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A simple noninvasive measurement of stenotic mitral valve area: An alternative approach using M-mode and Doppler echocardiography

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Summary

Doppler echocardiography is a widely used noninvasive technique to examine the mitral valve area (MVA) by obtaining mitral pressure half-time (PHT) and to assess the severity of the stenosis. However, several hemodynamic factors influence the PHT and may render the PHT data inaccurate in any measurement of MVA under certain conditions. Using a simple echo-Doppler (E-D) method, we assessed the MVA in a physiological equation. The mitral flow volume (MFV) is represented by MVA×transmitral mean flow velocity (mV)×diastolic filling time (DFT). Thus, the formula can be restated as MVA (cm^2)=MFV (cm^3)/mV (cm/sec)×DFT (sec). We measured MFV by M-mode, and mV and DFT by continuous wave Doppler echocardiography. This formula was tested in 43 patients with isolated mitral stenosis. MVA was obtained by the PHT and E-D methods, and the data obtained were validated against the results of cardiac catheterization. The results obtained using the E-D method showed much better correlation ($r=0.82$) with those of catheterization than those with the PHT method ($r=0.52$). The inter- and intraobserver variabilities

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were checked. The results obtained with the E-D method were found to be reproducible. To further validate the accuracy of the E-D method, MVA was measured by both methods at different R-R intervals after exercise and the results were compared. The MVA obtained by the PHT method showed marked variations; whereas, that obtained by the E-D method remained nearly constant. Similarly, in a patient with atrial fibrillation, the MVA assessed by the PHT method varied from beat to beat; whereas, the fluctuations in MVA were minimal using the E-D method.

We concluded that the E-D method can be reliable and clinically easily applicable for the accurate assessment of MVA.

Key words
Mitral valve area   Pressure half-time   Continuous wave Doppler echocardiography

Introduction

Libanoff & Rodbard[1] introduced the concept of pressure half-time (PHT) to determine the severity of mitral stenosis in patients undergoing cardiac catheterization. They reported that the time required for the diastolic left atrioventricular pressure difference to be decreased to half of its initial value varied inversely with the anatomic severity of the valvular stenosis. Hatle et al[2] clinically applied this concept. They measured PHT noninvasively using Doppler echocardiography and assessed the size of the mitral orifice by applying the simplified Bernuolli's equation. This method has been rapidly accepted for estimating the mitral valve area (MVA), both for the original and prosthetic valves. The evaluation using the PHT seems to be relatively unaffected by changes in other hemodynamic parameters, such as afterload, left ventricular filling pressure, heart rate and left atrial and ventricular compliance.

Some investigators[3,4] have demonstrated that hemodynamic changes cause variations in the pressure gradient across the stenotic valve. In most clinical situations, increasing the pressure decreases atrial and ventricular compliance. However, when anatomic shapes or physiological characteristics have independently changed either pressure or compliance, measurement of the MVA with the PHT method can be erroneous. Nakatani et al[5] have also mentioned limitations of PHT, emphasizing the usefulness of the continuity equation method for measuring the MVA.

In this report, we describe a simple echo-Doppler (E-D) method, as an alternative approach to the continuity equation, derived from a simple physiological concept governing the volume of flow of fluid from one chamber to another through an orifice to estimate MVA, together with our initial experience with its first application to clinical cardiology.

Patients and methods

Theoretical background

Using the PHT method as proposed by

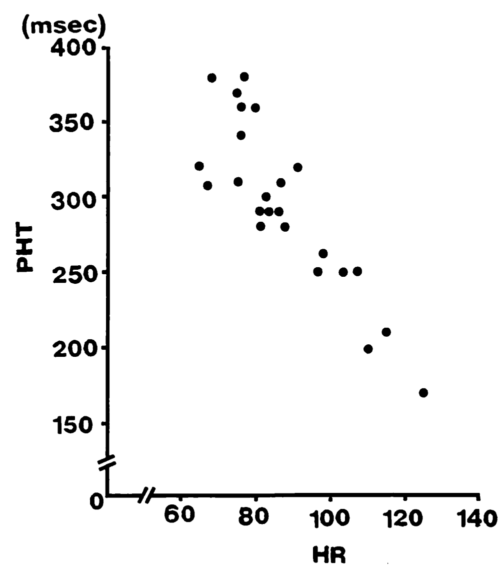

Fig. 1. Effect of exercise on pressure half-time (PHT) in a patient with mitral stenosis.
On X-axis heart rate (HR) is plotted against PHT on Y-axis. Note at different heart rates the PHT value obtained varied from 360 to 160 msec.

