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The Fractional Shortening–Velocity Ratio: Validation of a New Echocardiographic Doppler Method for Identifying Patients With Significant Aortic Stenosis

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Previous studies have shown that Doppler echocardiographic methods based on the continuity equation can accurately determine aortic valve area in patients with clinically significant aortic stenosis; nonetheless, methods based on the continuity equation are time-consuming and may not be technically possible in all subsets of patients. The purpose of this study was to develop and prospectively evaluate a simpler new noninvasive method for determining aortic valve area. With this new method, aortic valve area is obtained by dividing the percent fractional anteroposterior shortening at the midventricular level by $4V^2$, where V is the peak instantaneous Doppler-derived flow velocity across the aortic valve.

In the first part of the study, the fractional shortening–velocity ratio was used to examine a group of 25 patients evaluated retrospectively. There was a highly significant linear relation between the fractional shortening–velocity ratio (FSVR) and the aortic valve area (AVA) determined by the Gorlin formula at cardiac catheterization: FSVR = 1.1(AVA) − 0.1 ($r = 0.88$; significance of slope $p < 0.001$). Furthermore, a fractional shortening–velocity ratio <1.1 reliably identified all patients with clinically significant aortic stenosis (aortic valve area <1 cm^2), whereas a fractional shortening–velocity ratio <0.8 reliably identified all patients with critical aortic stenosis (aortic valve area <0.7 cm^2).

This new method was then validated by prospectively applying the fractional shortening–velocity ratio to a group of 44 patients from two separate institutions. This prospective study showed that a fractional shortening–velocity ratio <1.1 had a sensitivity of 90% to 96% and a positive predictive accuracy of 90% to 92% for identifying patients with significant aortic stenosis, whereas a fractional shortening–velocity ratio <0.8 had a sensitivity of 100% and a predictive accuracy of 74% to 88% for identifying patients with critical aortic stenosis.

In summary, the fractional shortening–velocity ratio is a new Doppler echocardiographic method that reliably identifies patients with clinically significant aortic stenosis. The simplicity of this new noninvasive method readily lends itself to routine clinical use.

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Recent advances in two-dimensional and Doppler echocardiography have dramatically increased the accuracy of the noninvasive assessment of aortic stenosis. Previous studies (1–10) have shown that methods based on the continuity equation provide an extremely accurate means for noninvasively determining valve area in patients with aortic stenosis. These methods, which are based on the assumption of constant volumetric blood flow at different locations in the heart, permit the calculation of aortic valve area when the aortic velocity profile and cross-sectional area and velocity profile of blood flow at another site of the heart can be obtained. Despite the current widespread acceptance of the continuity equation for determining aortic valve area, this method is not without limitations. For example, the requisite measurements are time-consuming and can be technically difficult in certain subsets of patients (4). Thus, methods based on the continuity equation may not be accurate or applicable in all clinical settings.

Accordingly, the purpose of the present study was to develop a simpler method for evaluating aortic stenosis that would 1) avoid the difficulties and errors inherent in measuring blood flow across a valve, 2) remain sensitive and

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accurate in low cardiac flow states, and 3) be applied easily in a general clinical setting.

Methods

Study patients. This study consisted of a retrospective series of 25 patients studied at the Medical University of South Carolina/Veterans Affairs Medical Center, Charleston and a prospective series of 44 patients studied at that institution (27 patients) and at the University of Connecticut (17 patients). In the first part of the study, data gathered retrospectively were used to develop a new echocardiographic Doppler method for identifying patients with significant aortic stenosis, namely, the fractional shortening–velocity ratio. Exclusion criteria for the retrospective analysis included evidence of regional left ventricular dysfunction and more than mild aortic insufficiency.

In the second part of this study, the fractional shortening–velocity ratio was applied prospectively to patients from two separate institutions to determine the sensitivity, specificity and predictive value of this ratio in identifying patients with significant aortic stenosis. No patients were systematically excluded from the prospective analysis.

