Value and limitations of Doppler echocardiography in the quantification of stenotic mitral valve area: comparison of the pressure half-time and the continuity equation methods

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ABSTRACT Two Doppler methods, the pressure half-time method proposed by Hatle and the method based on the equation of continuity, were used to estimate stenotic mitral valve area noninvasively, and the accuracy of these methods was examined in patients with and without associated aortic regurgitation. Mitral valve area determined at catheterization by the Gorlin formula was used as a standard of reference. The study population consisted of 41 patients with mitral stenosis, and 20 of the 41 patients had associated aortic regurgitation. According to the equation of continuity, mitral valve area was determined as a product of aortic or pulmonic annular cross-sectional area and the ratio of time velocity integral of aortic or pulmonic flow to that of the mitral stenotic jet. Mitral valve area was determined by the pressure half-time method as 220/pressure half-time, the time from the peak transmitral velocity to one-half the square root of the peak velocity on the continuous-wave Doppler-determined transmitral flow velocity pattern. The pressure half-time method tended to overestimate catheterization measurements, and the correlation coefficient for this relation was .69 (SEE = 0.44 cm²). The correlation coefficient improved to .90 when the patients with associated aortic regurgitation were excluded. Mitral valve areas determined by the continuity equation method correlated well with catheterization measurements at a correlation coefficient of .91 (SEE = 0.24 cm²), irrespective of the presence of aortic regurgitation. The ratio of the time-velocity integral of aortic or pulmonic flow to the time-velocity integral of mitral stenotic jet also correlated well with mitral valve area determined by catheterization at a correlation coefficient of .84 (SEE = 0.10). Thus we conclude that the pressure half-time method produces a significant overestimation of mitral valve area in patients with associated moderate-to-severe aortic regurgitation and that in such cases the continuity equation method should be used to quantify mitral valve area noninvasively. The simplified continuity equation method also provides an accurate estimate of mitral valve area with few limitations.


THE SEVERITY of mitral stenosis is assessed by measuring the transmural pressure gradient and/or the stenotic mitral valve area.1 The transmural pressure gradient can be estimated noninvasively by measuring transmitral flow velocity with continuous-wave Doppler echocardiography and by applying the simplified Bernoulli equation.2–4 However, recent investigations5,6 have demonstrated that the pressure gradient across the stenotic valve is subject to hemodynamic changes. On the other hand, stenotic valve area remains constant in various hemodynamic conditions.5, 6 Thus the stenotic valve area seems more useful than the pressure gradient across the stenotic valve in assessing the severity of valve stenosis.

Two-dimensional echocardiography provides an accurate and noninvasive measurement of mitral valve area7–9 and is currently the most widely used method for noninvasive estimation of mitral valve area. However, mitral valve area may not be estimated accurately by two-dimensional echocardiography in patients with extensively distorted and/or thickened mitral valves, especially after commissurotomy.9,10 Hatle et al.11 showed a new method for estimating stenotic mitral valve area based on Doppler echocardiographic measurements of transmitral flow velocity. This method employed measurements of the time interval between
the peak of the Doppler-estimated transmitial pressure gradient and one-half of the peak pressure gradient (pressure half-time method). Because it provides a physiologic or functional valve area, this method can be applied even in patients with extensively distorted and/or thickened mitral valves as well as after commissurotomy. More recently, several studies have demonstrated that the stenotic valve area can be estimated noninvasively with Doppler echocardiography by use of the equation of continuity. When there is a constant flow in a flow channel with the stenosis, a flow volume at the stenotic portion equals that at the nonstenotic portion, according to the equation of continuity as follows:

\[ A \times V = A' \times V' \]

where \( A \) and \( V \) represent the cross-sectional area and the mean velocity at the nonstenotic portion, respectively, and \( A' \) and \( V' \) represent the cross-sectional area and the mean velocity at the stenotic portion, respectively. This equation is valid not only in the constant flow channel but also in the pulsatile flow channel like the heart if the time for observations is one cardiac cycle. The equation of continuity would be used to estimate the aortic valve area as well as the mitral valve area.