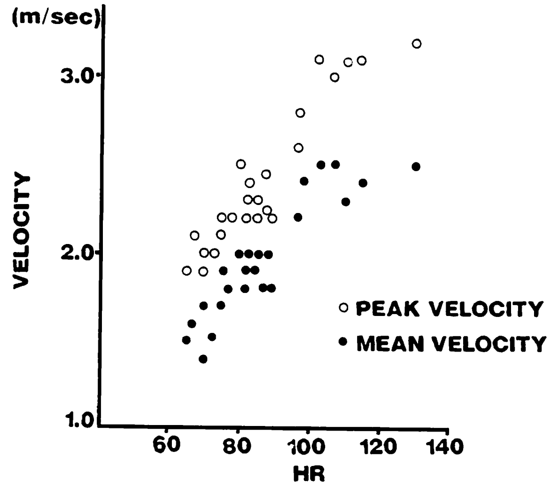

Fig. 2. Effect of exercise on the mean and peak velocities in the same patient as in Fig. 1.

Note that wide fluctuations are produced in both peak and mean velocities in the PHT.

HR=heart rate.

Hatle et al[2], we found that in a patient with mitral stenosis, changes in the heart rate during exercise produce wide fluctuations in the values of PHT which is measured with Doppler echocardiography (**Fig. 1**). Both the mean and peak flow velocities increased during exercise (**Fig. 2**), suggesting a change in the atrioventricular gradient due to an increase in the left atrial pressure following exercise. As the mitral orifice remains relatively fixed in size, especially in patients with mitral stenosis, we derived a simple formula from the physiological concept of the flow of fluid from one chamber to another, the 2 chambers being connected by an orifice (**Fig. 3**). This may be similar to the continuity equation.

Formula :

$$\text{Flow volume} = \text{area of an orifice} \times \text{velocity of flow} \times \text{time taken for that flow to occur} \quad (1)$$

On rearranging the formula,

$$\text{Area} = \frac{\text{flow volume}}{\text{velocity of flow} \times \text{time for flow}} \quad (2)$$

Thus, for the flow volume across MVA, the formula (2) can be described as,

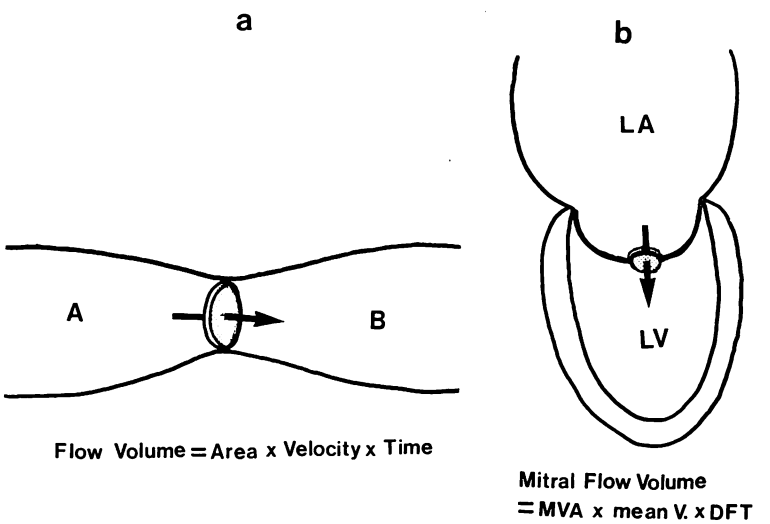

Fig. 3. Schematic representation of physiological principle governing flow of fluid from one chamber (A) **to another** (B) **via an orifice as seen in** (a), **and of the application of this principle to flow of blood from the left atrium** (LA) **to the left ventricle** (LV) **via mitral valve orifice** (b).

MVA=mitral valve area; mean V=mean velocity; DFT=diastolic filling time.

$$\text{MVA} = \frac{\text{mitral flow volume (MFV)}}{\text{mean mitral flow velocity (mV)} \times \text{diastolic filling time (DFT)}} \quad (3)$$

where, MFV (cm^3) can be obtained by Teichholz's method[6] from M-mode echocardiogram of the left ventricle, and mV (cm/sec) and DFT (sec) can be estimated by the continuous wave Doppler (CWD) tracing of the mitral inflow velocity.

