Mitral valve area by the pressure half-time method does not correlate with mean gradient in mitral valve repair patients†

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Received 23 August 2010; accepted after revision 5 October 2010; online publish-ahead-of-print 1 November 2010

Aims
Pressure half-time is an inaccurate measure of mitral valve area in many clinical situations. The utility of the pressure half-time method to calculate mitral valve area after mitral valve repair is not well defined.

Methods and results
Forty-two patients with a repaired mitral valve were identified. Mitral valve area was calculated by both the pressure half-time method and the continuity equation. The two mitral valve areas were then directly compared and also correlated with mean gradient. The two mitral valve areas were significantly different from one another with a mean of 1.81 ± 0.53 cm² by continuity equation and 2.65 ± 0.69 cm² by pressure half-time. The continuity equation correlated well with mean gradient (r = 0.63), whereas the correlation for pressure half-time was weak (r = 0.08).

Conclusion
A non-linear, inverse correlation was found between mitral valve area by the continuity equation and mean gradient. No correlation was found between the pressure half-time method for mitral valve area and mean gradient. The continuity equation likely provides a better estimate of mitral valve area in repaired mitral valves.

Keywords
Mitral valve area; Mitral valve repair • Pressure half-time • Continuity equation

Introduction
Mitral valve repair is the recommended procedure for patients with chronic, severe mitral insufficiency.1,2 Doppler echocardiography is the primary tool utilized to assess the repaired mitral valve, as it allows the clinician to evaluate for residual insufficiency, iatrogenic obstruction, and systolic anterior motion of the anterior mitral leaflet.1,3,4 As in native mitral stenosis or the assessment of a prosthetic mitral valve, the degree of obstruction after mitral valve repair can be evaluated by the standard parameters of mean gradient, pressure half-time, and mitral valve area.

The assessment of mitral valve area can be done by various techniques, including the continuity equation and the pressure half-time method. The pressure half-time method is simple; measuring the time it takes for the atrioventricular pressure gradient to fall by one-half of its initial value during ventricular diastole.5 It can easily be obtained either invasively or with Doppler ultrasound.5,6

The pressure half-time method has been found to have serious limitations in certain populations, including prosthetic mitral valves, mitral commissurotomy, tachycardia, arrhythmias, and aortic insufficiency.7–11 In normally functioning prosthetic mitral valves, the pressure half-time method has been shown to correlate more closely with ventricular compliance and heart rate than mitral valve area.12 Despite these recognized limitations, there is little data available regarding the validity of applying the pressure half-time method for calculating mitral valve area after mitral valve repair.13–15

The purpose of this study is to compare the pressure half-time method with the continuity equation and determine which method correlates more closely with mean transmural gradient.

†Presented at the 21st Annual Scientific Sessions of the American Society of Echocardiography, 15 June 2010, San Diego, CA, USA; the 12th Annual University of Minnesota Medical Department Research Day, 10 May 2010, Minneapolis, MN, USA.

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Methods

The institutional review board granted approval for a retrospective chart review of mitral valve repair patients having a post-operative echocardiogram performed during the period of 1 January 2006 through 30 June 2010. All patients’ primary indication for mitral valve repair was mitral insufficiency. The mechanism of each patient’s mitral insufficiency was determined according to the Carpentier classification. Patients were excluded if their operative note was unavailable or if they had more than mild mitral or aortic regurgitation noted on their post-operative echocardiogram. The study protocol allowed the echocardiogram to occur anytime in the post-operative period, provided that the repair was still competent. The study group consists of 42 patients without any exclusion criteria.

Collected data included: age, pressure half-time, mitral valve area calculated by the continuity equation and the pressure half-time method, mean transmitral gradient, heart rate, heart rhythm, stroke volume index, ejection fraction, and repair procedure. Echocardiographic measurements were obtained from review of the echocardiography report. Absent Doppler echocardiographic measurements were obtained by analysis of the digital images by a single cardiac sonographer (C.M.H.). The average of three to five cardiac cycles was reported when patients were in atrial fibrillation, whereas a single representative cardiac cycle was utilized for those in sinus rhythm.