In this study, we estimated mitral valve area noninvasively with Doppler echocardiography by use of the equation of continuity and compared the accuracy of this method with that of the Doppler pressure half-time method. Thus the objective of this study was to determine the relative accuracy of these two methods by using measurements obtained from cardiac catheterization as the gold standard.

Methods

Patients. The study population consisted of 41 patients with mitral stenosis (19 men and 22 women, ages 37 to 73 years, mean 48). All patients underwent diagnostic cardiac catheterization. The mean mitral valve area obtained by cardiac catheterization was 1.29 cm². Left ventriculography was performed in all patients, and patients with moderate or severe mitral regurgitation were excluded. Twenty patients had associated aortic regurgitation demonstrated by aortic root angiography, and 21 did not have associated aortic regurgitation. Doppler examination was performed 18 to 24 hr before cardiac catheterization in all patients.

Ultrasound examinations. The ultrasound examinations were performed with a duplex Doppler echocardiograph (Toshiba SDS-21B with SSH-40A) equipped with 2.4 MHz and 3.5 MHz phased-array transducers. Two-dimensional echocardiographic images and pulsed Doppler-determined flow velocity patterns were obtained with the same transducer array. Doppler measurements could be performed either in the pulsed Doppler mode or in the continuous-wave Doppler mode. In the pulsed Doppler mode, any cursor line could be interrogated for Doppler sampling, and the ultrasound beam direction and the sample volume were monitored as a bright line and a spot on the line in the two-dimensional echocardiographic image. The sample volume was a cylinder with a diameter of 5 mm and a length of 2 mm at a depth of 10 cm, and the pulse repetition rate was 4 or 6 kHz. In the continuous-wave Doppler mode, the beam direction of the transmitted ultrasound was fixed and displayed as a bright dotted line in the two-dimensional echocardiographic image. The beam direction of the received ultrasound was movable and displayed as a bright solid line in the two-dimensional echocardiographic image. In continuous-wave Doppler sampling, no specific depth gate was established. Doppler signals derived from structures were minimized by a high-pass filter, and all signals were analyzed in real time by fast-Fourier transform. The Doppler flow velocity pattern and simultaneous lead II electrocardiogram were displayed on a monitor and recorded on a strip-chart recorder at a paper speed of 50 or 100 mm/sec. The directions of the Doppler beams could be verified frequently during the examination by briefly switching to the imaging mode.

Each patient was asked to rest in a left lateral decubitus position and to breathe in a relaxed way during ultrasound examination. The transducer was placed on the cardiac apex and angled medially to depict the left ventricular inflow and the left atrium in the left anterior oblique equivalent view. The continuous-wave Doppler mode was used to measure flow velocity of the mitral stenotic jet (figure 1). In this measurement, we advanced the crossing point of transmitted and received ultrasound beam lines to the level of the mitral orifice and tilted the transducer slowly until the highest Doppler frequency shifts could be obtained with the aid of the audio signals and recorded the Doppler signals of mitral stenotic jet. Then we switched the system to the pulsed Doppler mode and positioned the sample volume just at the aortic annulus at the center axis of the left ventricular outflow tract and recorded the flow velocity pattern (figure 2, A). The Doppler incident angle was determined from the midsystolic gated echocardiographic image. The diameter of the aortic annulus was determined from midsystolic two-dimensional echocardiographic images. Midsystolic inner diameter of the aortic annulus was measured as an interval between the points at which the aortic cusps originated. Aortic regurgitation was