Noninvasive Studies

Doppler echocardiography. The systolic velocity profile across the aortic valve was recorded from the apical, suprasternal and right parasternal views using continuous wave Doppler ultrasound. The maximal flow velocity (mm/s) across the aortic valve (V_1) was determined from the outer envelope of the continuous wave Doppler spectral tracing. In all but two patients, the pressure decrease across the aortic valve was calculated using the $4V^2$ approximation of the Bernoulli equation, where V is the peak instantaneous Doppler-derived flow velocity across the aortic valve. In the two patients in whom the peak velocity under the aortic valve (V_2; measured by pulsed Doppler interrogation) was >1.2 m/s, the pressure gradient across the aortic valve was determined as $4(V_1^2 - V_2^2)$.

M-mode echocardiography. All M-mode studies were performed with the patient in the left lateral (30°) decubitus position using two-dimensional echocardiographic guidance and a parasternal long-axis view. M-mode tracings were recorded on hard copy printout (50 or 100 mm/s paper speed) with a simultaneous single lead electrocardiogram. The extent of left ventricular fractional anteroposterior shortening was measured at the midpapillary muscle level from the end-diastolic (EDD) and end-systolic (ESD) dimensions, using the leading edge to leading edge convention according to American Society of Echocardiography guidelines (11). Percent fractional shortening was calculated as (EDD − ESD)/EDD × 100. However, for the eight patients with regional left ventricular dysfunction in the prospective series, fractional shortening was calculated from the two-dimensional echocardiographic images (parasternal and apical windows) using a modification of a method developed by Quinones et al. (12), wherein the extent of "global" fractional shortening was obtained by averaging fractional shortening at the apex, midventricle and base of the left ventricle.

Cardiac Catheterization

In all patients, the pressure gradient across the aortic valve was measured by retrograde passage across the valve. Patients in the retrospective series were studied using Millar catheters, with simultaneous measurement of aortic and left ventricular pressures; 19 patients in the prospective analysis were studied using Millar catheters, whereas the remaining 25 patients were studied with fluid-filled catheters, with pressures recorded using simultaneous left ventricular and femoral artery pressures or during pullback. Given the technical limitations of accurately measuring angiographic cardiac output (13), thermodilution cardiac output was used throughout this study. No patient in this study had more than mild tricuspid or mitral regurgitation. Aortic valve area was determined using the Gorlin formula (14).

Fractional shortening–velocity ratio. The fractional shortening–velocity ratio (FSVR), although derived empirically, was based on the Gorlin formula (14). This ratio is obtained by dividing the extent of left ventricular fractional shortening (%FS) by the Doppler-derived pressure gradient across the valve ($4V^2$); where $FSVR = \%FS/4V^2$. Thus, the fractional shortening–velocity ratio incorporates an index of transvalvular valve flow in the numerator and an index of the transvalvular pressure gradient in the denominator. Therefore, this ratio should compensate for patients in whom pathologic flow states might result in "misleading" transvalvular pressure gradients.

Data analysis. Doppler and M-mode tracings were analyzed independently by two observers who were unaware of the catheterization results. Inter- and intraobserver variability for these measurements was <8%. For patients in sinus rhythm, 3 consecutive beats were analyzed; for patients in atrial fibrillation, 7 to 10 consecutive beats were analyzed.

Statistical analysis. Data are expressed as mean values ± SEM. Specific comparisons between groups were tested using Student's *t* test or one-way analysis of variance where appropriate. Two-way analysis of variance was used to test for differences in heart rate in the noninvasive and invasive studies in both the retrospective and prospective series. The correlation between the fractional shortening velocity ratio and aortic valve area determined at cardiac catheterization was assessed using least squares linear regression analysis. Sensitivity, specificity and predictive value were determined using standard formulas (15). Differences in proportions between different groups were assessed using chi-square

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Table 1. Patient Characteristics

	Retrospective	Prospective	
	MUSC (n = 25)	MUSC (n = 27)	UCONN (n = 17)
Age (yr)	63.5 ± 3.3 (40–84)	68.3 ± 2.4 (37–83)	73.1 ± 2.5 (57–86)
M/F (no.)	15/10	13/14	12/5

Data are expressed as mean values ± SEM; data in parentheses show the range of values in each individual group. F = female; M = male; MUSC = Medical University of South Carolina; UCONN = University of Connecticut.

analysis. A significant difference was said to exist at the $p < 0.05$ level.