The pressure half-time was measured as the deceleration slope from the peak E-wave velocity down to where the slope intercepted with the baseline. Mitral valve area by the pressure half-time method was calculated as follows: (Figure 1)

\[
\text{Mitral valve area = 220/p} \text{ressure half-time}
\]

Mitral valve area by the continuity equation was calculated as follows:

\[
\text{Mitral valve area} = \left( \frac{\text{left ventricular outflow tract (LVOT) radius}^2 \times \pi}{\text{LVOT velocity time integral (VTI)/Mitral valve VTI}} \right)
\]

Mean transmitral gradient was obtained by tracing the transmitral inflow pattern and applying the simplified Bernoulli equation. All left ventricular ejection fractions were visually assessed.

Echocardiograms were performed using a Philips IE33, a Sonos 7500 (Philips Medical Systems, Bothell, WA, USA) or an Acuson Sequoia (Acuson-Siemens Medical, Mountain View, CA, USA).

Statistics

Continuous variables are expressed as mean ± standard deviation, with the remaining data shown as a percentage. Comparisons are performed with an unpaired t-test and a value of <0.05 is considered to indicate a significant finding. Pearson’s correlation coefficient and Spearman’s Rank correlation coefficient were utilized to evaluate the strength and significance of the relationship between two variables. The Doppler measures used to calculate both mitral valve areas were re-evaluated in a subset of 25% of the patients to determine the inter and intra-observer reliability by calculating the interclass

![Figure 1](https://academic.oup.com/ehjcimaging/article-abstract/12/2/124/2396951/125)

Figure 1 Mitral valve area by the pressure half-time method. Continuous wave Doppler of the mitral inflow pattern, with the measurement of pressure half-time indicated by the red line of the mitral E-wave deceleration slope.
correlation coefficient. Statistical analyses were conducted using STATA 10.0 software (STATA statistics/Data analysis, TX, USA).

Results

Patient characteristics are provided in Table 1. All 42 patients had an annuloplasty product implanted to repair or support the repair procedure. In the majority of the patients (27), mitral insufficiency was due to a Carpentier type II mechanism, excessive leaflet mobility consistent with a flail or prolapse leaflet or segment. A full annuloplasty ring was used for 16 of these patients with the remaining 11 receiving an annuloplasty band or partial ring. A triangular resection of the P2 mitral segment was performed in 17 of the patients, whereas a quadrangular resection of P2 was performed in 8 patients. The other two type II patients had anterior leaflet pathology repaired with chordal replacement. Additional repairs included seven chordal shortening or replacement procedures, three P3 repairs, two commissural plications, and two sliding plasties.

Eleven patients had type I aetiology mitral insufficiency with 10 having an annular dilatation, and one having a mitral cleft. A full ring was used for six patients and a band or partial ring was used for the remaining five patients, with the cleft being repaired as well.

Four patients had a type III aetiology with one having a type Ilia aetiology (rheumatic valve disease) and three having a type IIIb aetiology (ischaemic). The individual with a type Ilia aetiology had a comissurotomy and annuloplasty band placed, whereas all three of the type IIIb patients had a full ring placed.

The mean age at the time of echocardiography for the 42 patients was 62 ± 12 years. Six (14%) of the patients were in atrial fibrillation at the time of their echocardiogram. The mean transmitral gradient was 4.6 ± 2.9 mmHg. The two mitral valve areas were significantly different from one another (P-value of < 0.0001), with a mean of 2.65 ± 0.69 cm² for pressure half-time and 1.81 ± 0.53 cm² for the continuity equation. The two mitral valve areas did not correlate well with one another with a Pearson correlation of r = 0.10 (Figure 2). Mitral valve area by pressure half-time had a range of 1.6–4.5 cm², whereas mitral valve area by the continuity equation had a range of 1.0–3.6 cm².