FIGURE 1. Continuous-wave Doppler recording of mitral stenotic jet. Mitral valve area based on the pressure half-time method was determined from the following measurements: Point A represents the peak velocity in early diastole and point B represents the point along the continuous-wave Doppler-determined flow velocity pattern at which the velocity has fallen to one-half the square root of its peak velocity. C is the time between point A and point B, and this is pressure half-time (in milliseconds). Mitral valve area is then obtained by dividing 220 (empirical constant) by the pressure half-time (C).
searched by pulsed Doppler echocardiography in all patients, and Doppler measurements in the right ventricular outflow tract were added in patients with associated aortic regurgitation. The transducer was placed in the third intercostal space at the left sternal border and was angled laterally to depict the right ventricular outflow tract and main pulmonary artery. Doppler recordings of flow velocity were obtained with the Doppler beam directed as parallel as possible to the long axis of the right ventricular outflow tract and with the sample volume positioned just at the pulmonic anulus at the center axis of the right ventricular outflow tract (figure 2, B). The Doppler incident angle and the diameter of the pulmonic anulus were measured from midsystolic echocardiographic images, and the midsystolic inner diameter of the pulmonic anulus was measured as an interval between the points at which the pulmonic cusps originated.

**Calculation of mitral valve area by the pressure half-time method.** Mitral valve area was determined by the pressure half-time method proposed by Hatle et al. from the continuous-wave Doppler tracing of transmitral flow. Pressure half-time was obtained by calculating the time required for the peak velocity to fall to one-half the square root of its peak value (figure 1). Mitral valve area was then calculated by dividing an empirically derived constant, 220, by the pressure half-time (in milliseconds).

**Calculation of mitral valve area by the continuity equation method.** In mitral stenosis, a flow volume through the mitral anulus during one cardiac cycle should be equal to stroke volume, according to the equation of continuity. Thus mitral valve area can be determined as a ratio of stroke volume to transmitral flow velocity integral over one cardiac cycle as follows:

\[
\text{mitral valve area} = \frac{\text{Stroke volume}}{TVI_m}
\]

where \(TVI_m\) represents the time velocity integral of mitral stenotic jet over one cardiac cycle. Because stroke volume equals the product of the cross-sectional area of the aortic or pulmonic anulus and the time-velocity integral of aortic or pulmonic flow velocity, mitral valve area can be calculated as:

\[
\text{mitral valve area} = \frac{\text{aortic (or pulmonic) cross-sectional area} \times TVI_a \text{ (or TVI_p)}}{TVI_m}
\]

where \(TVI_a\) and \(TVI_p\) represent the time-velocity integrals of the flow at the aortic and pulmonic anuli, respectively. Aortic (pulmonic) cross-sectional area was calculated from the midsystolic diameter of the aortic (pulmonic) anulus on two-dimensional echocardiographic images. Aortic and pulmonic flow velocity was corrected for the incident angle in seven of 21 patients and eight of 20 patients, respectively, because the angle was greater than 20 degrees in these patients. \(TVI_a\) (or \(TVI_p\)) was determined as an area under the envelope of the modal spatial Doppler frequency pattern measured by planimetry. Flow velocity of the mitral jet was not corrected for the angle, and \(TVI_m\) was determined by planimetry. When aortic regurgitation was associated with mitral stenosis, mitral valve area was determined as a product of pulmonic cross-sectional area and \(TVI_p/TVI_m\), and when aortic regurgitation was not associated with mitral

**FIGURE 2.** Measurements of the flow velocity and diameter in the left (A) and right (B) ventricular outflow tracts. The diameters of the aortic anulus and the pulmonic anulus are measured from the frozen midsystolic two-dimensional echocardiographic images. LA = left atrium; LV = left ventricle; AO = aorta; RV = right ventricle; PA = pulmonary artery.
stensosis, mitral valve area was determined as a product of aortic cross-sectional area and TVIa/TVIm.

The ratio of TVIa or TVIp to TVIm was devised as a simplified continuity equation method. Only when aortic regurgitation was associated with mitral stenosis was TVIp/TVIm used for the analysis.

Cardiac catheterization. All patients underwent left and right heart catheterization for determination of mitral valve area. Mitral valve area was calculated with the use of the Gorlin formula\(^1\) from cardiac output and the transmural pressure gradient. Cardiac output was determined by the dye dilution method and the transmural pressure gradient was calculated by planimetric determination of left ventricular and pulmonary capillary wedge pressures, which were simultaneously recorded at a paper speed of 100 mm/sec with a standard fluid-filled manometer system. Aortic root and left ventricular angiograms were obtained in all patients to determine the severity of regurgitation. The severity of aortic regurgitation was arbitrarily graded as follows: mild (12 patients), minimal dye in the upper part of the left ventricle and clearing in the next systole; moderate to severe (eight patients), dye in the left ventricle not clearing in the next systole, with progressive or rapid opacification of the left ventricle. The severity of mitral regurgitation was also determined angiographically, and only patients without regurgitation and those with mild regurgitation in whom minimal dye in the left atrium clearing in the next diastole were included in this study.

