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METHODS

# Determination of Aortic Valve Area by Two-Dimensional and Doppler Echocardiography in Patients With Normal and Stenotic Bioprosthetic Valves

ROBERT M. ROTHBART, MD, FACC, JORGE L. CASTRIZ, MD,* LINDA V. HARDING, RDMS, CHARLES D. RUSSO, MD, STEVEN M. TEAGUE, MD, FACC*

*Miami, Florida and Oklahoma City, Oklahoma*

**To assess the feasibility and accuracy of determining bioprosthetic aortic valve area from two-dimensional and Doppler echocardiographic measurements, three partially overlapping groups were selected from 55 patients with such bioprosthetic valves and adequate Doppler studies. These were Group 1, 37 patients with recent aortic valve replacement surgery and no clinical or echocardiographic evidence of valve dysfunction; Group 2, 12 patients with prosthetic valve stenosis documented by cardiac catheterization; and Group 3, 22 patients with both Doppler and catheterization studies in whom noninvasive and invasive determinations of aortic valve area could be directly compared.**

**Left ventricular outflow tract diameter was measured from two-dimensional still frame images. Flow velocity proximal to the aortic valve, transvalvular velocity and acceleration time were determined from pulsed and continuous wave Doppler spectra. Aortic valve gradient was calculated with the modified Bernoulli equation and valve area by the continuity equation.**

**In the 37 patients with a normally functioning valve, the calculated mean gradient ranged from 5 to 25 mm Hg (average 13.6 ± 5.2) and valve area from 1.0 to 2.3 $cm^2$ (mean 1.6 ± 0.31). Linear regression analysis of prosthetic aortic valve area determined by Doppler imaging and cardiac catheterization demonstrated a high correlation ($r = 0.93$) between the two techniques. Comparison of the patients with and without prosthetic valve stenosis revealed statistically significant differences in mean gradient (42.8 ± 12.3 versus 13.6 ± 5.2 mm Hg; $p = 0.0001$), acceleration time (116 ± 15 versus 80 ± 13 ms; $p = 0.0001$) and valve area by the continuity equation (0.80 ± 0.16 versus 1.6 ± 0.31 $cm^2$; $p = 0.0001$).**

**Individual ultrasound variables were assessed for their utility in recognizing bioprosthetic valve stenosis. When diagnostic criteria were selected to maintain absolute specificity, either an abnormally high mean gradient or a noninvasively determined valve area $<1$ $cm^2$ identified 92% of patients with a stenotic valve. Marginally lower sensitivity was associated with an elevated peak gradient or a prolonged acceleration time; each identified 75% of the patients with valve stenosis. However, measurement of the ratio of left ventricular outflow tract to transvalvular velocity time integrals further improved diagnostic accuracy. All 37 patients with a normal prosthetic valve had a ratio >0.35, whereas each of the 12 patients with valve stenosis had a lower ratio.**

**In conclusion, assessment of prosthetic aortic valve area by cardiac ultrasound is highly accurate and can be useful in the diagnosis of bioprosthetic aortic valve stenosis.**

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The accuracy of two-dimensional and Doppler echocardiography for determining transvalvular gradient (1–3) and aortic valve area (4–6) in adult patients with aortic stenosis has been well established. Considerably less information is available regarding the role of cardiac ultrasound in assessing *prosthetic* aortic valves. Doppler gradient estimates across bioprosthetic and Björk-Shiley valves (7–9) implanted in the aortic position have correlated well with measurements made at cardiac catheterization; however, this has not been the case for Starr-Edwards valves (10). In only one preliminary study (11) have noninvasive prosthetic valve area determinations been reported; these were obtained from patients with a normally functioning Björk-Shiley valve and were not verified by comparison with catheterization data.

From the Division of Cardiology, Department of Medicine, University of Miami School of Medicine, and Veterans Affairs Medical Center, Miami, Florida; and *Department of Medicine, Division of Cardiology, University of Oklahoma School of Medicine, Oklahoma City, Oklahoma.

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Address for reprints: Robert M. Rothbart, MD, University of Colorado School of Medicine, Division of Cardiology (B-130), 4200 East Ninth Avenue, Denver, Colorado 80262.



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Because stenosis of mechanical valves occurs infrequently, noninvasive techniques for identifying prosthetic valve stenosis are of greater clinical value in patients with a bioprosthetic device. Unfortunately, standard echocardiographic imaging employing M-mode and two-dimensional techniques often fails to adequately delineate the valve leaflets in these patients. As a result, it may be difficult or impossible to identify signs of valve dysfunction, including thickening, calcification or restricted leaflet motion. In these cases, noninvasive techniques to estimate aortic valve area could be extremely valuable. Thus, the present study was undertaken to assess the accuracy of two-dimensional and Doppler echocardiography in estimating bioprosthetic aortic valve area and to determine the value of this technique in the diagnosis of bioprosthetic valve stenosis.