The scatter plot for the mean gradient and mitral valve area by the continuity equation suggests a non-linear relationship (Figure 3A). This is corroborated by the Spearman Rank correlation (ρ = −0.63), which supports the observed non-linear relationship. Mean gradient and mitral valve area by pressure half-time were found to have no correlation (Figure 3B), as assessed by both Pearson’s Correlation (r = −0.08) and Spearman Rank Correlation (ρ = −0.04).

The 11 patients with a type I aetiology had a post-operative mean gradient of 6.4 ± 4.7 mmHg, a mean mitral valve area by the continuity equation of 1.53 ± 0.51 cm², and a mitral valve area by pressure half-time of 2.65 ± 0.86 cm². The 27 patients with a type II aetiology had a post-operative mean gradient of 3.7 ± 1.3 mmHg, a mean mitral valve area by the continuity equation of 1.93 ± 0.5 cm², and a mitral valve area by pressure half-time of 2.62 ± 0.61 cm². The difference between both mitral valve area by the continuity equation (P-value = 0.0325) and mean gradient (P-value = 0.0085) did reach statistical significance, whereas the difference between mitral valve area by pressure half-time was statistically insignificant. A comparison of annuloplasty product size (annuloplasty products are typically labelled according to their intertrigonal distance) found that patients with a type II aetiology received a significantly larger (P-value = 0.0025) annuloplasty product (30.3 ± 3.2 mm) compared with those with a type I aetiology (27 ± 1.5 mm). There was an insufficient amount of patients with a type Ilia or IIIb aetiology for any statistical comparisons.

Both heart rate (r = 0.26) and stroke volume index (r = −0.51) were found to correlate more strongly with mitral valve area by pressure half-time than mean gradient. The correlation between heart rate and mitral valve area by the continuity equation was r = 0.28, whereas the correlation between stroke volume index and mitral valve area by the continuity equation was r = −0.13.

The interclass correlation coefficient for inter and intra-observer reliabilities for mitral valve area by the continuity equation were 0.93 and 0.94, whereas those for mitral valve area by the pressure half-time method were 0.85 and 0.98, respectively.

Discussion

The calculation of mitral valve area is theoretically less dependent on flow or heart rate than mean gradient and therefore is an important parameter in the evaluation of diseased, replaced, or repaired mitral valves. 1,15 The calculations of mitral valve area by the pressure half-time method and continuity equation do not provide homogenous results after mitral valve replacement. 18 Mitral valve area by pressure half-time has been shown to be
Figure 2 Mitral valve area by continuity equation and pressure half-time. The scatter-plot comparison of mitral valve areas does not identify any pattern or relationship between the two mitral valve areas.

Figure 3 (A) Mean gradient and mitral valve area by the continuity equation. Scatter-plot supporting an exponential relationship between mitral valve area by continuity equation and mean gradient. (B) Mean gradient and mitral valve area by the pressure half-time method. Scatter-plot identifying no perceivable relationship between mitral valve area by pressure half-time and mean gradient.
inaccurate in prosthetic mitral valves, with Dumesnil et al. showing that in vivo mitral valve area by the continuity equation correlated strongly with in vitro mitral valve area, whereas in vivo mitral valve area by pressure half-time correlated weakly with in vitro mitral valve area. In mitral valve repair, there is no in vitro or ‘expected’ mitral valve area with which to correlate actual findings. We used mean gradient as a correlation parameter, since valve area is one of the most significant variables affecting the mean gradient, particularly in the setting of haemodynamically significant mitral obstruction. We found that mitral valve area by the continuity equation has a strong non-linear correlation with mean gradient, which is reflective of the known quadratic relationship between flow and pressure gradient expressed by the Bernoulli equation. Mitral valve area by the pressure half-time method was found to have no correlation with mean gradient.