Patients

The study group consisted of 43 patients with isolated mitral stenosis. There were 16 males and 27 females. Patients with significant mitral regurgitation or aortic regurgitation were excluded from the study. Their mean age was 46 years (19-65 years). All patients underwent diagnostic cardiac catheterization and left ventriculography, and 24 to 48 hours prior to cardiac catheterization Doppler examination was performed in all patients. The diagnosis of isolated mitral stenosis was confirmed and MVA was obtained.

Ultrasound examination

All patients were examined using CWD transducers with frequencies of 2.0 (Aloka) and 2.5 (Toshiba) MHz. Two commercially-available systems, Aloka SSD-870 and Toshiba SSH-65A were used. Patients were placed in the left lateral decubitus position and breathed normally during the ultrasound examination. Two-dimensional apical long- or 4-chamber views were obtained by placing the transducer on the cardiac apex. The direction of the jet through the stenotic mitral valve was determined by color Doppler echocardiography. The mitral flow velocity pattern was then recorded with patients in suspended respiration at the end of expiration, using CWD, while we listened to the high-pitched audio signals continuously.

At this time, an ideal position was also determined for obtaining the M-mode echograms in the short-axis view of the left ventricle from the parasternal area. Subsequently, the flow velocity of the mitral stenotic jet was obtained by CWD from the apical window, then the transducer was quickly repositioned in the previously determined left parasternal window to obtain the M-mode echograms of the left ventricle. For all patients an electrocardiogram and phonocardiogram were recorded simultaneously on the strip chart. The MFV was obtained using the Teichholz formula[6], an M-mode echogram obtained in the short-axis view of the left ventricle. The mV and DFT of the mitral stenotic jet were measured using CWD echograms.

Seven patients with mitral stenosis (NYHA II) were subjected to simple one-step exercise using Master's exercise equipment. The exercise was continued until the patients complained of shortness of breath or dyspnea. Then the patients were placed in a reclining position and several 5-second recordings of CWD and M-mode echograms were made in the positions described. The transducers were very quickly switched to and fro between the 2 positions and several observations were made until the heart rate returned to the control value. The protocol was repeated several times and the observations were made at different heart rates. In 3 of 7 patients, a sufficient number of recordings of M-mode and Doppler echograms were obtained to measure MVA at numerous different heart rates.

We also measured MVA in 4 patients undergoing percutaneous transvenous mitral valvuloplasty (PTMV), immediately before and after the procedure using the PHT and E-D methods, to determine the effect of acute change in the left atrial and ventricular compliance. The results were compared with the MVA obtained using Gorlin's formula[7].

Calculation of MVA by the E-D method

The MFV depends on the MVA, the mean transmitral flow velocity (mV) and the diastolic filling time (DFT). Thus, MVA can be calculated as follows:

$$\text{MVA (cm}^2) = \frac{\text{MFV (cm}^3)}{\text{mV (cm/sec)} \times \text{DFT (sec)}}$$

The mV × DFT, which is equal to the mitral flow velocity integral, was obtained by tracing the flow velocity pattern using a light pen system of the medical research system sigma 5. Three to 5 beats were averaged in patients with normal sinus rhythm. In patients with atrial fibrillation, CWD and M-mode echocardiograms were obtained and at the same R-R intervals the mV×DFT was obtained using 5 to 10 beats, with the values obtained being averaged.

Calculation of MVA by the PHT method

MVA was obtained by the PHT method as described by Hatle et al[2], from the CWD tracing of transmitral flow velocity. MVA was calculated by dividing 220 (an emperically-derived constant) by the PHT.

Cardiac catheterization

All patients underwent left and right heart catheterizations and the MVA was calculated using Gorlin's formula. Cardiac outputs were obtained by the thermodilution method.

Reproducibility of Doppler measurements

The intra- and interobserver variabilities were checked for 24 patients randomly selected for the MVA measurement by the PHT and E-D methods. The observers were blinded to each other's results and to the results of cardiac catheterization. The mean and standard deviations of the differences between the observations were $0.03 \pm 0.02\ cm^2$ (intraobserver) and $0.04 \pm 0.03\ cm^2$ (interobserver) for the MVA assessed by the PHT method, and $0.03 \pm 0.02\ cm^2$ (intraobserver) and $0.05 \pm 0.03\ cm^2$ (interobserver) for those assessed by the E-D method.

