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## Doppler Echocardiographic Measurement of Aortic Valve Area in Aortic Stenosis: A Noninvasive Application of the Gorlin Formula

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Thirty adult patients with aortic stenosis had Doppler echocardiography within 1 day of cardiac catheterization. Noninvasive measurement of the mean transaortic pressure gradient was calculated by applying the simplified Bernoulli equation to the continuous wave Doppler transaortic velocity recording. Stroke volume was measured noninvasively by multiplying the systolic velocity integral of flow in the left ventricular outflow tract (obtained by pulsed Doppler ultrasonography) by the cross-sectional area of the left ventricular outflow tract (measured by two-dimensional echocardiography). Noninvasive measurement of aortic valve area was calculated by two methods. In method 1, the Gorlin equation was applied using Doppler-derived mean pressure gradient, cardiac output and systolic ejection period. Method 2 used the continuity equation.

These noninvasive measurements were compared with

invasive measurements using linear regression analysis, and mean pressure gradients correlated well ( $r = 0.92$ ). Aortic valve area by either noninvasive method also correlated well with cardiac catheterization values (method 1,  $r = 0.87$ ; method 2,  $r = 0.88$ ). The sensitivity of Doppler detection of critical aortic stenosis was 0.86, with a specificity of 0.88 and a positive predictive value of 0.86. Cardiac output measured nonsimultaneously showed poor correlation ( $r = 0.51$ ).

Doppler echocardiography can distinguish critical from noncritical aortic stenosis with a high degree of accuracy. Measurement of aortic valve area aids interpretation of Doppler-derived mean pressure gradient data when the gradients are in an intermediate range (30 to 50 mm Hg).

(*J Am Coll Cardiol* 1986;8:1059-65)

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The accuracy of measurement of the mean transaortic pressure gradient by Doppler ultrasonography has been validated in numerous patients with aortic stenosis (1-5). However, the distinction between critical and noncritical aortic stenosis often requires calculation of the aortic valve area, which is dependent on a flow measurement. Recent reports (6-10) indicate that accurate measurement of cardiac output is possible using a combination of Doppler and two-dimensional echocardiographic techniques. In this study, we used Doppler echocardiographic measurement of both the transaortic pressure gradient and cardiac output to calculate aortic valve area. Our noninvasive measurements were then compared with the standard invasive application of the Gorlin formula.

### Methods

**Patient selection.** Forty-two consecutive patients with aortic stenosis had Doppler echocardiographic studies within 1 day of cardiac catheterization. Eleven patients with significant aortic regurgitation were excluded because this condition causes well established inaccuracies in the invasive measurement of valve area, although it should not have affected the noninvasive measurements done in this study. One patient with catheterization-documented aortic stenosis was excluded because an adequate continuous wave Doppler signal of the transaortic velocity could not be obtained. The remaining 30 patients ranged in age from 20 to 81 years (mean 60). The majority (24 of 30) had calcific aortic stenosis, 3 had rheumatic heart disease, 2 had congenital aortic stenosis and 1 had bioprosthetic aortic stenosis.

**Noninvasive measurements.** Echocardiographic recordings and calculations were performed by an investigator (P.T.) unaware of the catheterization data. Noninvasive recording of the transaortic flow velocity was obtained using continuous wave Doppler ultrasonography with an Irex Exemplar ultrasonograph. In most patients (23 of 30) the high-

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Manuscript received March 4, 1986; revised manuscript received May 22, 1986, accepted June 9, 1986.

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est velocities were recorded from the apical transducer location (Fig. 1). The suprasternal and the right parasternal position yielded the highest velocities in six patients and one patient, respectively. Assuming laminar flow, the pressure gradient ( $\Delta P$ ) across the aortic valve can be derived from the Doppler measurement of maximal flow velocity ( $V$ ) as described by the simplified Bernoulli equation,  $\Delta P = 4V^2$  (11). The simplified Bernoulli equation was applied to the velocity profile point by point, using the mean value theorem and a digitizing tablet interfaced to a Hewlett-Packard series 1000 computer (12). The mean pressure gradient from five velocity profiles was averaged to obtain a final mean transaortic pressure gradient.