Wilansky et al. published one of the few papers that evaluated the calculation of mitral valve area in mitral valve repair patients and found the two mitral valve areas, as calculated by the pressure half-time method and continuity equation, to be significantly different from one another. The exception was a subset of patients with pressure half-times ≥ 110 ms, which resulted in similar values for mitral valve area calculated by both the pressure half-time method and the continuity equation. We evaluated the subset of our patients with a pressure half-time value ≥ 110 ms and found nine patients within our study population. The mitral valve area by pressure half-time for this subset was 1.83 ± 0.2 cm² and the mitral valve area by continuity equation was 1.71 ± 0.5 cm². These two mitral valve areas were not statistically different from one another (P-value of 0.51). The mean gradient for this subset was 4.7 ± 3.9 mmHg. In addition, the Spearman Rank correlation between mitral valve area by continuity equation (ρ = −0.5) was quite similar to that found for mitral valve area by pressure half-time (ρ = −0.55) in this subset. This does suggest that mitral valve area by pressure half-time may be valid when pressure half-time is equal to or exceeds 110 ms.

The conclusion of Wilansky et al. was that, ‘the continuity equation appears to provide much more homogenous results in the calculation of valve area after surgery for mitral valve repair’, which our research corroborates. However, our study also shows a strong non-linear relationship between mitral valve area by continuity equation and mean gradient, while showing the overall poor relationship between mitral valve area by pressure half-time and mean gradient. These findings provide objective support that mitral valve area by the continuity equation is superior to mitral valve area by the pressure half-time method for accurately calculating mitral valve area after mitral valve repair. The lack of any correlation between mitral valve area by pressure half-time and mean gradient suggests that the pressure half-time method is likely inadequate for the calculation and reporting of mitral valve area after mitral valve repair. Mitral valve repair patients appear to be another subset of mitral pathology that is inadequately assessed by utilizing the pressure half-time method to calculate mitral valve area.

The inadequacy of the pressure half-time method in the present study is likely due to the pressure half-time being more closely related to variables other than valve area. Pressure half-time has been shown to be more closely related with diastolic filling time, stroke volume, and diastolic time interval than prosthetic design in a cohort of mitral valve replacements. It is likely that these observations are also applicable to repaired mitral valves. Supporting this is that both heart rate and stroke volume index correlated more strongly with mitral valve area by pressure half-time than mean transmitral gradient in our study.

The pressure half-time is also influenced by ventricular compliance. Mitral valve area by the pressure half-time has been shown to overestimate mitral valve area for patients with stiff left ventricles despite the presence of significant native mitral stenosis. Thus, the poor correlation between mitral valve area by the pressure half-time method and mean gradient in repaired mitral valves is likely the result of the pressure half-time method calculation being not specifically related to mitral valve area.

Mitral valve area and flow rate across the mitral valve are the primary determinants of the transmitral pressure gradient. Gorlin and Gorlin showed the relationship between flow and pressure gradient to be exponential, with more rapid increases in gradient as the mitral valve area decreased. Mitral valve area calculated by the continuity equation is shown to have the expected exponential relationship with mean gradient after mitral valve repair and likely provides a more accurate estimation of the actual mitral valve area.

The clinical implications of mitral valve area

Mitral valve area, calculated by the continuity equation, is an important clinical measurement after mitral valve repair, as smaller valve areas have been shown to be associated with residual pulmonary hypertension and reduced functional capacity. In that study mitral valve repair patients had a mean resting mitral valve area, calculated by the continuity equation, of 1.5 cm², a resting mean gradient of 6 mmHg and a resting pulmonary artery pressure of 42 mmHg, which suggests that these patients had moderate iatrogenic mitral stenosis. Thirteen (31%) of the 42 patients in our cohort had continuity equation mitral valve areas of 1.5 cm² or less, consistent with moderate iatrogenic mitral stenosis. The mean gradient was 7.2 ± 3.9, consistent with moderate mitral stenosis. Figure 3A shows that gradients increase exponentially with valve areas of ~1.5 cm² or less, thus supporting this as a threshold of haemodynamic significance.

