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Determination of Aortic Valve Area in Valvular Aortic Stenosis by Direct Measurement Using Intracardiac Echocardiography: A Comparison With the Gorlin and Continuity Equations

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Objectives. This study sought to 1) show that intracardiac echocardiography can allow direct measurement of the aortic valve area, and 2) compare the directly measured aortic valve area from intracardiac echocardiography with the calculated aortic valve area from the Gorlin and continuity equations.

Background. Intracardiac echocardiography has been used in the descriptive evaluation of the aortic valve; however, direct measurement of the aortic valve area using this technique in a clinical setting has not been documented. Despite their theoretical and practical limitations, the Gorlin and continuity equations remain the current standard methods for determining the aortic valve orifice area.

Methods. Seventeen patients underwent intracardiac echocardiography for direct measurement of the aortic valve area, including four patients studied both before and after valvuloplasty, for a total of 21 studies. Immediately after intracardiac echocardiography, hemodynamic data were obtained from transthoracic echocardiography and cardiac catheterization.

Results. Adequate intracardiac echocardiographic images were obtained in 17 (81%) of 21 studies. The average aortic valve area (mean ± SD) determined by intracardiac echocardiography for the 13 studies in the Gorlin analysis group was 0.59 ± 0.18 cm^2 (range 0.37 to 1.01), and the average aortic valve area determined by the Gorlin equation was 0.62 ± 0.18 cm^2 (range 0.31 to 0.88). The average aortic valve area determined by intracardiac echocardiography for the 17 studies in the continuity analysis group was 0.66 ± 0.23 cm^2 (range 0.37 to 1.01), and that for the continuity equation was 0.62 ± 0.22 cm^2 (range 0.34 to 1.06). There was a significant correlation between the aortic valve area determined by intracardiac echocardiography and the aortic valve area calculated by the Gorlin ($r = 0.78$, $p = 0.002$) and continuity equations ($r = 0.82$, $p < 0.0001$).

Conclusions. In the clinical setting, intracardiac echocardiography can directly measure the aortic valve area with an accuracy similar to the invasive and noninvasive methods currently used. This study demonstrates a new, quantitative use for intracardiac echocardiographic imaging with many potential clinical applications.

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In 1951, Gorlin and Gorlin introduced a formula for deriving the orifice area of a stenotic valve utilizing hemodynamic variables (1). Although this formula has undergone several revisions, the original formula continues to be widely used and is considered the "gold standard" for the determination of the aortic valve area. There are many theoretical and practical shortcomings in the use of the Gorlin equation (2–4). These shortcomings include the variability of the Gorlin constant at extremes of flow, as well as practical difficulties in obtaining an accurate cardiac output and mean transvalvular gradient.

Transthoracic echocardiography with Doppler is the standard noninvasive method for determining the aortic valve area by use of the continuity equation. Although there are fewer theoretical assumptions with the continuity equation, there remain practical limitations in the acquisition of accurate data. Validation of the continuity equation has been based on correlation with the Gorlin equation and in vitro models (5–8). In spite of their theoretical and practical shortcomings, the Gorlin and continuity equations remain the current standard methods for determining the aortic valve orifice area.

Intracardiac echocardiography is a new technology that has been used in the quantitation of left ventricular function and the morphologic evaluation of the aortic valve (9,10). Intracardiac echocardiography may be preferable to other methods that directly measure the aortic valve area, because images are obtained from within the valve. In addition, the ability to perform intracardiac echocardiography in the catheterization laboratory allows the acquisition of nearly simultaneous data, which makes a controlled comparison with the Gorlin and continuity equations possible.

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The purpose of this study was 1) to show that intracardiac echocardiography can allow direct measurement of the aortic valve area in a clinical setting in patients with moderate to severe valvular aortic stenosis, and 2) to compare the directly measured aortic valve area with the calculated aortic valve area using the Gorlin and continuity equations.

Methods

Study patients. Consecutive patients undergoing elective cardiac catheterization for the evaluation of valvular aortic stenosis were evaluated for entry into the study. Patients were not considered eligible for the study if they had mechanical prosthetic valves, hemodynamic instability or a mean gradient of <20 mm Hg, as determined by cardiac catheterization. For patients undergoing percutaneous aortic valvuloplasty the pre- and postvalvuloplasty images were analyzed separately.

