maximum instantaneous and mean gradients. The Doppler-derived gradient is not equivalent to the peak-to-peak catheter gradient and, if they are compared, the result is a consistent overestimation of the latter.

The ability of continuous-wave Doppler echocardiography to measure the aortic pressure gradient has been previously reported.[8–13] However, there are important differences between these reported series and our study. The results of the previous studies were obtained in relatively small numbers of patients and they included young patients, while we limited our study population to adults (≥50 years old). Furthermore, in these series the Doppler and catheter measurements were not obtained simultaneously, and were usually obtained on different days; correlations were calculated with either peak-to-peak or maximum catheter gradient and patients in whom inadequate Doppler echocardiograms were obtained were excluded. Our simultaneous Doppler-catheterization study specifically focused on consecutive patients 50 or more years old with valvular aortic stenosis since in this age group the noninvasive assessment of severity of disease has been reported to be the least accurate.[1–4, 9, 14]

To prove the validity of the Doppler technique, assessment of simultaneous Doppler-catheter pressure measurements and the instantaneous beat-to-beat relationship of the catheter and Doppler-determined gradients were deemed necessary. The lower correlation between the nonsimultaneous and simultaneous Doppler-catheter pressure measurements in the 46 patients in our study is believed to represent the effect of time elapsed between the studies and differences in hemodynamic state. In previous reports[11, 13] in which nonsimultaneous Doppler-catheter measurements were correlated, the maximum Doppler-derived velocities of a number of beats were averaged to calculate a representative gradient. This could result in inaccuracies if the maximum velocities of individual beats are averaged before the maximum gradient is derived with the modified Bernoulli equation. This was not a problem in our simultaneous Doppler-catheter study.

Whenever a correlative study is undertaken, one must consider the accuracy and limitations of the "gold standard" used for comparison. The fidelity of the fluid-filled catheter pressure measurement system and inherent presence of catheter-induced artifact are important considerations. An underdamped system or catheter artifact may lead to errors in estimation of maximum and mean pressure gradients, which may be

incorrectly interpreted as inaccuracies in the Doppler echocardiographic gradient measurements upon comparison. It should also be noted that in all previous Doppler-catheter correlative studies in patients with aortic stenosis, the catheter pressures were measured with fluid-filled catheters.[8–13] The use of high-fidelity transducer-tipped catheters may circumvent some of these problems. A closer Doppler-pressure correlation was shown in studies of experimental aortic stenosis in dogs[15] and in patients with aortic stenosis[16] when transducer-tipped rather than fluid-filled catheters were used for pressure recording. Furthermore, the method of measurement of pressure gradient at catheterization is also important in Doppler-catheter correlative studies. Simultaneous left ventricular and ascending aortic pressure measurements were rarely used in previous studies. In some, simultaneous left ventricular and peripheral arterial measurements were used to obtain the maximal pressure gradients.[11–13] Although the central aortic and peripheral arterial pressure waveforms (femoral, brachial, or radial) may be similar, there is pulse distortion (upstroke delay, systolic amplification, and ejection time prolongation) that increases in proportion to the distance from the ascending aorta.[17] The phase shift between the central and peripheral pressures leads to a spurious overestimation of the maximum and mean pressure gradient. The peak-to-peak gradient may underestimate the stenosis because of the systolic amplification of the peripheral arterial pulse. Folland et al.[18] have shown the inaccuracy in the use of mean aortic valve gradients obtained from peripheral pressure tracings. They recommend the use of simultaneous left ventricular and ascending aortic pressures whenever a high degree of accuracy is required, such as in validation studies in which catheter measurements are the reference standard.

A systematic attempt to correlate Doppler-determined and catheter measurements of mean pressure gradients has not previously been made. While the peak-to-peak catheter pressure gradient is easily obtained and commonly used, this is not a sound practice according to hydraulic principles, since the peak systolic left ventricular and ascending aortic pressures are nonsynchronous. The Doppler-derived gradient represents an instantaneous pressure difference, and therefore the maximum gradient as determined by Doppler echocardiography should always be interpreted as the maximum instantaneous gradient and should not be equated with peak-to-peak gradient. To estimate the peak-to-peak gradient from the maximum Doppler-derived gradient may be less reliable even when regression equations are used, as shown in our results. Clinically the mean Doppler-determined gradient may be the most useful expression of aortic valve gradient since it is directly comparable to the mean gradient measured by catheter used for calculation of aortic valve area.

There are potential limitations to the continuous-wave Doppler echocardiographic estimation of gradient. One cause of underestimation of aortic valve gradient is failure to obtain a small or zero angle of incidence between the ultrasound beam and the maximum systolic aortic jet. Although an angle of incidence of less than 20 degrees will underestimate the maximal velocity by less than 6%, the error in estimation of gradient will be higher since the gradient is proportional to the maximal velocity squared. A high-quality Doppler signal with a complete spectral envelope recorded from a single transducer position does not necessarily indicate that the angle of incidence is negligible. Therefore, a careful interrogation of multiple transducer positions is mandatory to minimize the potential cause of underestimation. As this study has shown, improvement in the Doppler technique through experience leads to a marked decrease in the underestimation of gradient.