Reproducibility of Doppler measurements. To test the reliability of Doppler measurements, we randomly selected 10 patients and determined mitral valve area based on the pressure half-time method and the continuity equation method by one observer on two occasions (intraobserver variability). Another observer independently performed the determination for the same 10 patients (interobserver variability). The observers were blinded to each other’s results as well as to the results of cardiac catheterization. The means and standard deviations of differences between observations were 0.02 ± 0.14 cm\(^2\) (intraobserver) and −0.06 ± 0.16 cm\(^2\) (interobserver) for mitral valve areas determined by the pressure half-time method, and 0.02 ± 0.15 cm\(^2\) (intraobserver) and −0.05 ± 0.13 cm\(^2\) (interobserver) for those determined by the continuity equation method.

Statistical analysis. All values were expressed as mean ± SD. Simple linear regression analysis was used for comparisons of catheterization and ultrasound methods. The significance of differences among groups was assessed with analysis of variance and a multiple comparison method. The significance of differences between paired measurements was assessed with Student’s paired t test.

Results

Comparison of catheterization and the pressure half-time method. Mitral valve area determined by the pressure half-time method correlated well with catheterization measurements at a correlation coefficient of .69 (p < .01, y = 0.67x + 0.49, n = 41, SEE = 0.44 cm\(^2\); figure 3). When patients with associated aortic regurgitation were excluded, the correlation coefficient improved to .90 (p < .01, y = 0.73x + 0.26, n =...
21, SEE = 0.28 cm²). On the other hand, when only the patients with associated aortic regurgitation were considered, the correlation coefficient was .39 (NS, y = 0.54x + 0.80, n = 20, SEE = 0.52 cm²). To examine the effects of the severity of aortic regurgitation on the inaccuracies of the pressure half-time method, the difference between catheterization-determined mitral valve area and that determined by the pressure half-time method was compared with the severity of aortic regurgitation (figure 4). The pressure half-time method had a tendency toward overestimation of the true mitral valve areas in patients with associated aortic regurgitation. The degree of the overestimation was related to the severity of aortic regurgitation, although there were wide overlaps between patients without aortic regurgitation and patients with mild aortic regurgitation and between patients with mild aortic regurgitation and patients with moderate-to-severe aortic regurgitation.

Comparison of catheterization with the continuity equation method and the simplified continuity equation method. Mitral valve areas determined by the continuity equation method were compared with catheterization measurements (figure 5). Mitral valve area, determined as a product of aortic annular cross-sectional area and TVIa/TVIm, correlated well with catheterization measurements at a correlation coefficient of .93 (p < .01, y = 0.85x + 0.06, n = 21, SEE = 0.26 cm²). Mitral valve area, determined as a product of pulmonic cross-sectional area and TVIp/TVIm, also correlated well with catheterization measurements at a correlation of .84 (p < .01, y = 0.84x + 0.21, n = 20, SEE = 0.22 cm²), and the overall correlation coefficient was .91 (p < .01, y = 0.84x + 0.15, n = 41, SEE = 0.24 cm²). Mitral valve areas were calculated by the continuity equation method based on both aortic and pulmonic measurements in 10 patients without aortic regurgitation, and they were compared with each other. There were no significant differences between them (aortic vs pulmonic, 1.4 ± 0.5 cm² vs 1.3 ± 0.4 cm², NS).