Statistical analysis

All values were expressed as means±SD. The data obtained by the ultrasound method and by cardiac catheterization were analyzed by simple linear regression analysis. The significance of the differences between paired measurements was assessed using the Student's paired t-test.

Results

Comparison of catheterization and the PHT measurements

Linear regression analysis was applied to the MVA data obtained by cardiac catheterization on the X-axis, and by the PHT method on the Y-axis (**Fig. 4**). The correlation coefficient was $r = 0.52$ and the regression equation was $Y = 0.51X + 0.39$ and $p < 0.01$.

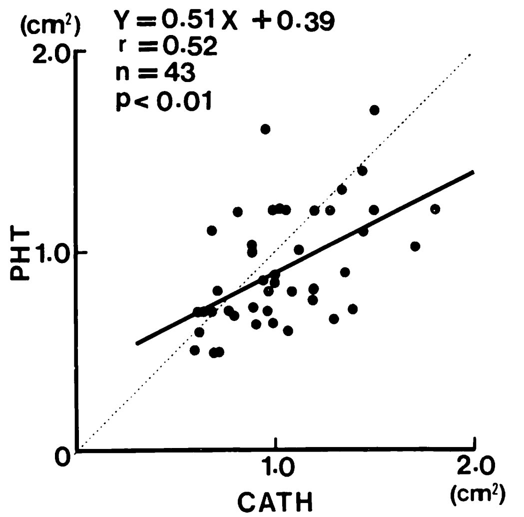

Fig. 4. Linear regression analysis of mitral valve area (MVA) based on the catheterization data (CATH) on X-axis, and that obtained by the PHT method on Y-axis.

Note that the correlation ($r = 0.52$) was not very strong with the regression fromula $Y = 0.51X + 0.39$ and $p < 0.01$. The solid line indicates regression line and the dotted line indicates line of identity.

Comparison of catheterization and E-D measurements

The MVA data obtained by the E-D method (on the Y-axis) were statistically analyzed and validated against the data obtained by catheterization (on the X-axis) using the linear regression analysis. Good correlations ($r = 0.82$) and regression equation ($Y = 0.78X + 0.24$ with $p < 0.01$) were obtained (**Fig. 5**).

We also compared between the MVAs obtained by the PHT method and those obtained by E-D method in 3 patients after exercise. In the remaining 4 patients who had exercised, the number of recordings of the M-mode and Doppler echocardiograms after exercise was not obtained. **Fig. 6** shows how measurements of MVA by the PHT method yielded varying results with the increase in the heart rate in the same patient. When the heart rate was 60–70 beats per min, the MVA was assessed as 0.6–0.7 cm^2.

In one patient, however, when the heart rate

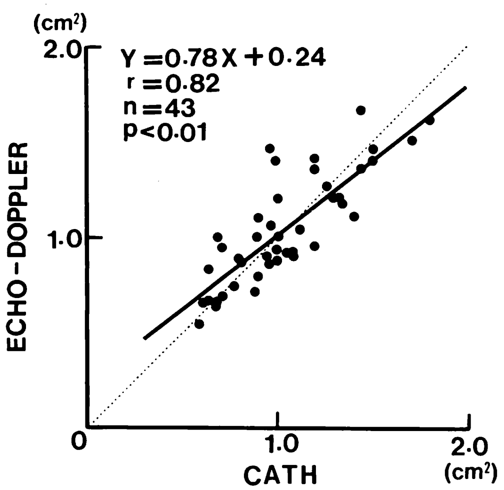

Fig. 5. Linear regression analysis of mitral valve area (MVA) obtained from the catheterization data (CATH) on X-axis, and that obtained by the E-D method on Y-axis.

Note that a very good correlation ($r=0.82$) was obtained with the regression formula $Y=0.78X+0.24$ and $p<0.01$. The solid line indicates the regressipn formula and the dashed line indicates the line of identity.