Results

Clinical features (Table 1). There was no significant difference in the age and gender of the patients in the retrospective or prospective series. The etiology of aortic stenosis was degenerative in 49 patients, congenital in 12 patients and rheumatic in 8 patients. Of the 69 patients in this study, 62 had sinus rhythm and 7 patients were in atrial fibrillation.

Echocardiographic Doppler and cardiac catheterization data (Table 2). When patients in the prospective series were grouped and compared with those in the retrospective series, there was no significant difference in the peak aortic valve pressure gradient ($p > 0.6$), fractional shortening–velocity ratio ($p > 0.46$) or aortic valve area ($p > 0.64$); however, the extent of fractional shortening was significantly greater ($p < 0.02$) for the patients in the retrospective series. Moreover, when heart rate data from the noninvasive and invasive studies were analyzed using a two-way analysis of variance, there was no significant difference in heart rate between the different studies, suggesting that the hemodynamic status of the patients was similar during the invasive and noninvasive studies. There was a difference of 11.5 ± 2.9 days between the echocardiographic-Doppler and invasive studies in the retrospective series and 4.7 ± 0.8 days between studies in the prospective series.

Fractional Shortening–Velocity Ratio

Retrospective series. Figure 1 summarizes the relation between the fractional shortening–velocity ratio and the aortic valve area (AVA) calculated from the data obtained during cardiac catheterization. There was a linear relation ($p < 0.001$, $r = 0.88$) between the fractional shortening–velocity ratio (FSVR) and aortic valve area (range 0.38 to 1.43 cm^2), where FSVR = 1.1(AVA) − 0.1 (significance of slope $p < 0.001$; significance of intercept $p > 0.35$; standard deviation 0.13). This correlation was not improved ($r = 0.68$) by using the mean as opposed to the peak Doppler pressure gradient across the aortic valve.

The dotted line in Figure 1 represents all patients in this study with significant aortic stenosis (defined as an aortic

Table 2. Doppler Echocardiographic and Cardiac Catheterization Data From 69 Patients

	Retrospective (n = 25)	Prospective (n = 44)	
	MUSC	MUSC	UCONN
Fractional shortening	38.4% ± 2.1% (16%–60%)	33.3% ± 1.8% (16%–52%)	30.8% ± 2.6% (12%–47%)
Peak AV Doppler pressure gradient (mm Hg)	60.0 ± 5.3 (25–125)	65.6 ± 5.0 (22–115)	40.8 ± 6.3 (13–100)
Fractional shortening–velocity ratio	0.76 ± 0.1 (0.19–1.7)	0.60 ± 0.1 (0.22–1.3)	1.1 ± 0.2 (0.31–2.8)
Noninvasive HR (beats/min)	68.2 ± 2.7 (48–91)	61.6 ± 2.3 (48–93)	69.5 ± 2.9 (54–78)
Aortic valve area (cm^2)	0.77 ± 0.06 (0.38–1.43)	0.74 ± 0.05 (0.35–1.50)	0.92 ± 0.12 (0.25–1.76)
Invasive HR (beats/min)	66.2 ± 2.4 (48–91)	68.3 ± 3.1 (48–89)	70.4 ± 4.2 (39–125)

Data are expressed as mean values ± SEM; data in parentheses show the range of values in each individual group. Data for the prospective series were grouped and compared with the retrospective series; this analysis showed that there was no significant difference in the extent of fractional shortening, Doppler-derived peak systolic pressure gradient across the aortic valve, fractional shortening–velocity ratio or aortic valve area. Differences in mean heart rate (HR) in the noninvasive and invasive studies were determined using two-way analysis of variance, testing for differences within and between groups. This analysis showed no difference in the mean heart data among groups ($p > 0.4$). AV = aortic valve.