## Methods

**Study patients.** The study group comprised 56 patients aged 37 to 81 years; 8 were women and 48 were men. The goals and methods of this investigation were explained to each subject and written informed consent was obtained according to the protocol approved by our institutional review boards.

Thirty-eight patients had undergone aortic valve replacement 1 to 24 months before entering the study; they denied all cardiovascular symptoms, had normal auscultatory findings, other than a grade 2–3/6 systolic ejection murmur, and had normal findings on cardiac ultrasound studies. Specifically, aortic valve leaflets, if imaged, measured <3 mm in thickness and demonstrated normal excursion without prolapse. No discordant motion of the sewing ring was visualized. Aortic regurgitation was judged by Doppler study to be either absent (n = 21) or mild (n = 17) with regurgitant flow detectable ≤1.5 cm proximal to the aortic valve. These patients were considered to have normal prosthetic valve function. A 24 month limit between valve replacement surgery and study entry was selected for this normal group, because bioprosthetic valve calcification or dysfunction is extremely unlikely within the first 2 years after implantation in adults (12,13).

*Twelve additional patients had bioprosthetic aortic stenosis (valve area <1.0 cm$^2$) verified by cardiac catheterization.* The remaining six patients had undergone aortic valve replacement surgery >24 months before Doppler studies (range 51 to 127 months), but cardiac catheterization performed within 2 months of the Doppler examination verified normal valve function. These 6 patients, together with all 12 patients with stenosis and 4 normal patients who had undergone postoperative catheterization formed a cohort of 22 patients whose noninvasive and invasive measurements of aortic valve area could be directly compared.

**Two-dimensional and Doppler echocardiography.** Echocardiographic examinations were performed with a Hewlett Packard 77020AC cardiac ultrasound system. The videotaped studies were reviewed and Doppler spectra measured on an off-line video analysis system (MicroSonics CAD886), which digitally samples such data at 10 ms intervals.

*Aortic valve area (AVA) was calculated with use of the continuity equation (4–6):*

$$AVA = \pi(D/2)^2(V_{LVOT}/V_{AV}),$$

where D = the diameter of the left ventricular outflow tract, $V_{LVOT}$ = the velocity time integral of flow from the left ventricular outflow tract and $V_{AV}$ = the velocity time integral of flow through the aortic valve. The diameter of the left ventricular outflow tract was measured as the perpendicular distance between the inner edges of its anterior and posterior aspects just proximal to the sewing ring of the aortic valve in left parasternal long-axis still frame images. Multiple measurements were performed in conjunction with slight changes in transducer angulation until a reproducible maximal value was obtained.

*Pulsed Doppler measurements of flow velocity in the left ventricular outflow tract* were recorded by placing the sample volume in the body of the left ventricle, advancing gradually toward the aortic valve until a marked increase in Doppler peak velocity was detected and then withdrawing slightly. The site identified by this method was typically 0.5 to 1 cm proximal to the aortic valve leaflets. If valve leaflet clicks were noted in the spectral tracing, the sample volume was considered to be improperly positioned and was moved to a slightly more proximal location. The highest velocity signals meeting the preceding criteria were selected for analysis; measurements from three successive curves were averaged. Filtering was maintained at a minimal level to facilitate accurate identification of flow onset and termination.

*Continuous wave Doppler spectra of transvalvular flow* were recorded from the apical, right parasternal and suprasternal transducer positions in all patients. Transducer position and angulation were manipulated until maximal velocities and the purest auditory signals were obtained. As was the case for pulsed Doppler ultrasound, the minimal low pass filter setting consistent with adequate definition of the spectral envelope was employed. Peak and mean velocities, as well as time to peak velocity, were measured automatically by our computer analysis system from the digitized Doppler spectra. Acceleration time was defined as the interval between initial and maximal flow velocity. Mean gradient was calculated by applying the modified Bernoulli equation (1) to velocity measurements obtained at 10 ms intervals throughout systole.

Doppler signals from one patient with a recently implanted and clinically normal valve were unmeasurable because of poor quality and were excluded from further data analysis. Thus, technically adequate examinations were

available in 55 (98%) of our 56 patients in the initial study group.

**Cardiac catheterization.** After sedation with 5 mg of oral diazepam, cardiac catheterization was performed in 4 of the patients with a recently implanted normal valve, in 12 patients with prosthetic valve stenosis and in 6 additional patients who had aortic valve replacement >24 months before catheterization and had no stenosis. A mean interval of 22 days (range 1 to 161) separated the echocardiographic study from catheterization. The clinical status of all patients remained stable during this interval.