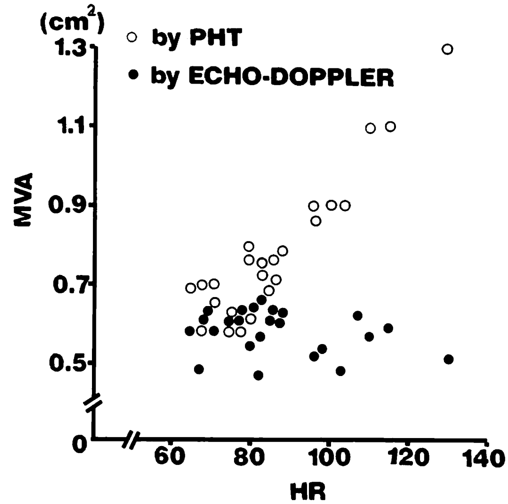

Fig. 6. Effect of exercise on mitral valve area (MVA) in a patient with mitral stenosis.

The open circles indicate MVA obtained at different heart rates by the pressure half-time method (PHT), while the closed circles indicate MVA obtained by the E-D method. Note how the MVA varied from 0.58 to 1.3 cm² by the PHT method, however, with the E-D method it only varied from 0.47 to 0.65 cm².

was increased up to 120 beats per min, the MVA value doubled. In this patient, MVA as assessed by the E-D method did not fluctuate as widely. By examining his mitral flow velocity (**Fig. 7**), one can observe that in the control study, his initial maximum velocity and mean velocity were 1.8 m/sec and 1.4 m/sec, respectively, and that the PHT measured was 328 msec. After exercise his initial maximum velocity and mV increased significantly (3.1 m/sec and 2.2 m/sec, respectively), and PHT decreased to 197 msec. This explains why MVA as obtained with the PHT method fluctuated widely yielding erroneous results. Similar results were obtained in other 2 patients after exercise.

Even though the samples of PTMV from our patients were small, the results indicate that probably an acute change in compliance provides accurate estimates (**Fig. 8**).

Figs. 9A, B show changes in the MVA as measured by the PHT and E-D methods at 34 consecutive R-R intervals in a patient with atrial fibrillation. The MVA obtained by the PHT method fluctuated widely (0.4 to 1.22 cm²), changing the assessment of stenosis from severe to moderate with changes in the R-R intervals. The MVA as obtained by the E-D method with the same 34 consecutive beats fluctuated less (0.68 to 1.0 cm²). The mean MVA value by the PHT method was 0.62 ± 0.21 cm²; whereas, with the E-D method it was 0.86 ± 0.10 cm². The MVA calculated from the catheterization data was 0.78 cm², which was close to the value obtained with the E-D method. With changes in the R-R intervals, the MVA measured by the E-D method changed minimally, but that measured by the PHT method changed from beat to beat, wherein with progressive increases in heart rate, the value of PHT decreased.

Discussion

Several methods have been described for the assessment of the severity of mitral stenosis, including Gorlin's equation, planimetric meas-

