A new method to calculate aortic valve area without left heart catheterization

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ABSTRACT Assessment of the severity of aortic stenosis remains a commonly encountered clinical problem. Noninvasive evaluation has to date not proven sufficiently accurate in most cases to permit clinical decision making in the individual patient. Therefore, cardiac catheterization and measurement of the valve area with use of the Gorlin equation remains the standard approach in patients with suspected aortic stenosis. Doppler ultrasound allows direct measurement of blood velocity in cardiac chambers. This technique was used to study 16 patients with suspected aortic stenosis after cardiac catheterization. Aortic valve area (AVA) was calculated with the equation AVA = CO/(SEP × mean velocity), where CO is cardiac output measured by thermodilution and SEP is the systolic ejection period derived from the Doppler tracings. The resulting value was compared with valve area calculated from cardiac catheterization data and an excellent correlation was noted (r = .99). This study demonstrates that Doppler ultrasound can be used to accurately measure aortic valve area without the need for left heart catheterization.

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CALCIFIC AORTIC STENOSIS is a common problem in the older adult population, with an estimated 5% of patients over the age of 75 years having some degree of restriction of valve motion. Since a critical degree of valvular narrowing may be life threatening, assessing the severity of the stenosis is of major clinical importance. Signs and symptoms such as angina, heart failure, or syncope suggest physiologically significant stenosis, as do findings of left ventricular hypertrophy on the electrocardiogram and calcification of the aortic valve on chest x-ray films. Phonocardiograms and carotid pulse tracings have been used to predict the degree of stenosis. Likewise, noninvasive measurement of maximal aortic cusp separation with M mode and two-dimensional echocardiography has been found to indicate the severity of aortic stenosis, and the use of two-dimensional echocardiography to directly measure the aortic valve area has been evaluated. Unfortunately, none of these noninvasive measurements have been sufficiently accurate to allow quantitation of aortic stenosis in individual patients. Therefore, the majority of adult patients with suspected aortic stenosis undergo left heart catheterization so that the severity of the lesion can be quantitated by determination of the valve area.

Doppler echocardiography offers a new noninvasive method for evaluation of aortic stenosis by direct measurement of flow velocity, which increases as the valve area is reduced. Several recent studies have found a good correlation between these increased velocities and the transvalvular pressure gradient calculated with use of a simplification of the Bernoulli equation.

However, the simple prediction of pressure gradient is not as useful to the clinician as is valve area since the pressure gradient may change substantially over time depending on afterload, autonomic tone, and left ventricular function. The cardiac output and heart rate likewise have major impact on the calculated valve area and may themselves change significantly with time. Accurate definition of valve area has been demonstrated in a group of pediatric patients, the majority of which had pulmonic stenosis, with use of Doppler velocities. However, the use of Doppler-derived flow velocity in the calculation of valve area in the older patient with calcific aortic stenosis and in whom echocardiographic examination is technically more demanding has not been reported. The current study was therefore undertaken to test the hypothesis that Doppler ultrasound could be used to accurately quantitate the valve area in an adult population with calcific aortic stenosis, thereby obviating the need for left heart catheterization.
catheterization to make this measurement. Flow velocity was used to calculate valve area with a modification of the Gorlin equation, and a new, more direct method to calculate valve area is described.

Materials and methods

Patient population. Sixteen consecutive adult patients undergoing cardiac catheterization for suspected valvular aortic stenosis were included in the study. Patients in whom aortic insufficiency was clinically believed to be a major hemodynamic lesion were excluded. Characteristics of the patient population studied were as follows. Their ages ranged from 46 to 85 years (mean 69); 12 were men and four women. Seven patients presented with angina, six with congestive heart failure, and seven with syncope. Ten patients exhibited left ventricular hypertrophy on electrocardiographic examination, and 12 had calcified aortic valves noted on routine posteroanterior and lateral chest x-rays.

The study was approved by the human investigation committee at Massachusetts General Hospital.