Intracardiac echocardiography. Under fluoroscopic imaging, an 8F multipurpose guiding catheter was placed in the left ventricle, through which a 4.8F, 20-MHz intravascular ultrasound catheter (Sonicath, Boston Scientific) was advanced over a 0.014-in. diameter guide wire. The imaging catheter was advanced to a position 1 cm distal to the end of the guiding catheter inside of the left ventricular cavity. The guiding catheter, imaging catheter, and guidewire were then manipulated as a unit slowly back and forth across the aortic valve until the minimal cross-sectional area was optimally imaged (Hewlett-Packard Sonos 100 Intravascular Imaging System). All images were recorded using simultaneous single-lead electrocardiography on super-VHS videotapes. Immediately after the intracardiac echocardiographic study was performed, data from transthoracic echocardiography and cardiac catheterization were sequentially obtained.

Cardiac catheterization. Right and left heart catheterization was performed in all patients. Cardiac output was determined by the Fick or thermodilution (valvuloplasty patients) methods. In studies using the Fick method, a metabolic rate meter (MRM-2 Oxygen Consumption Monitor, Waters Instruments) was placed and 10 readings were averaged to determine oxygen consumption. Supplemental oxygen was discontinued at least 10 min before measurement of oxygen consumption. In studies using the thermodilution method, five measurements were obtained and averaged. Left ventricular and central aortic pressures were simultaneously recorded halfway through the metabolic rate meter recordings (or halfway through the thermodilution recordings) using a dual sensor, micromanometer catheter (Millar Mikro-tip, model SPC-784A, Millar Instruments). When the micromanometer catheter was not used (three cases), simultaneous left ventricular and femoral artery pressures were recorded using a fluid-filled catheter system (11). Blood samples were subsequently taken from the pulmonary artery and the left ventricular cavity for the determination of oxygen content.

Transthoracic echocardiography. Immediately after the determination of cardiac output and mean transvalvular pressure gradient, transthoracic echocardiography was performed (Hewlett-Packard Sonos 1500 Ultrasound Imaging System). The left ventricular outflow tract diameter was obtained from the parasternal long-axis view. Pulsed wave Doppler samples were obtained in the apical five-chamber view (12). Spectral flow velocities were recorded from the left ventricular outflow tract with care taken to avoid prevalvular flow acceleration. Continuous wave Doppler flow signals across the aortic valve were then obtained from the apical, right parasternal, and suprasternal windows with an imaging transducer and dedicated Doppler transducer. When necessary, the patient was positioned in the left lateral decubitus position to obtain optimal echocardiographic data.

Data analysis: intracardiac echocardiography. All video images were analyzed off-line. Intracardiac echocardiographic images were prospectively graded for quality: grade I = >90% of the aortic valve border seen; grade II = 75% to 90% of the aortic valve border seen; grade III = <75% of the aortic valve border seen. Grade III images were excluded from further analysis. The aortic valve area was planimetered at its maximal systolic excursion during five separate systolic intervals and averaged. Each aortic valve area was measured by two independent observers (G.P.F., N.J.W.) for the determination of interobserver variability.

Cardiac catheterization. The mean gradient was determined by direct manual planimetry of the recorded pressure tracings using a mechanical polar planimeter (Los Angeles Scientific Instrument Co.). The pressure tracings from the fluid-filled catheter group were shifted so that the downslope of the left ventricular systolic tracing was superimposed on the dicrotic notch of the aortic tracing (11). Five consecutive systolic gradients were planimetered and averaged. All patients were in sinus rhythm. The aortic valve area was calculated by the Gorlin equation (1). Patients with 2+ or greater aortic insufficiency, as determined by transthoracic echocardiography and aortography, were excluded from this part of the analysis.

Transthoracic echocardiography. The continuous and pulsed wave Doppler data and left ventricular outflow tract diameter were measured off-line. The aortic valve area was calculated using the continuity equation (5). The measurements for intracardiac echocardiography, cardiac catheterization, and transthoracic echocardiography were made independently.