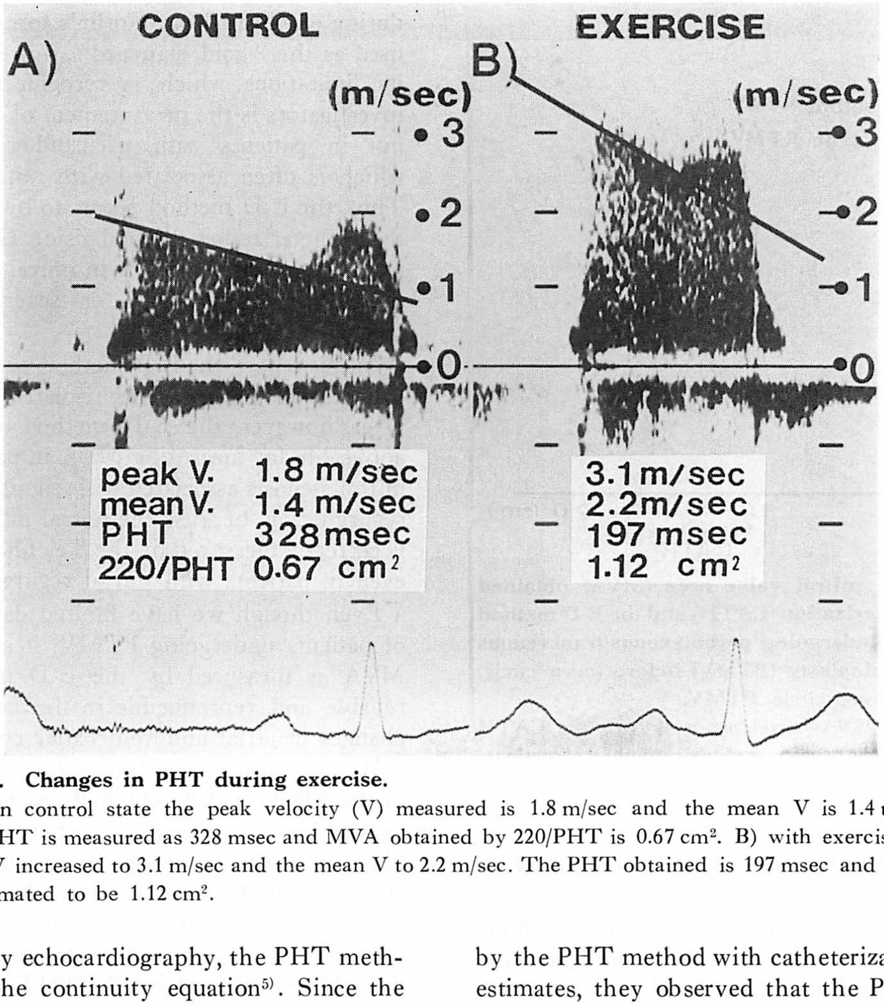

Fig. 7. Changes in PHT during exercise.
A) in control state the peak velocity (V) measured is 1.8 m/sec and the mean V is 1.4 m/sec. The PHT is measured as 328 msec and MVA obtained by 220/PHT is 0.67 cm^2. B) with exercise the peak V increased to 3.1 m/sec and the mean V to 2.2 m/sec. The PHT obtained is 197 msec and MVA is estimated to be 1.12 cm^2.

urements by echocardiography, the PHT method[2], and the continuity equation[5]. Since the initial work by Hatle et al[2] the PHT method has enjoyed wide popularity because of its simplified clinical application in assessing the MVA. Stamm & Martin[8] examined 27 patients with mitral stenosis using the PHT method, and reported a good correlation ($r=0.87$) between the values for the MVA estimated by Doppler PHT and by catheterization. Bryg et al[9] also reported an excellent correlation between valve area estimates by Doppler PHT, catheterization and echocardiographic planimetry in patients with atrial fibrillation and mitral regurgitation. Smith et al[10] used the PHT method to measure the MVA in patients after mitral commissurotomy. Comparing mitral area estimates by the PHT method with catheterization-based estimates, they observed that the PHT values were underestimated compared to the catheterization assessments of the valve areas in 15 of 18 patients. Subsequently, Wilkins et al[11] and Thomas et al[3] reported inaccurate assessments of the MVA using the PHT in patients undergoing balloon mitral valvotomy. They concluded that with sudden changes in compliance, the PHT method was rendered inaccurate. The PHT method of estimating MVA in left ventricular hypertrophy or ischemia and aortic regurgitation[7] may also be inaccurate.

The E-D method may be an alternative approach to the continuity equation method[5] and it depends on the simple physiological principle of flow of fluid volume from a first to a second

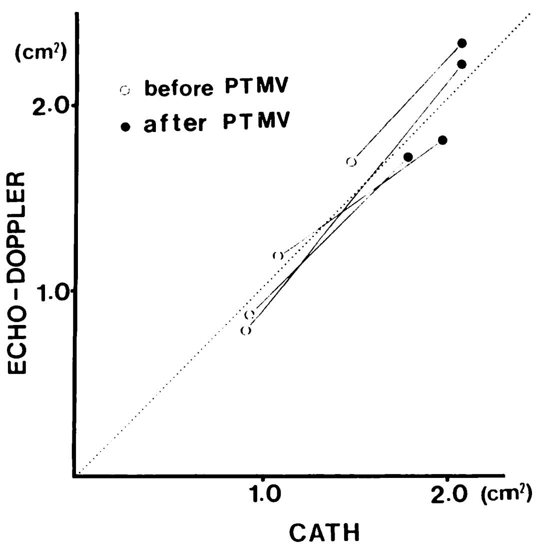

Fig. 8. The mitral valve area (MVA) **obtained by the catheterization** (CATH) **and the E-D method in patients undergoing percutaneous transvenous mitral valvuloplasty** (PTMV) **before** (open circle) **and after** (closed circle) **PTMV.**

Note that MVA correlated well with the CATH results, however, due to the small number of patients examined, it is not statistically significant.