Cardiac catheterization. Right heart catheterization was performed from the femoral vein with a thermistor-tipped catheter (Edwards, Inc.) that was advanced to the pulmonary artery. Left heart catheterization was performed from the femoral artery by the Seldinger technique. A pigtail catheter was advanced to the ascending aorta and balanced with a radial arterial catheter. The pigtail catheter was then advanced across the aortic valve. While the gradient between the left ventricular and radial pressure was recorded, cardiac output was determined in triplicate by thermodilution and averaged. Aortic valve gradients were measured from the pressure tracings with use of the average of 3 beats in patients in sinus rhythm and the average of 10 beats in patients with atrial fibrillation. The mean pressure gradient was calculated by planimetry. The left ventricular ejection time and heart rate were also measured directly from the pressure tracings and systolic ejection period was calculated as the product of the left ventricular ejection time and heart rate. Aortic valve area (AVA) was calculated with the formula of Gorlin and Gorlin, in which $\text{AVA} = \frac{\text{CO}}{44.5 \times \text{SEP} \times \sqrt{VP_2P_1}}$, where CO is the cardiac output, SEP is the systolic ejection period, and $VP_2P_1$ is the square root of the measured mean systolic pressure gradient between left ventricle and aorta.14

Doppler echocardiography. After removal of the arterial catheters, each patient was transported to the echocardiography laboratory and examined with a continuous-wave Doppler system (Irex Systems; Ramsey, NJ). Aortic flow velocity was recorded from both the apical and suprasternal windows. Fine adjustments in the direction and location of the transducer were made to determine the maximal velocity jet at each site with the feedback of the audio signal and the spectral velocity display. The velocity spectrum was recorded at a paper speed of 50 mm/sec. During recording of Doppler echocardiograms simultaneous thermodilution cardiac outputs were again obtained in triplicate. Doppler measurements were made by two independent observers who were blinded to the catheterization results. Measurements were made from the spectral velocity tracings that showed the highest measurable velocity. The apical recording was highest in 11 patients and the suprasternal was highest in five patients. No patients were excluded because of inability to obtain adequate Doppler tracings. The average systolic velocity was measured directly from the Doppler tracings by planimetry. Three heart cycles were used for patients in normal sinus rhythm and 10 cycles were used for patients in atrial fibrillation. The left ventricular ejection time and heart rate were measured directly from the Doppler tracings. Systolic ejection period was derived from the product of the left ventriculoarterial ejection time and heart rate. Figure 1 is an example of a tracing obtained from the suprasternal window with continuous-wave Doppler echocardiography in patient 4. The vertical lines define the duration of systolic flow across the valve. This was multiplied by the heart rate to obtain the Doppler systolic ejection period. The peak velocity is shown at 4.7 m/sec and the mean systolic velocity is shown at 3.5 m/sec.

Aortic valve area was then calculated by two methods with use of the Doppler data. In the first method, the mean velocity of systolic flow was used in conjunction with the systolic ejection period (SEP) and simultaneous thermodilution cardiac output (CO) to calculate the valve area with the equation $\text{AVA} = \frac{\text{CO}}{(\text{SEP} \times \text{mean velocity})}$. This equation was derived from the assumption that mean velocity (in cm/sec) times the duration of flow (in sec/min) times the cross-sectional area of the valve (in cm$^2$) should equal the cardiac output (in ml/min). In the second method of calculation, a formula previously described by Kosturakis et al.13 was used. In their method, the pressure component of the Gorlin equation is derived with the equation $P = 4V^2$, as described by Hatle et al.15 The final equation is then $\text{AVA} = \frac{\text{CO}0.9 \times \text{SEP} \times \text{maximal velocity}}{4V}$. Statistical methods. Comparison between the catheterization and Doppler measurements of a single observer was made by linear regression with the method of least squares. Interobserver error was calculated by two methods. The least squares method was used to derive a linear regression. In addition, the difference between the two observers’ measurements was calculated and expressed as a percentage of the mean of the two measurements.

Results

Data from cardiac catheterization are listed in table 1. The mean aortic valve gradient averaged 53.1 mm Hg (range 15 to 115), mean systolic ejection period was 26.5 sec/min (range 19.0 to 33.4), and mean cardiac output was 5.21 liters/min (range 2.86 to 7.43).

![FIGURE 1. Calculation of aortic valve area with continuous-wave Doppler ultrasound. A tracing obtained from the suprasternal view in patient 4 is shown. The vertical lines define the duration of flow across the valve in systole (LVET) at 0.27 sec. This was multiplied by the heart rate of 91 to obtain a systolic ejection period of 24.6 sec/min. The maximal velocity is the mean for an average of 3 beats and is 4.7 m/sec; the mean velocity for 3 beats is 3.5 m/sec. Simultaneous thermodilution cardiac output (CO) was 4.66 liters/min. With the use of the equation $\text{AVA} = \frac{\text{CO} \times \text{SEP} \times \text{mean velocity}}{4V}$, a valve area of 0.54 cm$^2$ was calculated.](image-url)
TABLE 1
Data obtained at catheterization

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>SEP (sec/min)</th>
<th>Peak gradient (mm Hg)</th>
<th>Mean gradient (mm Hg)</th>
<th>Cardiac output (l/min)</th>
<th>Valve area (cm²)</th>
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<tr>
<td>1</td>
<td>25.9</td>
<td>35</td>
<td>30</td>
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<tr>
<td>2</td>
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<td>3</td>
<td>19.4</td>
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<td>5</td>
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<td>7</td>
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<td>16</td>
<td>20.8</td>
<td>33</td>
<td>34</td>
<td>5.21</td>
<td>1.00</td>
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</table>

SEP = systolic ejection period.