As a simplified method, TVIa(TVIp)/TVIm was compared with mitral valve areas determined by cardiac catheterization (figure 6). TVIa(TVIp)/TVIm correlated well with mitral valve area determined by catheterization and the correlation coefficient was .84 (p < .01, y = 0.24x + 0.06, n = 41, SEE = 0.10). The correlation coefficient between TVIa/TVIm and mitral valve area determined by catheterization was .88 (p < .01, y = 0.26x + 0.04, n = 21, SEE = 0.11). On the other hand, the correlation coefficient for the relation of TVIp/TVIm and mitral valve area determined by catheterization was .63 (p < .01, y = 0.15x + 0.16, n = 20, SEE = 0.07).

**Discussion**

In this study, we compared the accuracy of two Doppler echocardiographic methods for determining mitral valve area, the pressure half-time method and the continuity equation method, by using catheterization based on the Gorlin formula as a gold standard and found that the continuity equation method is more accurate, especially in patients with associated aortic regurgitation. We further devised a simplified conti-
nuity equation method, the ratio of the time-velocity integral of flow at the aortic or pulmonic annulus to that of the mitral stenotic jet, and found that the simplified method can be also used for noninvasive quantification of mitral valve area with few limitations.

The pressure half-time method. The pressure half-time method, proposed by Hatle et al. 11 is now used in the clinical situation as a relatively popular Doppler method to estimate mitral valve area noninvasively. Recently, preliminary reports20, 21 indicated a possible limitation of this method. In cases of mitral stenosis associated with severe aortic regurgitation, the pressure half-time method is likely to overestimate the true mitral valve area. In this study, the relation between mitral valve areas determined by catheterization and the pressure half-time method was not good enough to estimate mitral valve area with this method. However, when patients with aortic regurgitation were excluded, the correlation coefficient and SEE improved from .69, SEE = 0.44 cm², to .90, SEE = 0.28 cm², respectively; thus, the poor correlation may be due to the inclusion of 20 patients with associated aortic regurgitation. Moreover, the degree of inaccuracy seemed to be related to the severity of aortic regurgitation. Although mild aortic regurgitation produced no significant inaccuracies of mitral valve area determined by the pressure half-time method, moderate-to-severe aortic regurgitation produced significant overestimation of mitral valve area. The effect of aortic regurgitation on pressure half-time may be explained by a steep elevation of left ventricular diastolic pressure and hence a steep reduction in transmural pressure gradient.

Similarly, under conditions of noncompliant left ventricle such as ischemic heart disease and cardiomyopathy, the pressure half-time method might produce overestimation. In this study, we observed one such case associated with mild aortic regurgitation, coronary heart disease, and elevated left ventricular end-diastolic pressure. Thus inaccuracies of the pressure half-time method seemed to be regulated by multiple factors such as severity of aortic regurgitation and compliance of the left ventricle; therefore we could not predict the degree of inaccuracies only from the degree of aortic regurgitation. Another possible explanation is that the aortic regurgitant jet might interfere with the mitral stenotic jet and provide an overestimation of mitral valve area. Mitral stenosis is often associated with aortic valvular disease; thus this limitation should be taken into account in the noninvasive quantification of mitral valve area with the pressure half-time method, although mild aortic regurgitation might not produce significant errors in its clinical use.

Unfortunately, cardiac catheterization and Doppler studies were not performed simultaneously in this study. Transvalvular flow could change substantially with alterations in cardiac output. This may explain in part a wider scatter of individual points in the relation of mitral valve area determined by the pressure half-time method and catheterization measurements.

The continuity equation method. The equation of continuity is the law of conservation of mass in hydrodynamics. This equation is valid not only in the constant flow channel but in the pulsatile flow channel like the heart, provided that flow volume during one cardiac cycle was considered. Several studies12–15 have demonstrated that aortic valve area could be determined accurately by Doppler echocardiography based on the equation of continuity, which showed the validity of the equation of continuity applied to the heart. This method might also be applicable to mitral stenosis.16 We applied this method to quantify the mitral valve area and found that this method is quite accurate in determining mitral valve area, irrespective of the presence of aortic regurgitation.