*Stroke volume* was measured by multiplying the systolic velocity integral in the left ventricular outflow tract by the cross-sectional area of the left ventricular outflow tract (13). Cardiac output was calculated as stroke volume multiplied by heart rate. The systolic velocity integral in the left ventricular outflow tract was obtained using pulsed Doppler ultrasonography from the cardiac apex (Fig. 1). The Doppler sample volume was placed in the left ventricular outflow tract just proximal to the aortic valve (proximal to the first appearance of the valve closure sound). The velocity profile was analyzed using the digitizing tablet and computer system described. The cross-sectional area of the left ventricular outflow tract was derived from a two-dimensional echocardiographic parasternal long-axis image using a Hewlett-

Packard 77020 AC ultrasonograph (Fig. 1). During the time of this study, we achieved optimal results using the Irex instrument to record continuous wave Doppler echocardiographic tracings, and the Hewlett-Packard instrument to obtain two-dimensional echocardiographic images.

*The left ventricular outflow tract diameter (D)* was measured from trailing edge to leading edge of the echoes (inside diameter) at the level of the aortic orifice, where the aorta joins the interventricular septum and joins the anterior leaflet of the mitral valve (6) (Fig. 1). This diameter is converted into cross-sectional area (A) using the equation:

$$A = \pi \left( \frac{D}{2} \right)^2.$$

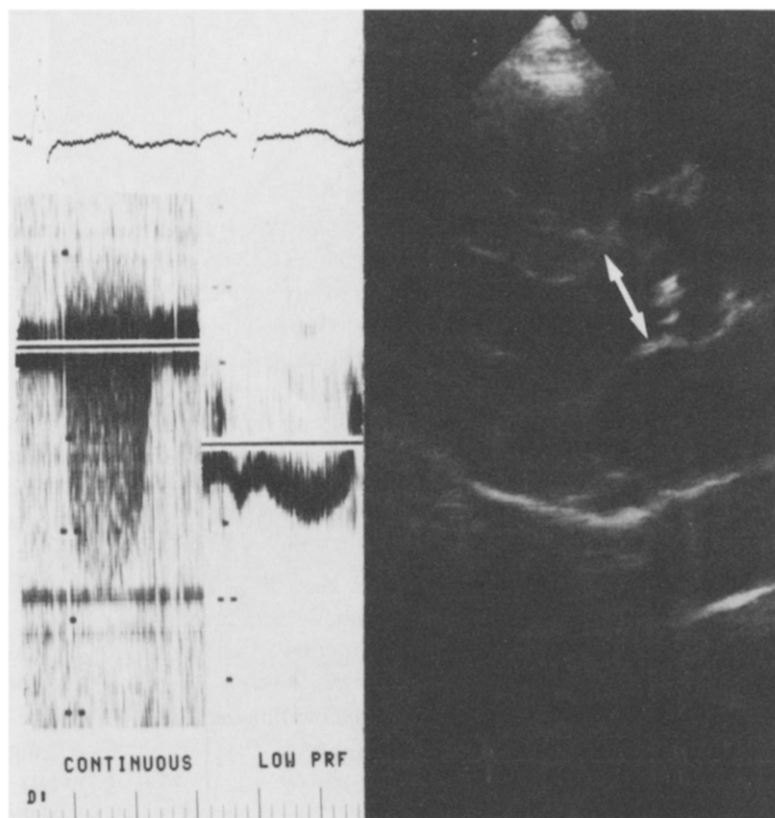
*Aortic valve area was calculated by the Gorlin equation (14):*

$$\text{Aortic valve area} = \frac{\text{Cardiac output/Systolic ejection period}}{44.5 \sqrt{\text{Mean transaortic pressure gradient}}}.$$

*The systolic ejection period is obtained from the measured ejection time and RR interval as:*

$$\frac{\text{Ejection time}}{\text{RR interval}} \times 60 \text{ seconds.}$$

*The ejection time* is defined noninvasively as the time interval between aortic valve opening and closure signals on the continuous wave transaortic Doppler tracing.