Valve area calculated with the Gorlin equation ranged from 0.27 to 2.3 cm² (mean 0.77).

Table 2 lists the Doppler-derived data for each of the 16 patients studied. The mean velocity across the aortic valve averaged 3.05 m/sec (range 1.37 to 4.40), average Doppler-derived systolic ejection period was 26.5 sec/min (range 17.6 to 46.8), and mean cardiac output measured by thermodilution in the echocardiography laboratory was 5.14 liters/min (range 3.67 to 6.73). The aortic valve area calculated with AVA = CO/(SEP × mean velocity) ranged from 0.26 to 2.14 cm² (mean 0.78). Figure 2 shows the correlation between aortic valve area calculated by the Gorlin equation using catheterization data and that calculated with AVA = CO/(SEP × mean velocity) from Doppler ultrasound data (r = .99 and p < .0001 for the comparison).

The aortic valve area calculated by substituting 4V² for P₂-Pᵢ in the standard Gorlin equation is compared with the valve area obtained at catheterization in figure 3 (r = .96 and p = .0001 for the comparison). Despite the short time interval, several of the patients had major hemodynamic changes between the times of the catheterization and Doppler studies. The mean percentage difference between the systolic ejection period derived from catheterization data and that derived from Doppler data was 5%, with a range of from 0% to 33% (r = .21, p = .001). The mean percentage difference in heart rate between the two studies was 10% (range 0% to 41%; r = .93, p = .001). However, the mean percentage difference in systolic ejection period (left ventricular ejection time × heart rate) between the two studies was 13%, with a range of from 3% to 31% (r = .18, p = .41). The mean percentage difference in thermodilution cardiac outputs measured in the two studies was 13%, with a range of 1% to 61% (r = .33, p = .21). Figure 4 shows the correlation between the peak-to-peak aortic gradient measured at catheterization.
Correlation of aortic valve areas determined with measured and predicted pressure gradients. Catheterization valve areas were calculated with the standard Gorlin equation and the measured pressure gradient across the valve; Doppler ultrasound was used to predict a pressure gradient (P) by the formula \( P = 4V^2 \), where \( V \) is the maximal observed velocity across the valve. The predicted gradient was then substituted for the measured gradient in the Gorlin equation, yielding \( AVA = CO/0.9 \times SEP \times \text{maximal velocity} \).

The interobserver variability for the Doppler-measured variables of left ventricular ejection time, mean velocity, maximal velocity, and aortic valve area, as calculated with the equation \( AVA = CO/(SEP \times \text{mean velocity}) \), is listed in Table 3 for two observers blinded to the catheterization results. Data listed are the mean percentage differences between the two observations and the r values calculated by linear regression.

**Discussion**

Nearly 35 years ago Gorlin and Gorlin\(^4\) described a method for calculating the orifice area of stenotic valves. They identified the variables necessary to calculate the valve area as the quantity of blood crossing the valve per unit time, the velocity of flow across the valve, and the duration of flow. The velocity of blood flow could not be determined by available hemodynamic methods and therefore it was derived as a constant times the square root of the measured pressure gradient. The recent advent of accurate Doppler echocardiographic techniques allows for the direct measurement of the velocity of blood flow through the valve. Therefore, the valve area can be directly calculated without the use of the Gorlin formula or a derived constant by use of Doppler echocardiography to solve the simple equation \( AVA = CO/(SEP \times \text{mean velocity}) \) (figure 1). Thus, this Doppler formula is actually a simpler way of calculating the valve area than is the Gorlin formula. Our data demonstrate an excellent correlation between the aortic valve area calculated using this direct Doppler equation and that calculated with

**TABLE 3**

<table>
<thead>
<tr>
<th>Interobserver variability</th>
<th>( r ) value</th>
<th>( p ) value</th>
<th>Mean percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVET</td>
<td>.92</td>
<td>.0001</td>
<td>7.8</td>
</tr>
<tr>
<td>Mean velocity</td>
<td>.94</td>
<td>.0001</td>
<td>9.5</td>
</tr>
<tr>
<td>Aortic valve area</td>
<td>.92</td>
<td>.0001</td>
<td>12.7</td>
</tr>
</tbody>
</table>

LVET = left ventricular ejection time.
the original Gorlin equation. The two patients with the largest valve areas both had larger calculated areas by the Gorlin formula than by the Doppler equation. This may reflect the fact that the Gorlin formula will by definition overestimate the valve area as the measured pressure gradient decreases, with the obvious example of an infinite valve area if there is no measured pressure gradient across the valve.