Statistical methods. The aortic valve area determined by intracardiac echocardiography was compared with the aortic valve area determined by the Gorlin and continuity equations using linear regression analysis and the Bland-Altman method (13). Error was expressed as the mean difference and as the standard deviation of the difference between the aortic valve area determined by intracardiac echocardiography and the Gorlin and continuity equations. The differences between the aortic valve areas determined by intracardiac echocardiography and the Gorlin and continuity equations were also determined and analyzed as a function of cardiac output, aortic valve area, image quality, and postvalvuloplasty status using the Student t test. The Wilks-Shapiro test to determine normality was also performed for these differences. Values for

Table 1. Mean Gradients by Catheterization and Doppler Ultrasound and Aortic Valve Areas by Gorlin Equation, Continuity Equation and Intracardiac Echocardiography

	Mean Gradient		AVA			
Pt No.	Catheterization (mm Hg)	Doppler (mm Hg)	Gorlin (cm^2)	Continuity (cm^2)	ICE (cm^2)	Clinical Characteristic
1	47	50	NA	0.42	0.54	2+ AI, fluid catheter
2	31	35	NA	0.75	1.02	3+ AI, fluid catheter, BAV
3	68	28	0.81	1.06	1.01	Native AS
4	67	67	0.75	0.54	0.72	Native AS
5	63	47	0.64	0.57	0.58	Prevalvuloplasty, TD
6	37	34	0.83	0.73	0.64	Postvalvuloplasty, TD
7	49	68	0.69	0.52	0.80	Native AS
8	38	35	0.66	0.50	0.63	Prevalvuloplasty
9	24	24	0.88	0.70	0.68	Postvalvuloplasty
10	63	53	NA	0.86	1.04	2+ AI, native AS
11	57	52	0.36	0.57	0.42	Native AS
12	34	31	0.31	0.34	0.38	Prevalvuloplasty, TD
13	23	23	0.45	0.38	0.41	Postvalvuloplasty, TD
14	22	35	0.70	0.49	0.52	Native AS
15	64	64	0.54	0.44	0.43	Native AS
16	46	45	0.45	0.67	0.49	Native AS, fluid catheter
17	36	20	NA	1.06	1.00	2+ AI, native AS
Mean ± SD*	45 ± 16	42 ± 15	0.62 ± 0.18†	0.62 ± 0.22	0.66 ± 0.23 0.59 ± 0.18†	

*Excluding grade III data. †For 13 patients in the Gorlin analysis group. AI = aortic insufficiency; AS = aortic stenosis; BAV = bioprosthetic aortic valve; NA = not applicable; Pt = patient; TD = cardiac output by thermodilution.

aortic valve area are expressed as the mean value ± SD (range). A p value <0.05 was considered significant.

Interobserver variability for the measurements of intracardiac echocardiographic images was determined by two independent observers. Linear regression analysis and the standard deviation of the difference were used to compare each observer's measurements.

Results

Seventeen patients with varying degrees of aortic stenosis met inclusion criteria and comprised the study group (mean age 71 years, range 40 to 86; 10 men, 7 women). Four patients underwent intracardiac echocardiographic imaging before and after aortic valvuloplasty. Of the 21 studies performed, intracardiac echocardiographic images of sufficient quality for analysis (grades I and II) were obtained in 17 (81%) (Table 1). Poor quality images (grade III) were obtained in four studies (19%). No easily identifiable features, such as aortic valve area by Gorlin or continuity, cardiac output, mean transvalvular gradient or postvalvuloplasty status, were predictive of poor image quality. Significant aortic insufficiency was present in four patients who were removed from analysis in the Gorlin group. Of the patients with adequate intracardiac echocardiographic images, four had cardiac outputs determined by the thermodilution technique and three had mean transvalvular gradients determined by fluid-filled catheters.

The average aortic valve area determined by intracardiac echocardiography for the 13 patients in the Gorlin analysis group was 0.59 ± 0.18 cm^2 (range 0.37 to 1.01 cm^2), and by the Gorlin equation, 0.62 ± 0.18 cm^2 (range 0.31 to 0.88 cm^2). The average aortic valve area determined by intracardiac echocardiography for the 17 studies in the continuity analysis group was 0.66 ± 0.23 cm^2 (range 0.37 to 1.04 cm^2), and by the continuity equation, 0.62 ± 0.19 cm^2 (range 0.34 to 1.06 cm^2). The aortic valve area determined by intracardiac echocardiography underestimated the aortic valve area determined by the Gorlin equation by an average of 5.1%. The aortic valve area determined by intracardiac echocardiography overestimated the aortic valve area determined by the continuity equation by an average of 6.2%. Intracardiac echocardiographic images of two stenotic aortic valves with planimetry of the aortic valve areas are shown in Figure 1.