*Pressure measurements in the left ventricle* were obtained by way of a 7F or 8F fluid-filled catheter passed retrograde across the aortic valve. Tracings from the proximal aorta were recorded after pullback. Aortic regurgitation was identified by aortic root angiography in the right anterior oblique projection employing 40 to 60 ml of contrast agent injected at a rate of 20 to 25 ml/s. Severity of regurgitation was graded on a scale from 0 to 4+ (14). Thermodilution cardiac output was employed for aortic valve area calculations by the Gorlin equation except in four patients with moderate or severe aortic regurgitation, in whom angiographic determination of cardiac output was used. Gradients were calculated by averaging measurements from three successive cardiac cycles.

**Statistical analysis.** Commercially available software (SAS, SAS Institute) was employed for data storage and analysis. The significance of differences between means was determined by paired or unpaired Student's *t* tests as appropriate; average values are reported as mean values ± 1 SD; correlation was assessed by linear regression analysis; and Pearson r values were compared by the test for differences between dependent correlations.

## Results

**Comparison of noninvasive (Doppler) and invasive aortic valve area measurements (Fig. 1).** There was a close and highly significant correlation between assessments made by cardiac ultrasound and catheterization ($r = 0.93$; $p = 0.0001$). Examination of the regression line, which has a slope close to 1 and intercept approximating 0, indicates that prosthetic aortic valve area measurements by the two techniques are comparable. However, there was a slight but significant tendency for the catheterization-derived valve areas to exceed the Doppler-derived values (in 68% of patients; $p = 0.05$). Average catheterization valve area was greater than that calculated by Doppler ultrasound (1.17 ± 0.47 versus 1.09 ± 0.38 $cm^2$), a difference that is marginally significant ($p = 0.056$).

**Normal valves.** Measurements of mean transvalvular gradient, acceleration time and valve area from the 37 patients with a normally functioning bioprosthetic aortic valve are presented in Figure 2 grouped according to external valve diameter. Mean gradient ranged from 5 to 25 mm Hg (average 13.6 ± 5.2) and acceleration time from 55 to 105 ms (mean 80.0 ± 13.0). Aortic valve area, calculated noninvasively by applying the continuity equation, ranged from 1.0 to 2.3 $cm^2$ (mean 1.6 ± 0.31).

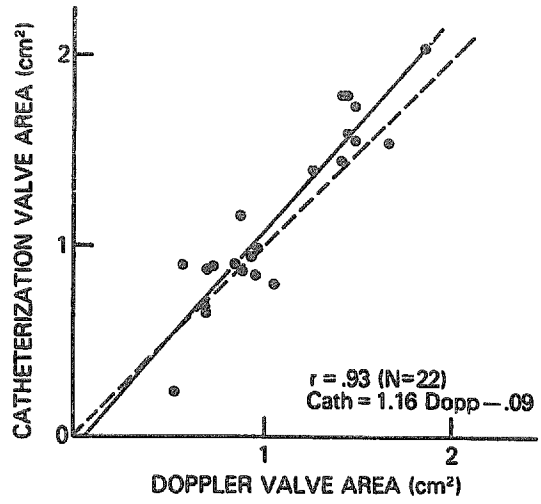


Figure 1. Scattergram of aortic valve area determined by Doppler (Dopp) versus valve area measurement by the Gorlin equation (Cath) for the 22 patients with cardiac catheterization data. The regression equation for the solid regression line is given. The dashed line of identity is also included.

Although individual Doppler valve area calculations varied considerably among patients with identically sized valves and there was substantial overlap between groups with different valve sizes, there was a significant correlation between Doppler valve area determinations and external valve diameters ($r = 0.35$; $p = 0.03$). A significant inverse relation existed between mean transvalvular gradient and valve size ($r = 0.43$; $p = 0.008$); a minimal correlation was found between acceleration time and valve size ($r = 0.19$; $p$ = NS).

**Stenotic valves.** The 12 patients with prosthetic aortic valve stenosis proved by cardiac catheterization had an aortic root diameter of 1.6 to 2.2 cm (mean 1.9 ± 0.08) and a left ventricular outflow tract velocity of 0.68 to 1.7 m/s (mean 1.2 ± 0.29), values similar to those observed in patients with a normal valve (1.6 to 2.2 cm [mean 2.0 ± 0.06] and 1.0 to 1.8 m/s [mean 1.3 ± 0.20], respectively). However, peak and mean gradients of 70 ± 21 and 43 ± 12 mm Hg, respectively, in the patients with a stenotic aortic valve greatly exceeded measurements in patients with a normal valve (26 ± 10 and 14 ± 5 mm Hg, respectively; $p = 0.0001$ for both comparisons) (Fig. 3). Acceleration time was significantly longer (116 ± 15 versus 80 ± 13 ms; $p = 0.0001$) and Doppler aortic valve area considerably smaller (0.82 ± 0.2 versus 1.63 ± 0.28 $cm^2$; $p = 0.0001$) in the patients with prosthetic valve stenosis.