chamber, the chambers being connected by an orifice. This is simple to use and the results obtained are reproducible. Mitral flow volume measurement by the Teichholz formula using M-mode is well-established and routinely used. We reported earlier the reliability of CWD echocardiography in measuring the pressure gradient across the mitral valve in patients with mitral stenosis[12]. The diastolic filling time and mean pressure gradient as measured with CWD are highly accurate and reproducible. The mean pressure gradient measured by CWD using a simplified Bernoulli's equation correlated well with that obtained by the simultaneous recording of pressure tracings. By contrast, with the PHT method as described by Hatle et al[2], an empirical formula is used. The E-D method has become quite comparable to the Gorlin's formula, but a major advantage is that the necessary data can be obtained noninvasively during one heart beat. Gorlin's formula is often used as the "gold standard", however, one of its limitations which is recognized by most investigators is the measurement of cardiac output in patients with tricuspid regurgitation which is often associated with mitral stenosis. Thus, the E-D method seems to be superior to the catheterization method using Gorlin's formula for measuring MVA in mitral stenosis associated with moderate or severe tricuspid regurgitation.

In this report, the E-D method was tested and validated in patients with isolated mitral stenosis, however, the E-D method seems to be applicable for measuring MVA in patients with mitral stenosis associated with significant mitral regurgitation, because the mitral inflow volume is correctly measured by the Teichholz formula, even in patients with mitral regurgitation.

Even though we have limited data (4 cases) of patients undergoing PTMV, it appears that MVA as measured by the E-D method was reliable and reproducible in the face of acute changes in atrial and ventricular compliances.

We have also demonstrated that measurement of the MVA at different R-R intervals yielded nearly the same results in patients with atrial fibrillation after exercise. As discussed previously, the PHT progressively decreases with increases in the heart rate in patients with normal sinus rhythm after exercise, thus renders MVA obtained by the PHT method inaccurate. However, with the E-D method, change in heart rate did not produce any significant differences in the MVA. Similarly, at varying R-R intervals (atrial fibrillation), the MVA as obtained by the E-D formula remained nearly constant; whereas, that obtained by the PHT method changed, thereby changing assessments from severe stenosis to moderate stenosis. These observations further validated the E-D method for the measurement of MVA.

Limitation of the E-D method

One of the disadvantages of the E-D method is that M-mode of the left ventricle in the short-axis must be taken very quickly after obtaining the CWD tracing, in order to use mitral inflow