There were significant correlations between the aortic valve area determined by intracardiac echocardiography and the Gorlin and continuity equations (Table 2, Fig. 2 and 3).

The mean difference between aortic valve area measurements obtained from intracardiac echocardiography and the Gorlin equation was analyzed as a function of cardiac output, aortic valve area (by intracardiac echocardiography), image quality and postvalvuloplasty status, and no statistically significant trends were found.

Interobserver variability, determined by two independent observers, of aortic valve area measurements obtained from

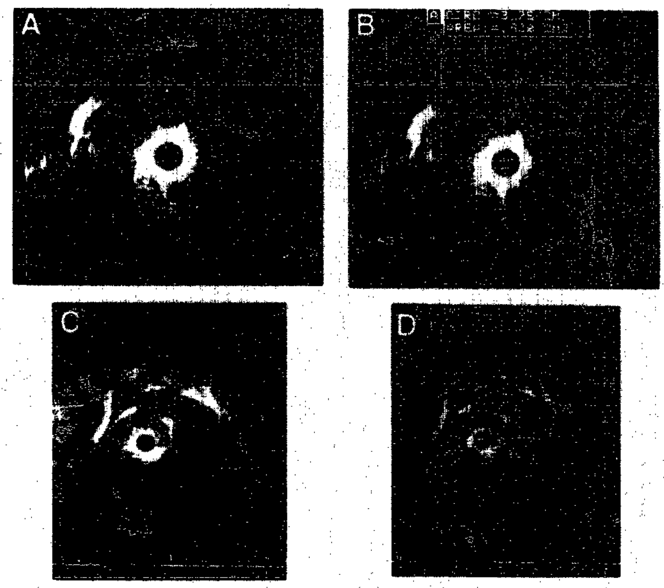


Figure 1. Intracardiac echocardiographic images of **(A, C)** representative stenotic aortic valves and **(B, D)** the same stenotic aortic valves with the planimetered areas demonstrated.

intracardiac echocardiography revealed a close correlation ($r = 0.97$, $p < 0.001$, standard deviation of the difference = $0.05\ cm^2$).

Discussion

Clinicians largely rely on the combination of symptoms and valve area in the management of patients with valvular aortic stenosis. To this end, an accurate method of determining the aortic valve area would be clinically useful.

Limitations of current standards. The currently used invasive standard—the Gorlin equation—has been extensively used over the past four decades and has proved to be prognostically valuable. However, the Gorlin equation has many well-described theoretical and practical limitations (2,3). The equation uses a constant that is inaccurate in low flow states and also assumes a single coefficient of discharge and contraction over a range of valve morphologies. In addition, the Gorlin equation requires data that are difficult to acquire accurately, such as oxygen content, oxygen consumption and mean transvalvular gradient. In spite of the equation's widespread acceptance and use, it has been inadequately validated in the clinical setting (2).

The currently used noninvasive standard—the continuity equation—has been extensively compared with the Gorlin equation and has been validated in several in vitro hemodynamic models (5–8). Although the continuity equation has few theoretical considerations, it has many practical limitations in data acquisition. The major theoretical consideration is that the continuity equation (like the Gorlin equation) determines the cross-sectional area at the vena contracta. This is the cross-sectional area to which flow is confined by the stenotic orifice, which, by definition, is smaller than the actual orifice area. A major technical limitation with accurate data acquisition is in the measurement of the left ventricular outflow tract diameter. Inaccuracies in the measurement of the left ventricular outflow tract diameter are magnified when the value is squared to calculate the left ventricular outflow tract area. In addition, accurate Doppler samples are often difficult to obtain, especially in older patients with ectatic aortas and poststenotic dilation. If the Doppler samples are not obtained in the same direction of flow, an underestimation of the velocities will be made (12). Prevalvular flow acceleration and nonuniform left ventricular outflow tract flow velocities are additional sources of error that may be introduced into the continuity calculation (14). Like all indirect methods, the continuity equation has been incompletely validated in the clinical setting owing to difficulty in obtaining direct measurements for comparison.