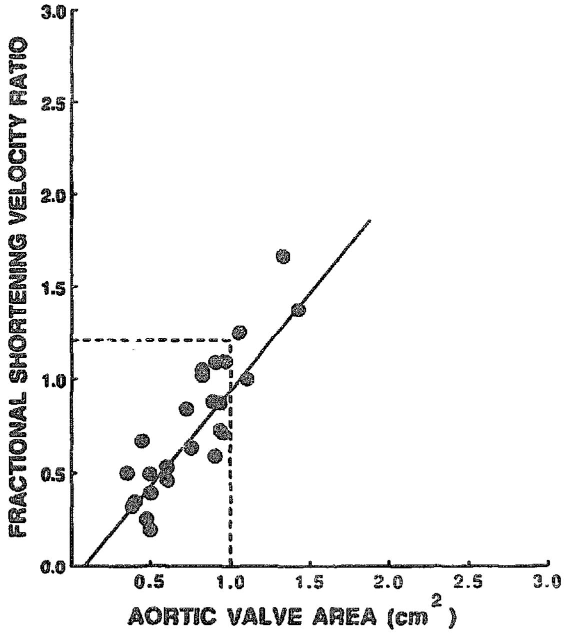

Figure 1. Relation between the fractional shortening-velocity ratio and aortic valve area (AVA) in the series of 25 retrospectively studied patients. There is a highly significant linear relation ($p < 0.001$) between the fractional shortening-velocity ratio (FSVR) and aortic valve area (range 0.38 to 1.43 cm^2) determined by the Gorlin formula at cardiac catheterization, where FSVR = 1.1(AVA) − 0.1 (significance of slope $p < 0.001$; $r = 0.88$; SD 0.13). The linear regression variable for this equation met the criteria for a line of identity (significance of y intercept $p > 0.35$). The dotted line represents all patients with an aortic valve area <1 cm^2.

valve area <1 cm^2) (16). A fractional shortening-velocity ratio <1.2 identified all patients in this series with significant aortic stenosis. To determine which cutoff value for the fractional shortening-velocity ratio would have the best overall sensitivity, specificity and predictive value for identifying patients with an aortic valve area <1 cm^2, we systematically examined ratios between 0.6 and 1.2 (Table 3). A fractional shortening-velocity ratio <1.1 had the best combined sensitivity (100%), specificity (75%) and predictive accuracy (positive test 88%; negative test 100%) in identifying patients with significant aortic stenosis. To determine a sensitive and specific fractional shortening-velocity ratio cutoff value that could be used to identify patients with "critical" aortic stenosis (defined as an aortic valve area <0.7 cm^2) (16), the above analysis was repeated (Table 3). A fractional shortening-velocity ratio <0.8 had the best combined sensitivity (100%), specificity (73%) and predictive accuracy (positive test 71%; negative test 100%) for identifying patients with "critical" narrowing of the aortic valve area. Identical results were obtained with respect to sensitivity, specificity and predictive accuracy when a fractional shortening-velocity ratio <0.8 was used to identify patients with a "critical" aortic valve area <0.75 cm^2 (17).