If the Doppler gradients, acceleration times and valve

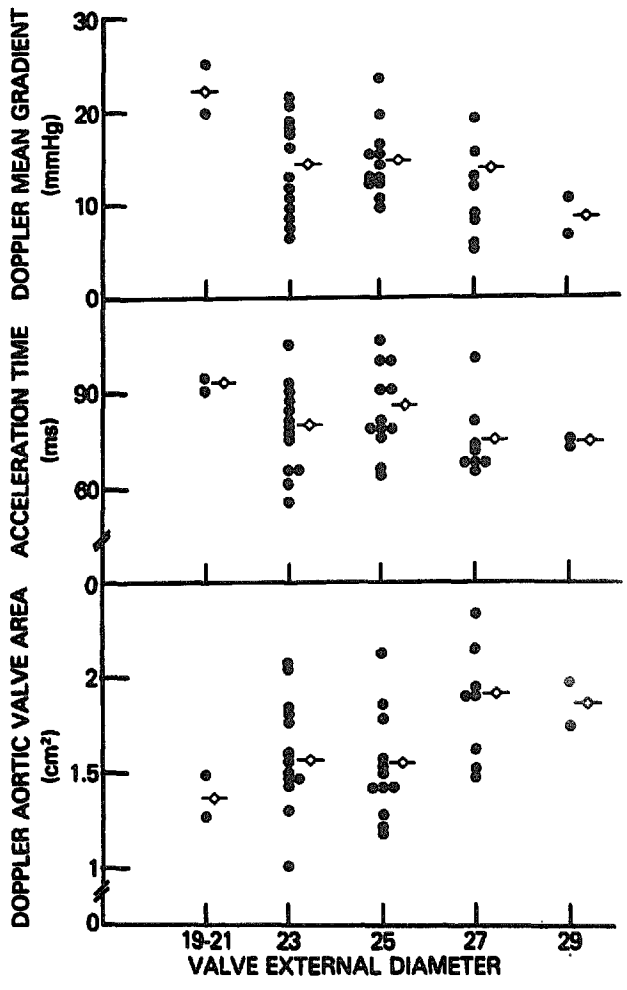


**Figure 2.** Doppler mean gradient, acceleration time and aortic valve area for 37 normally functioning prosthetic valves of different sizes as measured by valve external diameter (mm). Group means are indicated by an open diamond.

areas recorded in our 37 normal patients are considered to represent the normal ranges for these variables, then 75% of examinations in the 12 patients with bioprosthetic valve stenosis would have yielded an abnormal acceleration time or an elevated peak gradient, and an increased mean gradient or a decreased valve area would have been recorded in 92%. For every patient with stenosis, at least two of these four variables were abnormal.

An alternative strategy would be to select criteria so as to minimize the total number of errors in assigning patients to the normal group or the group with stenosis. Pursuing this course leads to identification of a normal peak gradient as <48 mm Hg, a normal mean gradient as <26 mm Hg, a normal acceleration time as ≤100 ms and a normal Doppler valve area as >1.1 $cm^2$. Table 1 presents the sensitivity, specificity and total predictive accuracy for abnormalities of individual Doppler measurements in identifying patients with prosthetic aortic valve stenosis. Although both acceleration time and peak gradient provide excellent separation of patients with a normal valve from those with stenosis, mean gradient and Doppler valve area are superior variables, each misclassifying only 1 of the 49 patients.

**Effect of aortic regurgitation.** Mild aortic regurgitation was detected during the Doppler examination in 42% of our patients with a normal valve. Earlier studies (6,15) indicated that systolic flow velocity in the left ventricular outflow tract may increase in patients with substantial aortic regurgitation. Average peak velocity measured immediately proximal to the aortic valve in the 17 patients with a normal valve and aortic regurgitation (1.32 ± 0.22 m/s) did not differ significantly from the velocity obtained in those with a normal valve without regurgitation (1.38 ± 0.22 m/s), lending support to our judgment that regurgitation was mild.

In 8 (36%) of the 22 patients who underwent cardiac catheterization, aortic root angiography revealed aortic regurgitation ≥2+. In these patients, average left ventricular outflow tract velocity exceeded the mean value recorded in the 14 patients with 0 or 1+ regurgitation (1.41 ± 0.18 versus 1.20 ± 0.24 m/s; $p = 0.05$).