Direct imaging and measurement of aortic valve area. An ideal method of determining the aortic valve area is by direct measurement. Direct measurement overcomes many of the practical and theoretical shortcomings associated with indirect methods. From a practical standpoint, direct measurements have a single parameter rather than the many necessary for the indirect methods; thus, there is less introduction of variability. Direct measurements of the mitral valve area by transthoracic echocardiography are well established and have been validated in vitro (15,16). Direct measurement of the aortic valve area by transthoracic echocardiography is difficult owing to the degradation of image quality caused by heavy calcification as well as

Table 2. Intracardiac Echocardiographic Correlations

Equation	Correlation Coefficient (r)	p Value	Mean Difference (cm^2)	SD of Differences (cm^2)
Gorlin	0.78	0.002	0.03	0.12
Continuity	0.82	<0.0001	0.04	0.13

the limitations of resolution in the range of the area being measured.

Other methods of directly measuring the aortic valve area have been successful compared with the Gorlin and continuity equations. Computed tomography, magnetic resonance imaging, and transesophageal echocardiography have demonstrated good correlations with either the Gorlin or continuity equations; however, these comparisons were generally nonsimultaneous, with small patient numbers (17–22).

Compared with other methods, intracardiac echocardiography has many advantages in directly measuring the aortic valve area. Intracardiac echocardiography has proved to be accurate in the quantitative determination of left ventricular volumes and the qualitative evaluation of the aortic valve (9,10). Other studies utilizing catheter-based ultrasound imaging techniques have also demonstrated a high degree of accuracy in the measurement of cardiac dimensions (9,23–28). In the current study, we had no difficulty in measuring aortic valve areas <0.4 cm^2. This ability to measure a small orifice is probably the result of high near-field resolution as well as positioning the transducer within the valvular orifice. Imaging from within the valve causes less shadowing of the orifice from calcified leaflets, resulting in improved definition of the orifice edges. Computed tomography and magnetic resonance imaging cannot be performed simultaneously with cardiac catheterization, making an accurate comparison with indirect methods difficult. Additionally, computed tomography and magnetic resonance imaging probably lack the temporal resolution needed to accurately distinguish the rapid changes in aortic valve area, which occur throughout the cardiac cycle. Transesophageal echocardiography could potentially be used as an alternative method of determining the aortic valve area; however, a large number of these patients also require coronary angiography. As such, this strategy would likely necessitate an additional test with the associated risks and patient discomfort. Because intracardiac echocardiography is catheter based, it can be easily performed in conjunction with cardiac catheterization, with no additional patient discomfort.

Results of current study. This study demonstrated the feasibility of directly measuring the aortic valve area using intracardiac echocardiography, with successful imaging in 81% of the studies. There were no complications and the additional time required in each case for intracardiac echocardiography imaging was minimal.

Sources for the discrepancies seen between the aortic valve area determined by intracardiac echocardiography and the Gorlin and continuity equations are probably the result of inaccuracies in each of the three methods. The directly measured aortic valve area underestimated the aortic valve area derived by the Gorlin equation by an average of 5.1%. Factors in the Gorlin equation that may account for a portion of the discrepancy between the two groups include inaccuracies in the acquisition of oxygen content, oxygen consumption and mean pressure gradient. As the Gorlin equation calculates the area

Figure 2. Correlation plot of the aortic valve area derived from the Gorlin equation compared with the aortic valve area determined by intracardiac echocardiography (ICE). **Dashed line** = regression line; **solid line** = line of identity.

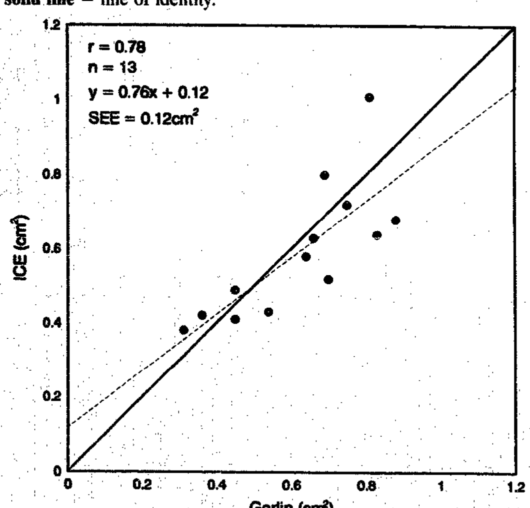
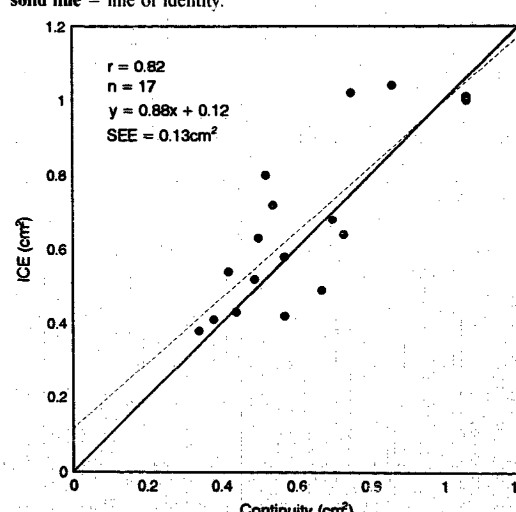