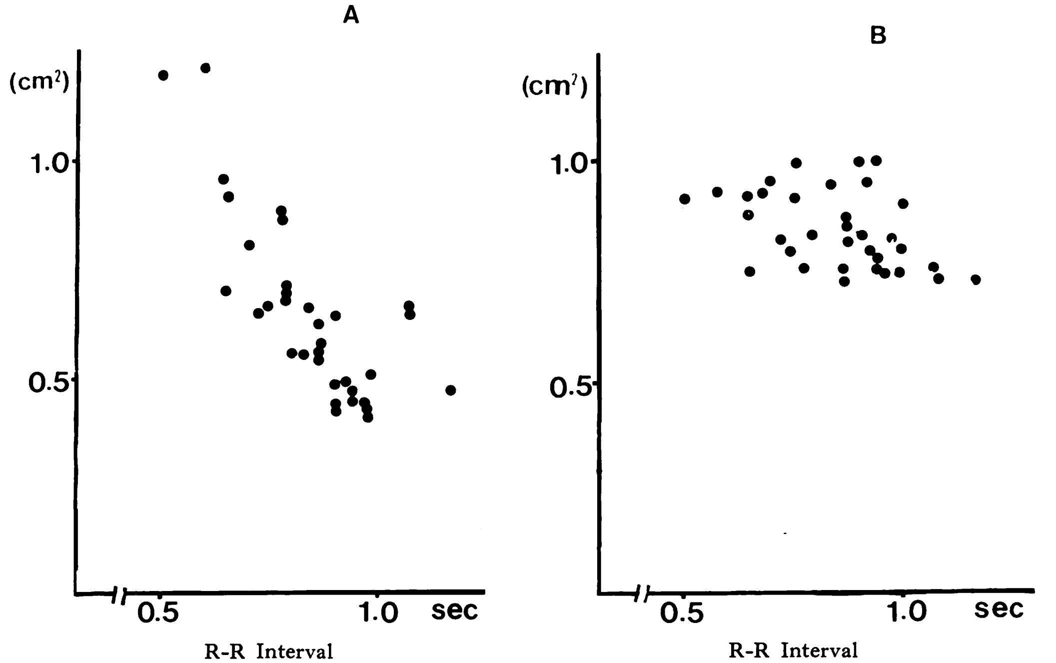

Fig. 9. The comparison of mitral valve area (MVA) **obtained at different R-R intervals.**
Note in Fig. 9A MVA measured by the PHT method fluctuates widely from 0.4–1.22 cm^2, at different R-R intervals in a patient with atrial fibrillation.
Fig. 9B shows that the MVA obtained by the E-D method is constant at similar R-R intervals. Note that the value of MVA fluctuates in smaller range (0.68–1.0 cm^2).

volume data for the calculation. What is more, if a cursor is not correctly placed, the true short-axis view of the left ventricle may not be obtained, and this may lead to erroneous measurement of MVA. In atrial fibrillation, similar R-R intervals should be carefully chosen for the CWD tracing of mitral inflow and the M-mode tracing of the left ventricle in the short-axis.

Another disadvantage is that, in patients with significant aortic regurgitation or left ventricular segmental wall motion disorder, the E-D method does not provide accurate estimates of MVA because of the erroneous measurement of the mitral flow volume by the Teichholz formula.

However, the major advantages seem to be simplicity, reproducibility, and validity as opposed to the catheterization MVA.

Conclusion

Described here is a simple E-D method, which may be an alternative approach to the continuity equation method for calculating MVA. It is based on the physiological principle governing the flow of fluid from one chamber to another chamber, these chambers being connected by an orifice. The MVA obtained by the E-D method was validated as opposed to that obtained from the catheterization data. It is very easy to use and the results are reproducible even in patients with atrial fibrillation after exercise, or after an acute change in the left atrial and ventricular compliances, following PTMV. We concluded that the E-D method is useful for clinical application due to its simplicity and reproducibility.

要　約

ドップラー心エコー図法による僧帽弁狭窄の弁口面積の評価：新しい簡易式による測定

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連続波ドップラー法によって算出される pressure half-time (PHT) は，僧帽弁狭窄の弁口面積 (MVA) を評価する簡便な方法として臨床的に広く用いられている．しかし PHT に影響を及ぼす因子は複雑で，僧帽弁狭窄の MVA は一定でも，血行動態が異なるとその値は変化する可能性がある．そこで我々はある一定の管腔を通過する時の流体力学の基本に従って，ドップラー心エコー図法を用いて MVA を測定する新しい簡易式を作成し，その妥当性を検討した．すなわち MVA＝僧帽弁流入血流量 / 平均流入速度×流入時間，ここで僧帽弁流入血流量は M モード心エコー図を用いて左室拡張末期容量－左室収縮末期容量として求め，平均流入速度×流入時間は連続波ドップラー法を用いて速度波形の拡張期の積分値 (velocity integral) として測定した．この式から求めた MVA の値の妥当性を検討するために，心カテーテル検査を施行した 41 例の僧帽弁狭窄例で Gorlin の式で求めた MVA 値と比較した．その結果は非常に良い相関 (r＝0.82) を示し，PHT と Gorlin の式との相関 (r＝0.52) よりも良好であった．この簡易式を用いて測定した MVA の再現性も検討したが，interobserver および intraobserver variabilities とも良好であった．さらにこの簡易式から測定される MVA の値の安定性を証明するために，運動負荷後の回復過程にみられる種々の異なる心拍数で MVA を測定し，同一例の異なる心拍数での変動を検討した．この時，同時に PHT を用いて測定される値の変動も観察した．その結果，PHT で求められる MVA は心拍数が速くなるにつれて増加し，同一例でも安静時と運動直後では著しい差異がみられた．これに対して，簡易式で求めた値は心拍数の変動にかかわらずほぼ一定であった．また同様に心房細動の例でも，この簡易式を用いると，異なる R-R 間隔で測定した MVA の値の変動はわずかであった．なおこの式は僧帽弁狭窄に僧帽弁逆流を合併している例でも同様に応用することが可能である．

結語：今回提唱する MVA を測定する新しい簡易式は理論に基づいて作成されたもので，簡便でかつ心拍数の影響も受けず，再現性がある．僧帽弁狭窄の MVA を求める新しいドップラー心エコー図法として，今後，臨床的に応用できるものと思われる．

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