Table 3. Sensitivity, Specificity and Predictive Accuracy of Different Fractional Shortening-Velocity Ratios

			Predictive Accuracy	
	Sensitivity	Specificity	+ Test	− Test
FSVR < 1.2 (%)	100 (100)	75 (25)	88 (45)	100 (100)
FSVR < 1.1 (%)	100 (100)	75 (25)	88 (45)	100 (100)
FSVR < 1.0 (%)	81 (100)	100 (53)	100 (59)	100 (100)
FSVR < 0.9 (%)	81 (100)	100 (53)	100 (59)	100 (100)
FSVR < 0.8 (%)	67 (100)	100 (73)	100 (71)	57 (100)
FSVR < 0.7 (%)	57 (90)	100 (93)	100 (90)	44 (93)
FSVR < 0.6 (%)	42 (90)	100 (93)	100 (90)	33 (93)

The sensitivity, specificity and predictive value of fractional shortening-velocity ratios (FSVR) from 0.6 to 1.2 were determined for patients with an aortic valve area <1 cm^2 (shown above) and <0.7 cm^2 (shown below in parentheses). A fractional shortening-velocity ratio <1.1 had the best combined sensitivity, specificity and predictive value for identifying patients with an aortic valve area <1 cm^2, whereas a fractional shortening-velocity ratio of <0.8 had the best combined sensitivity, specificity and predictive value for identifying patients with an aortic valve area <0.7 cm^2. + = positive; − = negative.

Prospective series. Because the cutoff values for the fractional shortening-velocity ratios were determined on the basis of retrospectively gathered data, it was important to evaluate the fractional shortening-velocity ratio in a group of prospectively studied patients. Accordingly, we examined a group of 29 consecutively studied patients at the Medical University of South Carolina/Veterans Affairs Medical Center, Charleston who had both Doppler echocardiographic studies and cardiac catheterization. Two patients were excluded from this study because it was not possible to obtain reliable echocardiographic images; no patients were excluded on the basis of aortic insufficiency or regional left ventricular dysfunction. When a fractional shortening-velocity ratio <1.1 was used to identify patients with an aortic valve area <1 cm^2, the sensitivity was 96%, specificity 50% and predictive accuracy of positive and negative tests 92% and 67%, respectively. When fractional shortening-velocity ratio <0.8 was used to identify patients with an aortic area <0.7 cm^2, the sensitivity was 100%, specificity 62% and predictive accuracy of positive and negative tests 74% and 100%, respectively.

To be certain that this new Doppler echocardiographic method would be applicable at other institutions, we used the fractional shortening-velocity ratio to identify significant aortic stenosis in a group of 17 patients studied at the

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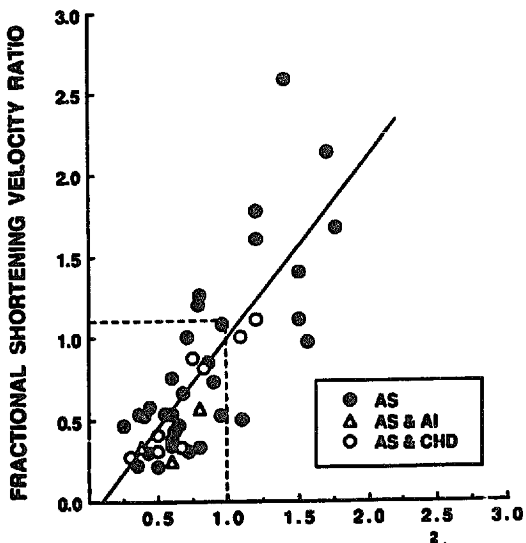

Figure 2. Relation between the fractional shortening-velocity ratio (FSVR) and aortic valve area (AVA) in the prospective series of 44 patients studied. The **dotted line** represents all patients with an aortic valve area <1 cm^2 who were correctly identified by a fractional shortening-velocity ratio <1.1 (that is, true positive results). Patients with aortic stenosis (AS) are shown by the **closed circles**, patients with aortic stenosis and coronary heart disease (CHD) with regional left ventricular dysfunction are shown by the **open circles** and patients with aortic stenosis and moderate aortic insufficiency (AI) are shown by the **open triangles**. There was a highly significant linear relation between fractional shortening-velocity ratio and aortic valve area (range 0.25 to 1.76 cm^2) determined by the Gorlin formula at cardiac catheterization; where FSVR = 1.1(AVA) − 0.1 (significance of slope $p < 0.0001$; r = 0.79; SD 0.13). The linear regression variable for this equation met the criteria for a line of identity (significance of y intercept $p > 0.37$).