**Contribution of left ventricular outflow tract measurement to valve area determination.** Two-dimensional imaging generally provided unambiguous and reproducible identification of the maximal inner diameter of the left ventricular outflow tract. Consequently, this measurement was used in the continuity equation for the calculation of valve area. In some laboratories the left ventricular outflow tract is not measured; rather, the external diameter of each valve as specified by the manufacturer is employed to determine valve area. For five of our patients, whose valve replacement surgery had occurred many years earlier, records specifying the size of the device implanted could not be located. In the

**Table 1.** Sensitivity, Specificity and Total Predictive Accuracy of Doppler Variables in the Diagnosis of Prosthetic Valve Aortic Stenosis

| Parameter | Normal Value | Sensitivity | Specificity | TPA |
|---|---|---|---|---|
| Acceleration time | ≤100 ms | 0.83 | 0.95 | 0.92 |
| Peak gradient | <48 mm Hg | 0.75 | 1.00 | 0.96 |
| Mean gradient | <26 mm Hg | 0.92 | 1.00 | 0.98 |
| Doppler aortic valve area | >1.1 $cm^2$ | 1.00 | 0.97 | 0.98 |

TPA = total predictive accuracy.

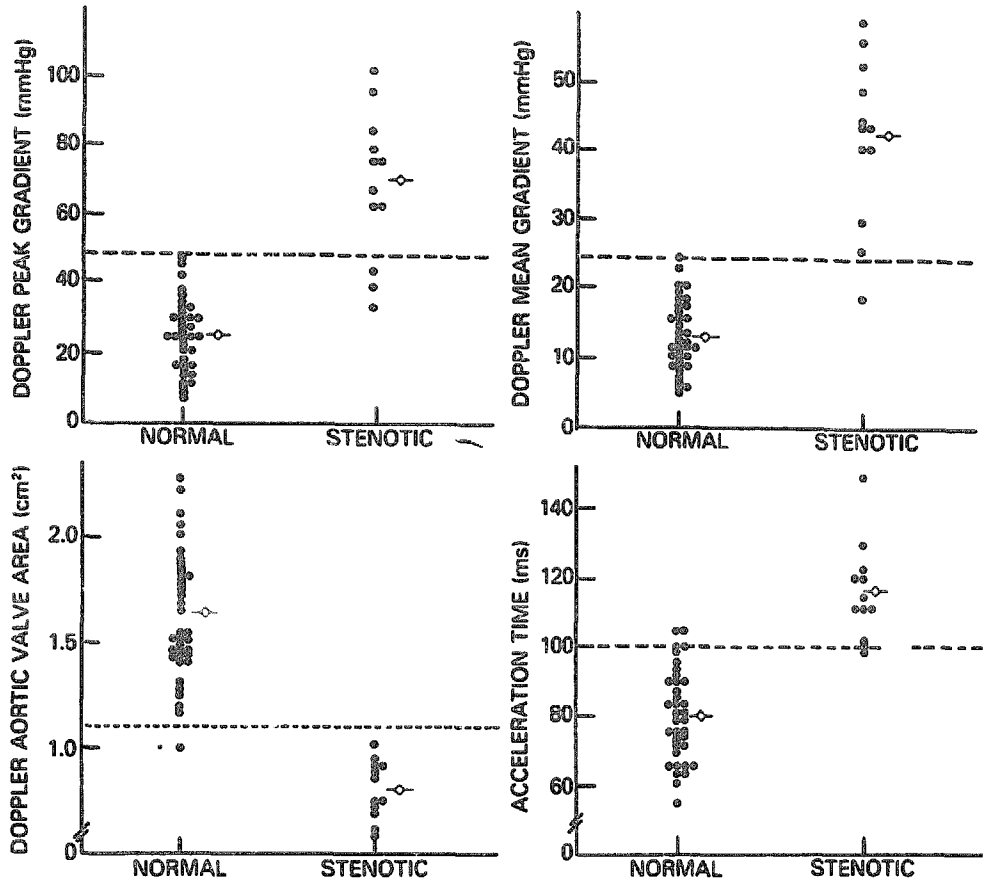


**Figure 3.** Doppler peak and mean gradients, aortic valve area and acceleration time for patients with normal (n = 37) and stenotic (n = 12) valves. Group means are indicated by an **open diamond**. The **dashed horizontal lines** denote the variable values used in the analysis of sensitivity and specificity.

remaining 50 patients, there was a weak but statistically significant correlation between our measurement of left ventricular outflow tract diameter and the manufacturer's valve size (r = 0.31; p = 0.025). This unimpressive correlation can be explained if one considers the distribution of valve sizes in our patients, 43 (86%) of whom had 23, 25 or 27 mm devices. With an expected measurement error of 1 to 2 mm (6), the ability to correctly categorize valve size in these patients is limited.