Previous studies by Hatle et al.12 and others11, 15, 16 have found a good correlation between the peak velocity measured across the aortic valve and the measured peak-to-peak gradient at cardiac catheterization calculated with \( P = 4V^2 \). We also found a good correlation between these variables. Substituting \( 4V^2 \) for the measured pressure gradient in the Gorlin equation is a more circuitous method of calculating aortic valve area with data from Doppler ultrasound than is the direct solution of the equation \( A = CO/(SEP \times \text{mean velocity}) \). However, with the use of simultaneous thermodilution cardiac output and Doppler-derived systolic ejection period, the Gorlin equation using \( 4V^2 \) instead of a measured pressure gradient yielded a good correlation with valve area measured with the original Gorlin equation (figure 3). A formula identical to that with which the data shown in figure 3 were calculated has been reported previously in a series of pediatric patients, most of whom had pulmonic valve stenosis.13

The fact that the substituted Gorlin equation using \( 4V^2 \) and the direct solution of the Doppler-derived equation described in this report give similar results is not surprising. The numerator is the same in both circumstances and the denominators both contain the systolic ejection period. The differences are that the simpler Doppler equation uses the mean velocity across the valve while the substituted Gorlin equation uses the maximal velocity. Because the factor of 4 is within the square root function, two times the Gorlin constant of 44.5 divided by 100 (derived from conversion of meters to centimeters) gives a ratio of 0.89 in the denominator. In our study the mean velocity averaged 70% of the maximal velocity, although the ratio ranged from 51% to 80%. Thus, the two equations are numerically very similar, although conceptually quite different.

Several potential problems remain regarding the use of Doppler ultrasound to quantitate aortic stenosis. Foremost is the possible inability to obtain adequate Doppler recordings of the high-velocity aortic jet. In our adult population, this problem did not occur in any patient in which the window at either the apex or suprasternal notch yielded a good tracing. It should be noted, however, that the Doppler ultrasound studies must be done slowly and carefully; often up to 30 min is necessary for the velocity recording alone. In addition, obesity or concomitant lung disease can make adequate tracings unobtainable in some patients. An inadequate Doppler tracing would lead to an underestimation of the maximal velocity, and therefore an overestimation of the valve area. Theoretically it would not be possible to underestimate the valve area, because a jet of falsely high velocity should not be obtainable. Patients with coexistent aortic insufficiency were not studied so that its effect on the calculation of aortic valve area by the Doppler equation remains to be defined. As with the Gorlin equation, it is likely that the new method will overestimate the severity of the stenosis in the presence of aortic regurgitation.

Our data demonstrate that the Doppler ultrasound technique can be used to directly calculate the aortic valve area by the simple equation \( AVA = CO/(SEP \times \text{mean velocity}) \), thereby obviating the need for the expense and risk of left heart catheterization. Interobserver variability was minimal and in no patient was the difference in calculated aortic valve area between observers more than 0.3 cm². Right heart catheterization and thermodilution cardiac outputs were used in our study so that only the validity of the new equation using Doppler-determined velocity would be tested. Previous work in our17, 18 and other19 laboratories suggest that cardiac output can be calculated as \( CO = \pi (D/2)^2 \times \text{mean vel}_{\text{pulm}} \times SEP_{\text{pulm}} \), where D is the pulmonary arterial diameter measured by two-dimensional echocardiography, mean vel\(_{\text{pulm}}\) is the Doppler-derived mean velocity across the pulmonic valve, and SEP\(_{\text{pulm}}\) the systolic ejection period. Substituting this formula for cardiac output in the Doppler equation yields

\[
AVA = \pi \left( \frac{D}{2} \right)^2 \times SEP_{\text{pulm}} \times \text{mean vel}_{\text{pulm}} \\
SEP_{\text{aortic}} \times \text{mean vel}_{\text{aortic}}
\]

An obvious extension of the current study would be to determine if this completely noninvasive method for measurement of aortic valve area is technically feasible and acceptably accurate.

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References

DIAGNOSTIC METHODS—VALVULAR HEART DISEASE


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