University of Connecticut. In this analysis, a fractional shortening-velocity ratio <1.1 had a sensitivity of 90%, specificity of 86% and positive and negative predictive accuracy of 90% and 86%, respectively, in identifying patients with an aortic valve area <1 cm^2. When a fractional shortening-velocity ratio <0.8 was used to identify patients with an aortic valve area <0.7 cm^2, the sensitivity was 100%, specificity 90% and predictive accuracy of positive and negative tests 88% and 100%, respectively.

Figure 2 depicts the relation between the fractional shortening-velocity ratio and the aortic valve area for all patients in the prospective series, including eight patients with coronary heart disease and regional left ventricular dysfunction and three patients with moderate aortic insufficiency. The dotted line represents all patients with an aortic valve area <1 cm^2 who were correctly identified by a fractional shortening-velocity ratio <1.1 (that is, true positive results). The major finding shown in Figure 2 is that a fractional shortening-velocity ratio <1.1 reliably identified patients with clinically significant aortic stenosis and coexisting aortic insufficiency or regional left ventricular dysfunction.

Comparison of the fractional shortening-velocity ratio with other simplified Doppler methods. Previous Doppler echocardiographic studies have shown that patients with critical aortic stenosis may be reliably identified using a mean aortic valve pressure gradient >50 mm Hg (1) or a peak Doppler velocity >4 m/s (10). Accordingly, we compared the sensitivity of the fractional shortening-velocity ratio <0.8 with that of the two other simple Doppler methods. Chi-square analysis showed that a fractional shortening-velocity ratio <0.8 was significantly ($p < 0.05$) more sensitive (94%) than either a mean aortic valve gradient >50 mm Hg (sensitivity 48%) or peak Doppler flow velocity >4.0 m/s (sensitivity 45%) in identifying patients with critical aortic stenosis. Thus, the fractional shortening-velocity ratio, a combined echocardiographic-Doppler method, was more sensitive than other Doppler methods that measure pressure gradient alone.

Discussion

Fractional shortening-velocity ratio to assess aortic stenosis severity. In this study, we developed and validated a new simplified echocardiographic-Doppler method to identify patients with significant aortic stenosis, namely, the fractional shortening-velocity ratio. The sensitivity and accuracy of this method are demonstrated by three separate lines of evidence. First, there was a highly significant linear relation ($p < 0.001$, r = 0.88) between the fractional shortening-velocity ratio and aortic valve area determined by the Gorlin formula at cardiac catheterization (Fig. 1). Indeed, the linear regression variables for this equation met the criteria for a line of identity. Second, when a fractional shortening-velocity ratio <1.1 was used to identify patients with significant aortic stenosis, defined in this study as an aortic valve area <1 cm^2 (16), the sensitivity, specificity and positive predictive accuracy of this new method was 100%, 75% and 88%, respectively. Similarly, when a fractional shortening-velocity ratio <0.8 was used to identify patients with critical aortic stenosis, defined as an aortic valve area <0.7 cm^2 (16), the sensitivity, specificity and positive predictive accuracy of this method was 100%, 73% and 71%, respectively. The applicability of the fractional shortening-velocity ratio was then tested prospectively in a study conducted at two separate institutions. This prospective study showed that a fractional shortening-velocity ratio <1.1 had a sensitivity of 90% to 96% and a positive predictive accuracy of 90% to 92% in identifying patients with significant aortic stenosis, whereas a fractional shortening-velocity ratio <0.8 had a sensitivity of 100% and a predictive accuracy of 74% to 88% in identifying patients with critical aortic stenosis.