*When the prosthetic valve diameter is substituted for the left ventricular outflow tract measurement in the continuity equation,* there is a respectable correlation between the noninvasively and the invasively determined valve area in the 22 patients with catheterization (r = 0.78; p = 0.0001). However, this correlation is inferior to the result obtained when the actual measured outflow tract diameter is used (r = 0.93; p = 0.001 for comparison of the two correlation coefficients). In fact, when we neglected subvalvular area and considered only the remaining term from the continuity equation, namely, the ratio of the left ventricular outflow tract velocity time integral to transvalvular velocity time integral, the correlation with the catheterization valve area was high (r = 0.87; p = 0.0001). Thus, the outflow tract measurement contributes little to the accuracy of our noninvasive valve area determinations based on the continuity equation.

In Figure 4 the relation between the velocity time integral ratio and catheterization valve areas is graphically presented. The distribution of ratios for patients with and without prosthetic valve stenosis is also shown. There is a complete separation between these two groups; all patients with stenosis had a ratio <0.35, whereas a larger ratio was recorded for all those with a normal valve.

## Discussion

Accurate determinations of transvalvular aortic gradient and valve area have been achieved by Doppler techniques (1–6). The feasibility of applying these methods to patients with a bioprosthetic aortic valve is much less certain. Verification of Doppler findings by pressure measurements in a substantial number of patients with a normally functioning bioprosthesis has not been reported. Sequential or simultaneous Doppler and catheterization data are available for <20 patients with bioprosthetic aortic stenosis (7–9); noninvasive assessment of aortic valve area was not performed in any of these cases.

*We restricted our study to bioprosthetic valves for two reasons.* First, the central pattern of flow through these devices is similar to that of stenotic native valves for which the accuracy of valve area determinations from echocardiographic and Doppler measurements has been verified. Sec-