**Figure 1.** **Left panel,** Representative continuous wave Doppler measurement from the apical transducer position of transaortic blood flow velocity. **Center panel,** Representative pulsed Doppler (LOW PRF) measurement, from the apical transducer position, of blood flow velocity in the left ventricular outflow tract. **Right panel,** Representative two-dimensional echocardiographic parasternal long-axis view of the left ventricular outflow tract. Measurement is made perpendicular to the outflow tract (**arrows**), taking care to exclude calcium deposits.

A second noninvasive method for calculating aortic valve area used only the continuity equation (14):

$$\text{Area}_{\text{LVOT}} \times \text{SVI}_{\text{LVOT}} = \text{Area}_{\text{AV}} \times \text{SVI}_{\text{AV}},$$

or:

$$\frac{\text{Area}_{\text{LVOT}} \times \text{SVI}_{\text{LVOT}}}{\text{SVI}_{\text{AV}}} = \text{Area}_{\text{AV}},$$

where  $\text{SVI}_{\text{AV}}$  is the integral of the maximal transaortic velocity profile obtained with continuous wave Doppler ultrasonography;  $\text{SVI}_{\text{LVOT}}$  is the integral of the left ventricular outflow tract velocity profile obtained with pulsed Doppler ultrasonography;  $\text{Area}_{\text{AV}}$  is the aortic valve cross-sectional area; and  $\text{Area}_{\text{LVOT}}$  is the cross-sectional area of the left ventricular outflow tract (measurement described previously).

**Invasive measurements.** Invasive measurements were performed by an investigator (M.Y.) who was unaware of

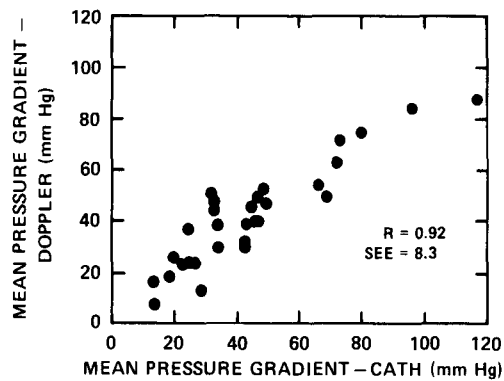
the echocardiographic data. Left-sided heart catheterization was performed by the retrograde femoral artery technique. The mean transaortic pressure gradient was obtained by comparing the left ventricular pressure profile with the aortic pressure profile. Five pressure gradient profiles were integrated and averaged using a digitizing tablet interfaced to a Hewlett-Packard series 1000 computer with a program that applied the mean value theorem. The Gorlin equation was used to calculate aortic valve area. Cardiac output was measured by the Fick method (15).

**Statistical methods.** Comparisons between invasive and noninvasive measurements were made by linear regression analysis using the least-squares method. To test interobserver variability, the left ventricular outflow tract measurement was repeated by a second observer (P.Y.). This variability was expressed as the percent error for each measurement determined as the difference between the two observations divided by the mean value of the two observations.