The actual burden of moderate or severe iatrogenic mitral stenosis following a mitral valve repair is unknown. Thirty-one percent of the patients in our cohort had at least moderate mitral stenosis. In 60% (7 of 13) of these patients, mitral insufficiency was due to a type I or Ilib aetiology. These 13 patients were found to have received significantly smaller annuloplasty products (size = 27.5 ± 2.3; P-value of 0.01) compared with those with less than moderate mitral stenosis (size = 30 ± 3).

One operative strategy in type I or Ilib aetiologies is to place a small, restrictive ring to surgically downsize the mitral annulus, while the typical repair strategy in type II mitral insufficiency is to repair the mechanism of the regurgitation and then place a correctly sized or large annuloplasty product. Restrictive annuloplasty has been shown to be associated with moderate iatrogenic mitral stenosis. The patients with moderate to severe
iatrogenic mitral stenosis in our cohort, regardless of mitral insufficiency aetiology, were found to have received significantly smaller annuloplasty rings or bands. Two (5%) of the patients in our cohort had haemodynamic variables suggestive of severe iatrogenic stenosis. This was clinically important for both patients as they had recurrent heart failure. Both patients underwent cardiac catheterization, which corroborated the echocardiographic haemodynamics and confirmed severe mitral stenosis. The actual occurrence of severe iatrogenic mitral stenosis following a mitral valve repair is not established but it is likely uncommon. Five per cent of the patients in the present study had severe, symptomatic iatrogenic mitral stenosis.

The actual burden of iatrogenic mitral stenosis, following a mitral valve repair, is likely related to the aetiology of the mitral insufficiency, the repair strategy employed, and the size of the annuloplasty product implanted. Incorporating this information into the echocardiography report, along with mean gradient and mitral valve area by the continuity equation, will likely provide an improved understanding of the performance of a repaired mitral valve.

**Limitations**

This research is retrospective in nature and therefore all the associated limitations of retrospective research are applicable. The echocardiograms were performed by various sonographers and interpreted by various cardiologists, which likely results in an element of inter-observer variability. While flow variations, as well as heart rate, may account for the subtle differences between some mean gradient values and mitral valve area by the continuity equation; it cannot account for the lack of any relationship between mean gradient and mitral valve area by the pressure half-time method.

We did not consider the effect of mitral invariance, which may be of importance when using the simplified Bernoulli equation to estimate gradients in the setting of low flow velocities associated with a non-restrictive orifice.24 This has been shown to result in an underestimation of the actual pressure gradient between the left atria and left ventricle for individuals with non-restrictive flow, when using the simplified Bernoulli equation.24 This does not invalidate the concept of the present study though, as the observed quadratic relationship between mitral valve area by the continuity equation and mean gradient would still be present and an underestimation of mean gradients for those with non-restrictive orifices is not the reason for a lack of correlation between mitral valve area by the pressure half-time method and mean gradient.

The continuity equation for mitral valve area becomes less reliable in the presence of moderate or more mitral or aortic insufficiency by disproportionately increasing the flow and velocity time integrals through the affected valve. This will subsequently result in an overestimation of mitral valve area in aortic insufficiency and an underestimation of mitral valve area in mitral insufficiency. No patient in our cohort had more than mild mitral or aortic insufficiency but this limitation must be considered when applying the continuity equation to calculate mitral valve area.

**Conclusion**

A non-linear, inverse correlation was found between mitral valve area by the continuity equation and mean gradient, whereas essentially no correlation was found between mitral valve area by pressure half-time and mean gradient. The continuity equation likely provides a better estimate of mitral valve area in repaired mitral valves and therefore should be the preferred method for calculating mitral valve area after mitral valve repair.

**Author contribution**

C.M.H. conceptualized the study, collected, and interpreted the data and drafted the manuscript; W.B.N. reviewed, revised, and provided final approval for the manuscript; G.A.N. reviewed and revised the manuscript; I.A. provided statistical assistance and reviewed and revised the manuscript; R.D. reviewed, revised, and provided final approval for the manuscript.

**Conflict of interest**: none declared.

**Funding**

Funding was provided by the Regions Hospital section of cardiology.

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