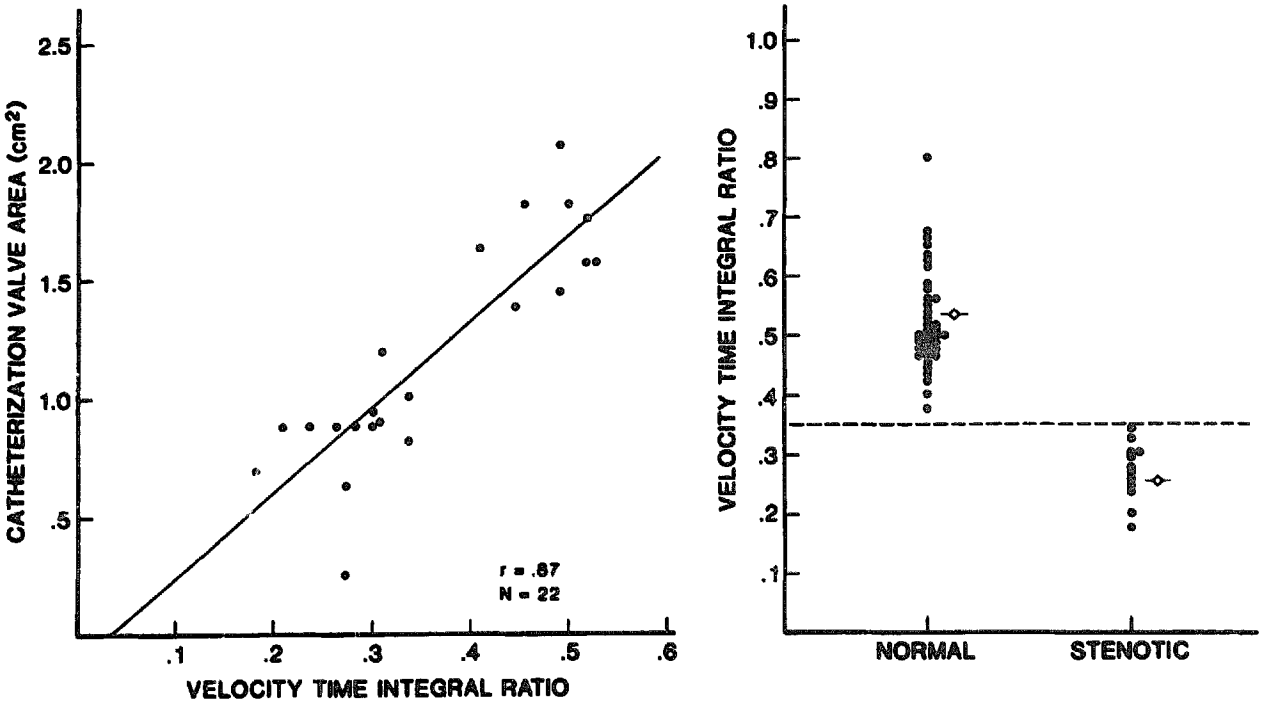


**Figure 4.** Analysis of the relationship between the velocity time integral ratio (i.e., the ratio of the area under the left ventricular outflow tract pulsed Doppler velocity curve to the area under the continuous wave Doppler transvalvular flow spectrum) and prosthetic aortic valve area measured at cardiac catheterization. In the **left panel**, linear regression analysis reveals a correlation coefficient of 0.87 for this comparison among the 22 patients with catheterization data. The regression line is shown. In the **right panel**, velocity time integral ratios are presented for the 37 patients with a clinically normal valve and the 12 with stenosis proved by catheterization. The patients with a normal valve had a ratio in excess of 0.35, whereas lower values were recorded in the 12 patients with stenosis.

ond, because the vast majority of cases of prosthetic valve stenosis occur in patients with a bioprosthesis, normative data for this type of valve are clinically important.

**Normal aortic bioprosthetic valves.** Evaluation of aortic valve area by the continuity equation requires a measurement of subaortic diameter from parasternal echocardiographic images, pulsed Doppler recordings obtained from the apical transducer position and continuous wave Doppler evaluation from the apex or right parasternal region. Although acquiring this information requires a high degree of technical skill, feasibility in the current study was excellent, with adequate data obtained from 98% of our study cohort of 56 patients.

The peak and mean gradients recorded by Doppler study in our group with a normal bioprosthetic valve were similar to values previously reported from both noninvasive (7–9) and invasive (16,17) studies in patients without apparent bioprosthetic aortic valve dysfunction. Although a relatively high gradient was present in patients with a valve of the smallest dimensions and a substantially lower gradient was recorded from patients with a valve of the largest dimensions, there was considerable overlap across valve size groups and no difference at all in valve gradient between patients with the two most commonly implanted sizes, 23 and 25 mm. Nevertheless, a moderate and significant inverse correlation between peak or mean gradient and external valve diameter was demonstrated. This is consistent with observations from other laboratories (18). Because valve gradient is related to both effective valve orifice and transvalvular flow, the marked heterogeneity in measured gradients may reflect, at least in part, differences in cardiac output among patients.

Our measurements of Doppler acceleration time for the normal bioprosthetic valves are in the range of earlier reports for native aortic valves without stenosis (19,20). There was no significant relation between external valve diameter and acceleration time in our normal group.

The wide range of Doppler aortic valve areas (all $\geq 1$ cm$^2$) recorded in our patients with a normal valve is similar to the values previously reported from catheterization studies (16,17). Although a substantial fraction of the variability in the calculated noninvasive valve area is undoubtedly accounted for by measurement errors in velocity and distance determinations, a portion is related to actual differences in valve size, which was significantly correlated with the Doppler-determined area. Moreover, studies (21,22) in which the area of normal prosthetic valves was measured by the Gorlin equation at rest and during exercise have suggested that the effective orifice of these devices is not constant. Increases in cardiac output are associated with a greater calculated valve

area. Thus, differences in Doppler valve area determinations among patients with a single valve size may be partially genuine, resulting from differences in transvalvular flow.

*The calculated Doppler valve areas for the normal group and the group with bioprosthetic stenosis overlapped only once.* The patient had a 23 mm Hancock valve without clinical evidence for dysfunction that had been implanted 12 months before his echocardiographic and Doppler study, at which a valve area of 1.0 $cm^2$ was determined. Mild aortic regurgitation was present. Velocity measurements in the left ventricular outflow tract and at the valve level were within 1 SD of the group mean value; however, the measured diameter of the outflow tract (1.6 cm) was 2 SD below the mean, the lowest value recorded in any patient with a normal bioprosthesis. Although this measurement could have been in error, the outflow region of the left ventricle may actually have been narrowed, either by postoperative tissue ingrowth, improper suture placement or other problems related to valve implantation. Because the patient was asymptomatic, determination of subvalvular and valve areas by cardiac catheterization was not deemed clinically appropriate; consequently, it is uncertain whether the noninvasive findings are erroneous or reflect mild subvalvular stenosis.

As was the case in earlier studies (8,23), many (42%) of our patients with a clinically normal and recently implanted prosthetic valve had mild aortic regurgitation by Doppler study. Our measurements of left ventricular outflow tract velocities demonstrated no difference between patients with and without regurgitation, thus confirming that the volume of regurgitant flow was small.