**Table 1.** Invasive and Noninvasive Measurements in 30 Patients With Aortic Stenosis

Case	Mean Transaortic Pressure Gradient		Cardiac Output		Systolic Ejection Period		Heart Rate		Aortic Valve Area		
	Cath	Dop	Cath	Dop	Cath	Dop	Cath	Dop	Cath	Dop <sub>1</sub>	Dop <sub>2</sub>
1	13.7	16.4	4.5	3.1	21.3	21.8	62	63	1.31	0.80	0.89
2	13.9	7.6	5.3	3.5	23.1	17.5	70	62	1.57	1.62	1.42
3	18.6	18.6	4.1	3.1	20.9	17.2	63	55	1.03	0.96	0.83
4	20.1	25.6	4.0	5.5	21.0	21.5	58	68	0.97	1.15	1.05
5	23.0	23.0	7.7	6.8	18.7	15.8	85	75	1.90	2.00	1.44
6	24.6	36.9	4.5	6.9	25.9	20.4	64	63	0.81	1.26	1.11
7	25.6	24.2	8.5	6.9	25.0	19.0	75	51	1.51	1.64	1.57
8	27.1	23.9	5.1	4.5	15.6	18.8	65	66	1.42	1.10	1.13
9	28.7	13.0	5.1	3.0	22.3	18.7	74	59	0.97	1.02	0.90
10	32.1	50.7	7.9	7.6	21.7	20.0	78	71	1.45	1.20	1.38
11	32.8	44.1	4.7	6.0	17.9	19.2	58	57	1.03	1.06	1.07
12	32.8	47.5	5.0	5.9	23.4	21.3	61	66	0.84	0.91	0.91
13	34.1	38.3	2.3	3.3	27.4	24.0	92	100	0.36	0.49	0.42
14	34.2	29.8	5.5	4.6	23.1	24.5	72	67	0.92	0.78	0.79
15	42.7	29.9	4.9	4.7	23.1	18.5	70	57	0.72	1.07	0.96
16	42.9	39.3	5.1	3.6	23.4	23.7	72	78	0.75	0.55	0.56
17	43.0	31.8	3.2	3.8	27.5	27.1	90	96	0.40	0.57	0.55
18	44.8	46.0	5.9	5.9	24.6	26.6	85	86	0.81	0.74	0.76
19	45.7	39.9	7.3	2.9	19.0	13.7	53	49	1.22	0.76	0.60
20	46.9	49.6	3.9	3.7	18.4	18.8	54	60	0.70	0.63	0.64
21	46.9	40.2	3.8	4.0	27.9	14.9	69	57	0.45	0.70	0.67
22	48.6	52.7	4.4	5.8	20.9	22.5	57	56	0.68	0.80	0.86
23	49.4	46.8	2.9	2.8	30.4	25.1	100	75	0.31	0.38	0.34
24	65.9	54.2	2.8	2.6	25.5	21.9	74	89	0.30	0.36	0.34
25	68.9	49.8	4.2	3.4	21.4	20.0	61	61	0.53	0.53	0.50
26	72.3	63.2	4.7	3.2	24.1	20.9	75	65	0.50	0.43	0.44
27	73.2	71.9	3.8	3.6	27.3	29.8	86	93	0.35	0.28	0.26
28	80.1	74.9	4.8	5.5	23.7	22.5	85	75	0.52	0.64	0.57
29	96.4	84.2	5.0	5.7	30.0	23.4	88	67	0.39	0.59	0.55
30	117.0	88.0	8.6	4.5	27.7	19.2	84	56	0.60	0.56	0.54

Cath = by or at cardiac catheterization; Dop = by or during Doppler echocardiography; Dop<sub>1</sub> and Dop<sub>2</sub> = by Doppler echocardiography using the Gorlin equation and the continuity equation, respectively.



**Figure 2.** Mean pressure gradient at cardiac catheterization (CATH) compared with mean pressure gradient by Doppler echocardiography.

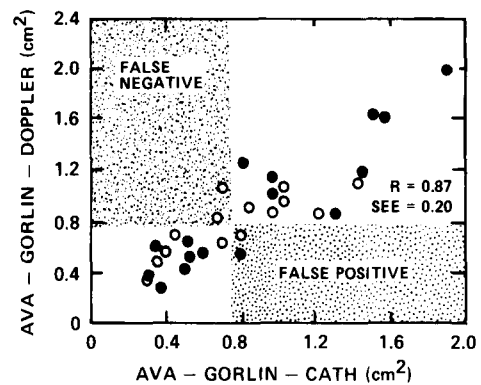
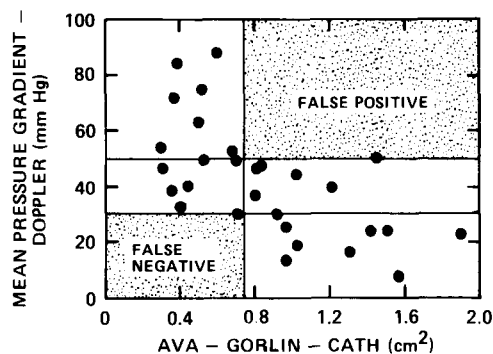
## Results

The values obtained by Doppler echocardiography and cardiac catheterization for mean transaortic pressure gradient, cardiac output, systolic ejection period, heart rate and aortic valve area are given in Table 1.