Third, to determine whether this combined Doppler echocardiographic method was as sensitive as other "simplified"

Doppler methods, we compared a fractional shortening–velocity ratio <0.8 with two previously reported Doppler methods (1,10). This analysis showed that the fractional shortening–velocity ratio was significantly more sensitive than either mean aortic valve pressure gradient >50 mm Hg (1) or peak aortic velocity >4 m/s (10) for identifying patients with critical aortic stenosis. The increased sensitivity of the fractional shortening–velocity ratio reflects the fact that this method incorporates an index of transvalvular valve flow into the calculation of aortic valve area, thus allowing the correct classification of patients in whom pathologic flow states result in "misleading" transvalvular pressure gradients.

Previous studies. As noted in two recent reviews (18,19), several noninvasive methods have been developed to assess the severity of aortic stenosis. Currently, however, most centers use some application of continuous wave Doppler ultrasound to assess the severity of aortic stenosis. Warth et al. (20) were the first to determine aortic valve area using a combination of thermodilution cardiac output to assess flow across the aortic valve and continuous wave Doppler ultrasound to measure the pressure gradient across the aortic valve. More recently, however, investigators and clinicians (1–10) have employed the continuity equation to assess the degree of severity of aortic stenosis. This equation, which describes flow across a fixed orifice as the product of orifice area and flow velocity, has been applied to flow across the aortic (1,2,6–8), mitral (6,7,9) and pulmonary valves (6) with good results. Of all the different applications of the continuity equation, the one that has gained the most widespread clinical acceptance (both because it is relatively easy to image and this site can be used in patients with aortic insufficiency) has been to measure blood flow across the outflow tract of the aortic valve. Studies (1,3,4,6,7,9) comparing the accuracy of the continuity equation obtained from left ventricular outflow tract measurements against results obtained with the Gorlin formula at catheterization have shown a good correlation ($r = 0.86$ to 0.95) between the two methods. The results of the present study, in which there was a close correlation ($r = 0.88$) between fractional shortening–velocity ratio and aortic valve area determined by the Gorlin formula at cardiac catheterization, appear comparable with those obtained with the continuity equation.

It should be noted, however, that the continuity equation is not without certain limitations. First, there are inherent difficulties in the measurement of the left ventricular outflow tract, which may become particularly problematic in elderly patients, those with emphysema or those with calcification of the aortic anulus, in whom the echocardiographic images are suboptimal. Second, as noted recently by Skjaerpe et al. (4), recording optimal peak subvalvular aortic flow velocity can be time-consuming and lead to ≤14% error in calculating valve area. Thus, given these limitations, it is not surprising that the continuity equation cannot be applied easily or even accurately in all clinical situations.

Limitations of study. One limitation of the fractional shortening–velocity ratio pertains to patients with significant aortic stenosis and more than mild (>grade +1) mitral regurgitation. In this subset of patients, the fractional shortening–velocity ratio might be expected to yield false negative results because the values for this ratio would be spuriously high secondary to the increased fractional shortening observed in mitral regurgitation. A second potential limitation of this study is the use of regional (midventricular) fractional shortening as a measure of global left ventricular function. In this regard, it is noteworthy that we were able to use the fractional shortening–velocity ratio successfully (Fig. 2) in eight patients with aortic stenosis and regional left ventricular dysfunction by averaging the extent of fractional shortening at the apex, midventricle and base of the ventricle (12). Finally, it should be recognized that although the relation between the fractional shortening–velocity ratio and aortic valve area is linear for patients with clinically significant aortic stenosis, this relation becomes nonlinear for patients with a normal valve area and a transvalvular aortic valve pressure gradient <10 mm Hg.

Conclusions. This study shows that the fractional shortening–velocity ratio is a sensitive and accurate noninvasive method for identifying patients with clinically significant aortic stenosis. The major advantage of this new technique compared with methods based on the continuity equation is the relative ease with which the requisite measurements can be recorded and analyzed. Given the sensitivity of this new method, the fractional shortening–velocity ratio may be employed as an independent method for identifying patients with significant aortic stenosis. Furthermore, it may be used to provide a simple alternative assessment of any questionable or equivocal aortic valve area measurements obtained using the continuity equation.

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