The Doppler-measured aortic valve gradient, used in conjunction with clinical data and a complete two-dimensional echocardiographic study, should greatly assist in the noninvasive assessment of adults with suspected aortic valvular stenosis. It may be particularly helpful in the serial systematic follow-up of older patients in whom severity of aortic stenosis is on the borderline of the range normally justifying surgical replacement and in whom progression of stenosis is suspected or anticipated. In patients with left ventricular dysfunction and depressed cardiac output, Doppler-determined gradient alone may not be sufficient for clinical management and the determination of aortic valve area may be necessary. There have been preliminary studies in which attempts were made to noninvasively determine aortic valve area[10, 13] with the Doppler-derived aortic velocity and cardiac output measured by the thermodilution technique or by Doppler methods.[19, 20]

In conclusion, a continuous-wave Doppler echocardiographic examination by an experienced echocardiographer can reliably estimate the maximum instantaneous and mean pressure gradient in adults with aortic valve stenosis. This information, along with other noninvasive data, will aid in the clinical management of such patients.

We thank A. A. Bove, M.D., for his valued advice and use of computer facilities. We also thank Elizabeth Dunnett for assis-

tance with manuscript preparation and the technical and secretarial staff of the Echocardiographic and Cardiac Catheterization Laboratories.

References

1. Finegan RE, Gianelly RE, Harrison DC: Aortic stenosis in the elderly; relevance of age to diagnosis and treatment. N Engl J Med **281:** 1261, 1969
2. Roberts WC, Perloff JK, Costantino T: Severe valvular aortic stenosis in patients over 65 years of age: a clinicopathologic study. Am J Cardiol **27:** 497, 1971
3. Demaria AN, Bommer W, Joye J, Lee G, Bouteller J, Mason DT: Value and limitations of cross-sectional echocardiography of the aortic valve in the diagnosis and quantification of valvular aortic stenosis. Circulation **62:** 304, 1980
4. Nair CK, Aronow WS, Sketch MH, Mohiuddin SM, Stokke K, Ryschon K: Correlation between calcific aortic stenosis diagnosed by two-dimensional echocardiography and cardiac catheterization. Clin Cardiol **7:** 280, 1984
5. Hatle L, Angelsen B: Doppler ultrasound in cardiology: physical principles and clinical applications. Philadelphia, 1982, Lea and Febiger, p 89
6. Lima CO, Sahn DJ, Valdes-Cruz LM, Goldberg SJ, Barron JV, Allen HD, Grenadier E: Noninvasive prediction of transvalvular pressure gradient in patients with pulmonary stenosis by quantitative two-dimensional echocardiographic Doppler studies. Circulation **67:** 866, 1983
7. Fyfe DA, Currie PJ, Seward JB, Tajik AJ, Reeder GS, Mair DD, Hagler DJ: Continuous-wave Doppler determination of the pressure gradient across pulmonary artery bands: hemodynamic correlation in 20 patients. Mayo Clin Proc **59:** 744, 1984
8. Hatle L: Noninvasive assessment and differentiation of left ventricular outflow obstruction with Doppler ultrasound. Circulation **64:** 381, 1981
9. Hatle L, Angelsen BA, Tromsdal A: Noninvasive assessment of aortic stenosis by Doppler ultrasound. Br Heart J **43:** 284, 1980
10. Kosturakis D, Allen HD, Goldberg SJ, Sahn DJ, Valdes-Cruz LM: Noninvasive quantification of stenotic semilunar valve areas by Doppler echocardiography. J Am Coll Cardiol **3:** 1256, 1984
11. Stamm RB, Martin RP: Quantification of pressure gradients across stenotic valves by Doppler ultrasound. J Am Coll Cardiol **2:** 707, 1983
12. Berger M, Berdoff RL, Gallerstein PE, Goldberg E: Evaluation of aortic stenosis by continuous wave Doppler ultrasound. J Am Coll Cardiol **3:** 150, 1984
13. Warth DC, Stewart WJ, Block PC, Weyman AE: A new method to calculate aortic valve area without left heart catheterization. Circulation **70:** 978, 1984
14. Voelkel AG, Kendrick M, Pietro DA, Parisi AF, Voelkel V, Greenfield D, Askenazi J, Folland ED: Noninvasive tests to evaluate the severity of aortic stenosis: limitations and reliability. Chest **77:** 155, 1980
15. Callahan MJ, Tajik AJ, Su-Fan Q, Bove AA: Continuous wave Doppler–catheterization correlation of pressure gradients in experimental aortic stenosis. Circulation **70** (suppl II): II-114, 1984 (abst)
16. Smith MD, Dawson P, Elion J, Wisenbaugh T, Handshoe S, Kwan OL, Demaria AN: Comparative correlation of continuous wave Doppler spectral measurements with hemodynamic parameters in patients with aortic stenosis. Circulation **70** (suppl II): II-116, 1984
17. Kroeker EJ, Wood EH: Comparison of simultaneously recorded central and peripheral arterial pressure pulses during rest, exercise and tilted position in man. Circ Res **3:** 623, 1955
18. Folland ED, Parisi AF, Carbone C: Is peripheral arterial pressure a satisfactory substitute for ascending aortic pressure when measuring aortic valve gradients? J Am Coll Cardiol **4:** 1207, 1984
19. Fisher DC, Sahn DJ, Friedman MJ, Larson D, Valdes-Cruz LM, Hotowitz S, Goldberg SJ, Allen HD: The mitral valve orifice method for noninvasive two-dimensional echo Doppler determinations of cardiac output. Circulation **67:** 872, 1983
20. Goldberg SJ, Sahn DJ, Allen HD, Valdez-Cruz LM, Hoenecke H, Carnahan Y: Evaluation of pulmonary and systemic blood flow by two-dimensional echocardiography using fast-Fourier transform spectral analysis. Am J Cardiol **50:** 1394, 1982