**Pressure measurements.** As previously reported by many laboratories, we found an excellent correlation between mean transaortic pressure gradient, determined by Doppler ultrasonography, and mean pressure gradient obtained at catheterization. The correlation coefficient in this group of non-simultaneous recordings was 0.92 (Fig. 2).

*The aortic valve area as determined by cardiac catheterization is compared with the mean transaortic pressure gradient as determined by Doppler ultrasonography in Figure 3.* Patients can be classified into three groups as defined by the horizontal lines: those with a mean transaortic pressure gradient greater than 50 mm Hg, those with a mean pressure gradient less than 30 mm Hg and those with an intermediate gradient. Critical aortic stenosis is indicated by a vertical line drawn at 0.75 cm<sup>2</sup> (16). With one exception, all patients with a mean pressure gradient greater than

**Figure 3.** Aortic valve area (AVA) determined at cardiac catheterization (CATH) compared with mean pressure gradient by Doppler echocardiography. **Horizontal lines** indicate 30 and 50 mm Hg. The **vertical line** is drawn at 0.75 cm<sup>2</sup>.

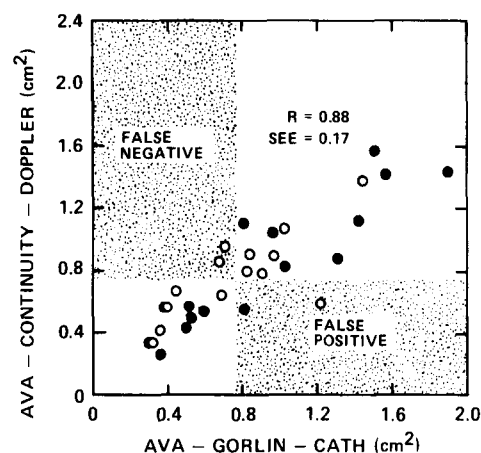


**Figure 4.** Aortic valve area (AVA) determined at cardiac catheterization (CATH) compared with aortic valve area by Doppler echocardiography. Both methods use the Gorlin equation. **Stippled areas** represent false negative and false positive regions. **Open circles** represent 14 patients with a mean pressure gradient of 30 to 50 mm Hg by Doppler echocardiography. **Solid circles** represent the remaining 16 patients.

50 mm Hg had critical aortic stenosis, whereas all except one patient with a mean pressure gradient less than 30 mm Hg had noncritical disease. Fourteen patients had a mean pressure gradient between 30 and 50 mm Hg; in these patients a distinction between critical and noncritical aortic stenosis could not be made (4). In this group, aortic valve area determinations would be particularly helpful.

**Aortic valve area measurements.** Figure 4 plots aortic valve area as determined by the Gorlin equation using Doppler ultrasound-derived cardiac output, systolic ejection period and mean pressure gradient versus aortic valve area obtained by cardiac catheterization. The correlation coefficient ( $r$ ) is 0.87. Four areas of Figure 4 are designated by stippled regions arranged to highlight critical aortic stenosis

**Figure 5.** Aortic valve area (AVA) determined at cardiac catheterization (CATH) using the Gorlin formula compared with aortic valve area by Doppler echocardiography using the continuity equation. **Stippled areas, open circles and solid circles** as in Figure 4.



defined by either technique. In 26 of the 30 patients, the results of both techniques were in agreement with the diagnosis of either critical or noncritical aortic stenosis. Two patients were diagnosed as having critical aortic stenosis by Doppler measurement but had noncritical aortic stenosis at catheterization (false positive findings), and two patients had critical disease by catheterization but noncritical disease by Doppler measurement (false negative findings). Using catheterization results as a reference standard, the sensitivity of Doppler echocardiographic detection of critical aortic stenosis was 0.86, with a specificity of 0.88 and a positive predictive value of 0.86.