This method, however, also has several theoretical and practical limitations. First, it is slightly complicated compared with the pressure half-time method. Second, in some cases it is somewhat difficult to obtain a clear echocardiographic image of the pulmonary artery22, 23; however, the pulmonic orifice could be more clearly imaged with two-dimensional echocardiography. In this study, we referred to additional real-time echocardiographic images to locate the conjunctive portion of the pulmonic cusps to the orifice because moving anatomic structures are more easily recognized on real-time than on stop-frame images.23 Furthermore, we examined the patients in a left lateral decubitus position to reduce the covering effect of the left lung and searched for another echocardiographic window to depict the pulmonic annulus more axially. To determine the reliability of our measurements of pulmonic annular diameter, we randomly selected 10 patients and measured pulmonic annular diameter in the same patient by one observer on two occasions (intraobserver variability). Another observer independently performed the determination for the same 10 patients (interobserver variability). The means and standard deviations of differences between observations were 0.2 ± 1.2 mm (intraobserver) and −0.5 ± 1.4 mm (interobserver). Thus pulmonic annular diameter seemed to be measured with few errors by two-dimensional echocardiography.

The last limitation is that this method should underestimate the mitral valve area in patients with associ-
ated mitral regurgitation. This is a most important limitation, since mitral regurgitation produces augmentation of the Doppler measurement of TVIm. This limitation, however, would be overcome by performing additional Doppler echocardiographic examinations, because the presence and the severity of mitral regurgitation can be evaluated by pulsed Doppler echocardiography.24, 25

The simplified continuity equation method. Mitral valve area by the continuity equation method was determined as a product of aortic or pulmonic annular cross-sectional area and the ratio of TVIa or TVIp to TVIm. If aortic or pulmonic annular cross-sectional areas were similar among individuals, mitral valve areas would be directly proportional to the ratio of TVIa or TVIp to TVIm. Thus we devised the simplified continuity equation method by using the TVIa (TVIp)/TVIm ratio as a Doppler parameter and compared this parameter with mitral valve area determined by catheterization. The correlation coefficient for the relation between TVIa/TVIm and mitral valve area determined by catheterization was .88. This finding indicates that interindividual variability of aortic annular cross-sectional area was so small that we can use the simplified parameter as an estimate of mitral valve area. On the other hand, TVIp/TVIm correlated with mitral valve area determined by catheterization at a correlation coefficient of .63, although the SEE was small. Interindividual variability of pulmonic annular cross-sectional area might be larger than that of aortic annular cross-sectional area. In patients with pulmonary hypertension, which is a common complication of mitral stenosis, pulmonic root diameter often enlarges, and this may explain the relatively large interindividual variability of pulmonic annular diameter. Thus we conclude that mitral valve area can be estimated by the simplified continuity equation method and that when measurements are done in the pulmonic anulus, effects of annular diameter should be taken into consideration.

Clinical implications. In the present study we described the values and limitations of two Doppler echocardiographic methods for quantifying mitral valve area, the pressure half-time method and the continuity equation method. The continuity equation method provides an alternative by which we can check the accuracy of two-dimensional echocardiography and the pressure half-time method in patients on which all three can be performed. In this study, both Doppler measurements were compared with two-dimensional echocardiographic results in 15 patients without distorted mitral valves. There were good correlations between them (r = .71, SEE = 0.44 cm² for the pressure half-time method; r = .85, SEE = 0.24 cm² for the continuity equation method).

The overall superiority in accuracy was found in the continuity equation method compared with the pressure half-time method. The simplified continuity equation method also seemed to be clinically useful. However, every method has different disadvantages and/or limitations. In patients with associated aortic regurgitation, the pressure half-time method can produce a significant error. On the other hand, in patients with associated mitral regurgitation, the continuity equation method can produce a significant underestimation. Thus the values and limitations of each method should be considered when one or both methods is used for the noninvasive quantification of mitral valve area.

Conclusions. Mitral valve area determined by the continuity equation method correlated with that determined by catheterization as well as or even better than that determined by the pressure half-time method. The continuity equation method might be more complicated for clinical use but was more accurate, especially in patients with associated moderate-to-severe aortic regurgitation. Mitral valve area can be also estimated accurately with the simplified continuity equation method, although special care should be taken in patients with a dilated pulmonic anulus.

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