**Accuracy of noninvasive aortic bioprosthetic valve area determinations.** Prosthetic valve areas computed from echocardiographic and Doppler measurements by application of the continuity equation were accurate and highly correlated with area determinations based on cardiac catheterization data. Of the two terms that contribute to the continuity equation computation, the ratio of subvalvular to transvalvular velocity time integrals was considerably more important in the relation between noninvasive and invasive valve areas than was the left ventricular outflow tract diameter, which adds only marginally to the correlation. Otto et al. (6) reached a similar conclusion in their study of native aortic valve stenosis, reporting that a velocity time integral ratio of ≤0.3 (similar to our value of 0.35) accurately identified patients with an aortic valve area ≤1.0 $cm^2$.

*Two factors account for the limited importance of outflow tract measurements.* First, these values are squared in valve area calculations, considerably magnifying the measurement error of 1 to 2 mm inherent in two-dimensional echocardiographic distance determinations. Second, these measurements would not be expected to accurately differentiate among the >85% of our patients who had a prosthetic valve with a diameter differing from that of other patients by ±2 mm. As a result, the subvalvular area term could be neglected without materially impairing our ability to estimate prosthetic valve area noninvasively.

Use of the manufacturer's specified valve diameter in the continuity equation impaired the correlation between invasive and noninvasive determinations of prosthetic valve area. This finding implies that the size of the subvalvular region in patients with a prosthetic aortic valve is not adequately estimated by the sewing ring diameter. The area proximal to the valve may be narrowed by the aortic anulus, fibrosis or granulation tissue in some patients, whereas subvalvular dilation may be present in others.

Of the eight patients in our catheterization cohort with moderate or severe aortic regurgitation by angiographic estimate, six (75%) had concomitant prosthetic valve stenosis. Left ventricular outflow tract velocity was significantly greater in these 8 patients than in the remaining 14 patients with 0 to 1+ regurgitation, reflecting the increased systolic flow required to maintain adequate forward cardiac output in the face of substantial regurgitation. The impact of aortic regurgitation on the accuracy of the continuity equation, if any, could not be determined because of the small number of patients with significant regurgitation.

**Aortic bioprosthetic valve stenosis.** Echocardiographic imaging alone was relatively insensitive in its ability to suggest a diagnosis of bioprosthetic aortic stenosis. In only 4 of our 12 patients were thickened leaflets with obviously restricted motion identified. Addition of continuous wave Doppler data improved our ability to identify the patients with valvular stenosis. Acceleration time and peak gradient tended to be greater in patients with prosthetic valve stenosis than in patients with a normal valve, but there was imperfect separation between the two groups. Computation of mean pressure gradient improved the overall diagnostic accuracy to 98%. Although mean pressure gradient was an excellent predictor of prosthetic aortic stenosis in this study, this variable will tend to be insensitive in patients with depressed cardiac output. Accordingly, estimation of valve area by the continuity equation or by the ratio of left ventricular outflow tract to transvalvular velocity time integrals is preferable. This latter Doppler variable identified all patients in our study with and without prosthetic valve stenosis.

**Study limitations.** Application of the continuity equation to the calculation of aortic valve area from echocardiographic and Doppler measurements demands a high degree of technical skill. Use of this technique by investigators without adequate training might seriously compromise accuracy.

Because the left ventricular outflow tract dimension is squared in the calculation of aortic valve area, small errors in this measurement can produce substantial inaccuracy in valve area estimates. A measured difference of only 2 mm in an aortic anulus with a diameter of 20 mm will result in a 19% difference in the valve area calculation.

Because few valves with an external diameter <23 mm are implanted in patients in our institutions, our experience with smaller bioprosthetic valves is limited. Were more such patients available, we might have observed greater overlap of Doppler variables between normally functioning small prosthetic valves and larger stenotic valves.

The Doppler criteria optimizing differentiation between the normal group and the group with stenosis were selected retrospectively. A prospective evaluation will be needed to adequately evaluate the accuracy of the techniques described here.

Finally, in this study, we compared Doppler findings in two types of patients selected to maximize the differences between them: those with an apparently normal valve and those with proved stenosis; asymptomatic patients whose aortic valve replacement occurred >2 years before their echocardiographic studies were excluded. Hoffman et al. (24) serially examined such patients with Doppler ultrasound and reported progressive increases in transvalvular gradient, which may reflect a gradual decrease in valve area over time. Such patients should be included in future studies to assess the ability of these noninvasive techniques to differentiate mild from critical prosthetic valve stenosis.

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