When the continuity equation was used to calculate aortic valve area by Doppler technique (Fig. 5), the statistical analysis was nearly identical to that described in Figure 4. The two noninvasive techniques are directly compared in Figure 6, demonstrating an extremely close correlation ( $r = 0.96$ ).

**Cardiac output measurements.** When cardiac output determinations by Doppler study and cardiac catheterization were compared, the correlation was poor, with an  $r$  value of 0.51 and slope of the regression line of 0.59. The level of correlation resulted in part from the nonsimultaneous nature of our measurements. The heart rate at the time of Doppler study and that during catheterization were quite different in many patients (Table 1). Clearly, the measurements were made under different physiologic conditions.

## Discussion

**Critical versus noncritical aortic stenosis.** Of the 30 patients, 26 were correctly identified noninvasively as having either critical or noncritical aortic stenosis. The Doppler ultrasound-derived pressure gradient information alone was often sufficient to determine the severity of aortic stenosis (Fig. 3). Patients who have a mean pressure gradient greater than 50 mm Hg are likely to have critical aortic stenosis. When the mean pressure gradient is less than 30 mm Hg, patients are likely to have noncritical disease (4). In our

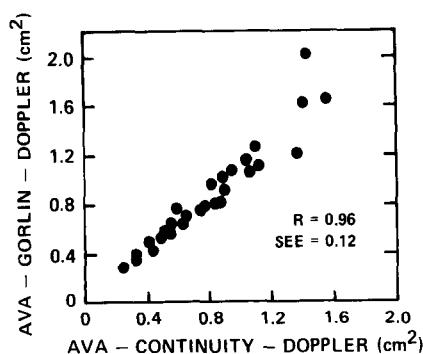
group of patients, 14 had a mean transaortic pressure gradient between 30 and 50 mm Hg and therefore could not be distinguished by pressure gradient information alone. In 11 of these 14 patients, we could accurately distinguish critical from noncritical aortic stenosis by calculation of aortic valve area (Fig. 4 and 5). There were two false positive measurements and one false negative measurement by our strict criteria. Sensitivity of the addition of calculated valve area to Doppler pressure gradient data in patients with pressure gradients between 30 and 50 mm Hg, was 0.86, specificity was 0.71 and positive predictive value was 0.75. Adding the aortic valve area calculation to the pressure gradient determination enhanced our ability to separate critical from noncritical aortic stenosis in these patients.

As emphasized in Figure 6, either the Gorlin equation or the continuity equation can be used to calculate aortic valve area noninvasively because the results are nearly identical. This is not surprising when one considers that the Gorlin equation is derived in part from the continuity equation (14). Although both methods provide similar accuracy, the continuity equation has a practical advantage in that there is no need to calculate heart rate or systolic ejection period.

**Comparison with previous studies.** In a preliminary study of nine patients with aortic stenosis, Holmvang et al. (17) found good correlation ( $r = 0.94$ ) between Doppler echocardiographic and catheterization-derived aortic valve area. Our data are very similar to those in a series reported by Skjaerpe et al. (18) using the continuity equation ( $r = 0.82$ ). Previous investigators (1-5) have demonstrated a close correlation between Doppler echocardiographic and catheterization-derived transaortic pressure gradients. Mean gradients have been found to correlate more closely than maximal gradients. In a recent study of 100 patients with aortic stenosis, Currie et al. (5) found a much stronger correlation when the Doppler examination and catheterization were performed simultaneously ( $r = 0.93$ ) than when these evaluations were nonsimultaneous ( $r = 0.79$ ). This difference is likely due to a significant variation in stroke volume under conditions of noninvasive versus invasive procedures.