Figure 3. Correlation plot of the aortic valve area derived from the continuity equation compared with the aortic valve area determined by intracardiac echocardiography (ICE). **Dashed line** = regression line; **solid line** = line of identity.



at the vena contracta, an underestimation of the directly measured area would theoretically be expected. Because there was no statistical difference between the two sets of data, a larger study will probably be necessary to test this theoretical concern. No relationship was found when the mean difference between the aortic valve area determined by intracardiac echocardiography and the Gorlin equation was analyzed as a function of cardiac output or valve area.

The directly measured aortic valve area overestimated the continuity-derived aortic valve area by 6.2%. Like the Gorlin equation, the continuity equation calculates the effective aortic valve area, which, by definition, is smaller than the actual orifice area. This may theoretically explain the systematic underestimation seen in the present study. Another possible explanation for the overestimation seen by direct measurement is that the values obtained for the continuity equation used the time velocity integrals, which calculate the mean aortic valve area throughout the systolic period, as opposed to direct measurement in which the maximal aortic valve area during the systolic period was used. However, when the mean difference between the aortic valve area determined by intracardiac echocardiography and the aortic valve area calculated by the continuity equation was analyzed as a function of cardiac output or valve area, no relationship was found.

Another possible source of discrepancy is due to inaccurate imaging of the true aortic valve area by intracardiac echocardiography. Off-axis imaging of the orifice may have contributed to the error by overestimating the true aortic valve area. Image distortion due to nonuniform transducer rotation may have also caused an overestimation of aortic valve area measurements. The exact maximal excursion of the aortic leaflets may have been missed owing to the temporal resolution of the video system (one updated image every 33 ms). In addition, the complex three-dimensional shape of certain orifices made accurate planimetry in a single two-dimensional plane difficult. Rapid movement of the imaging transducer within the aortic valve orifice during systole made optimal imaging of the leaflet edges challenging in certain cases. In spite of these possible sources of error, good correlation and agreement between the aortic valve area determined by intracardiac echocardiography and the aortic valve area calculated by the Gorlin and continuity equations were found.

Clinical implications and conclusions. In this study, the feasibility of using intracardiac echocardiography to measure the aortic valve area directly in a clinical setting was established. The correlation and agreement between intracardiac echocardiography and the standard methods for determining the aortic valve area demonstrate the relative accuracy of this new technique. Given the limitations and indirect nature of the Gorlin and continuity equations, this study was unable to define the "true" accuracy of intracardiac echocardiographic measurements. Additionally, intracardiac echocardiography enabled the first nearly simultaneous comparison of the Gorlin and continuity equations with a directly measured aortic valve area in a clinical setting. Further study with direct measurements of the aortic valve area in a larger population of patients with valvular aortic stenosis is necessary to evaluate the entire range of clinical situations, for example, in the patient with a low cardiac output and a low mean gradient in the presence of apparently severe aortic stenosis. One such patient was included in the current study and intracardiac echocardiography proved useful in defining the severity of valvular stenosis. Intracardiac echocardiography performed in conjunction with provocative maneuvers, such as inotropic stimulation, would presumably reveal changes in the orifice size and be useful in determining the etiology of clinical symptoms in this setting (29). Intracardiac echocardiography may also prove useful in the evaluation and guidance of percutaneous aortic valvuloplasty procedures. Thus, this study demonstrates a new, quantitative use for intracardiac echocardiographic imaging with many potential clinical applications.

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