Previous studies (6-10) correlating Doppler measurement of flow in the left ventricular outflow tract or aorta (in patients without aortic stenosis) with Fick and thermodilution measurements of cardiac output have described correlation coefficients varying from 0.87 to 0.96. We used the left ventricular outflow tract for our measurements because it has several theoretical advantages over other potential sites (that is, mitral and tricuspid inflow or pulmonary outflow). The left ventricular outflow tract is relatively easy to image by two-dimensional echocardiography, whereas the pulmonary outflow tract image is often difficult to obtain in adults. The Doppler flow signal in the left ventricular outflow tract is also easy to obtain. In addition, as dem-

**Figure 6.** Aortic valve area (AVA) determined by Doppler echocardiography using the continuity equation compared with aortic valve area by Doppler echocardiography using the Gorlin equation.



onstrated by Ihlen et al. (6), the left ventricular outflow tract diameter remains relatively constant from diastole to systole, as opposed to the mitral and tricuspid inflow diameters, which are constantly changing. This provides assurance that the measured diameter represents the actual mean diameter of flow throughout systole.

**Study limitations.** Despite the advantages of using the left ventricular outflow tract for measurements, this method is not without pitfalls. Most investigators agree that the outflow tract diameter measurement is the most problematic part of the examination. In patients with aortic stenosis and a heavily calcified aortic valve, this task becomes even more difficult. Our routine measurement involved sweeping the imaging plane medially and laterally through the left ventricular outflow tract in the parasternal long-axis view to assure that our measurement was taken at the widest outflow tract diameter. In addition, a short-axis view was used to confirm the circular configuration. Although the left ventricular outflow tract was approximately circular in all patients, it was never perfectly circular. Furthermore, the left ventricular outflow tract often narrows slightly during systole. Thus, the assumption of a static, perfectly circular left ventricular outflow tract is another source of error in the diameter calculation. Measurements were taken from trailing edge of the septal aortic junction to leading edge of the mitral aortic junction (inside diameter) during mid-systole, taking care to differentiate calcium deposits from the anterior and posterior walls of the outflow tract. A systematic evaluation showed significant interobserver variability. A blinded comparison of diameter measurement by observers P.T. and P.Y. resulted in a mean percent error of 8.0 (SD  $\pm$  7.0). This small variation becomes significant when the radius is squared during its conversion to cross-sectional area. Given a 2.0 cm diameter left ventricular outflow tract (the actual mean of all diameter measurements was 2.03 cm), an 8% error in diameter measurement will change the ultimate cardiac output determination by 15%.

*Another source of error is the underestimation of velocities if the sound beam is not aligned exactly parallel with blood flow. The Doppler velocity measurement varies with the cosine of the angle between the direction of blood flow and the sound beam. A reasonable assumption is that our alignment to blood flow is  $\pm$  20°. An angle of 20° results in underestimation of the actual velocity by approximately 6%. This angle effect could therefore result in a 6% error in cardiac output measurement.*

*A seemingly insurmountable source of confusion in evaluating the accuracy of Doppler measurement of cardiac output is the lack of a reliable reference standard for comparison. All available clinical measurements of cardiac output are indirect. In one study (19) comparing the Fick method with indicator-dilution methods, the indicator-dilution technique resulted in measurements that were between +38% and -57% of Fick measurements. Other studies (20) sup-*

port this finding. Reproducibility of these methods is generally  $\pm$  10% (21-23). In our study, noninvasive cardiac output measurements correlated less closely with invasive measurements than did mean pressure gradients. Skjaerpe et al. (18) reported a similar poor correlation ( $r = 0.45$ ) between nonsimultaneous Doppler echocardiographic and Fick-determined output. Part of the reason for this poor correlation is the nonsimultaneous nature of our invasive and noninvasive measurements. Table 1 implicates poor cardiac output correlations rather than pressure gradient correlations as the cause of most of our false positive and false negative aortic valve area measurements.

**Conclusions.** Aortic valve area calculation using Doppler echocardiography can help distinguish patients with critical aortic stenosis from those with noncritical aortic stenosis determined by catheterization. This noninvasive technique is especially useful in patients with a mean trans-aortic pressure gradient less than 50 mm Hg. Aortic valve area determinations by Doppler echocardiography using either the Gorlin equation or the continuity equation yield similar results, but the continuity equation is simpler to use.

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We are grateful to Liv Hatle, MD for her review of our data and assistance in measuring the left ventricular outflow tract diameters. We also express our gratitude to Gretchen Houd and Joan Rosel for their assistance in preparation of the manuscript.

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