Noninvasive Assessment of Atrioventricular Pressure Half-time by Doppler Ultrasound

Liv Hatle, M.D., Bjørn Angelsen, Dr. Techn., and Arve Tromsdal, M.D.

SUMMARY The mean pressure drop across the mitral valve and atrioventricular pressure half-time were measured noninvasively by Doppler ultrasound in 40 normal subjects, in 17 patients with mitral regurgitation, 32 patients with mitral stenosis and 12 with combined stenosis and regurgitation. In normal subjects pressure half-times were 20-60 msec, in patients with isolated mitral regurgitation 35-80 msec and in patients with mitral stenosis 90-383 msec. There was no significant change in pressure half-time with exercise or on repeat examinations, indicating relative independence of mitral flow. In 25 patients with mitral stenosis and seven with combined stenosis and regurgitation, pressure half-time was related to mitral valve area calculated from catheterization data. Increasing pressure half-times occurred with decreasing mitral valve area, and this relationship was not influenced by additional mitral regurgitation. Noninvasive measurement of pressure half-time together with mean pressure drop was useful for evaluating patients with mitral valve disease.

IN PATIENTS with mitral stenosis, the pressure drop across the mitral valve can be estimated noninvasively using velocity measurements obtained from a Doppler ultrasound probe positioned at the cardiac apex.\(^1\),\(^2\) Suitable approximations are used to calculate this pressure drop, but its accuracy in predicting the degree of stenosis will be affected by heart rate and cardiac output in the same manner as invasive pressure measurements.

Most invasive studies use calculations of mitral valve area to determine the severity of mitral stenosis. However, Libanoff and Rodbard\(^3\),\(^4\) suggested a different technique for estimating severity, using the left atrial and left ventricular pressure measurements: the pressure half-time. This is a measurement of the time taken for the pressure drop to fall to one-half its initial value, and was shown to be independent of heart rate and cardiac output. Since maximal blood velocity in the mitral jet is directly related to the pressure drop, and since we observed a linear fall in maximal velocity throughout early diastole on the Doppler recordings, it appeared likely that the pressure half-time could be estimated noninvasively from these measurements.

In this study we measured atrioventricular pressure half-time noninvasively by ultrasound in normal subjects, in patients with isolated mitral regurgitation, in patients with mitral stenosis and in patients with both stenosis and regurgitation. It was also measured during exercise and repeatedly in mitral stenosis and combined stenosis and regurgitation, and it was related to mitral valve area (MVA) calculated from catheterization data.

Patients and Methods

Ultrasonic Examination

The ultrasonic Doppler instrument used to measure mitral flow velocity is described in detail elsewhere.\(^5\),\(^6\) The instrument can be used either in a pulsed mode or as a continuous wave meter. The ultrasonic frequency is 2 MHz. In the pulsed mode using repetition frequencies of 6.7 and 9.8 kHz, velocities up to 1.7 m/sec can be measured within 7 cm from the transducer and 1 m/sec within 12 cm. The velocities are measured in a cylindrical volume about 15 mm in diameter and 7.5 mm long.

In the continuous mode, velocities up to 6 m/sec can be measured, but with loss of range resolution. A maximum frequency estimator was used to obtain maximal velocity from the Doppler signal. The ultrasonic measurements were done as described earlier.\(^2\) With the transducer in the apical area the Doppler signal of mitral flow was first detected. The transducer was then moved and angulated until maximum Doppler shift in the mitral jet was found, using the audio signal as a guide, and confirmed by the maximal velocity recorded. In this position mean and maximum velocities were recorded on a Mingograph together with ECG and phonocardiogram. From the maximum velocity curve, pressure drop during diastole was calculated as described earlier\(^7\) from the formula \(P_1 - P_2 = 4v^2\), where \(P_1 - P_2\) is the pressure drop across the valve and \(v\) is the maximal velocity in the mitral jet. The pressure drop was calculated for several points during diastole and mean pressure drop from the curve drawn through these points. The pressure half-time \((t_{1/2})\) is the time required during diastole for the pressure difference \((P_1 - P_2)\) across the mitral valve to fall to one-half of its initial value at the onset of diastole \((t = 0)\), so

\[
P_1 - P_2 \ (t_{1/2}) = \frac{1}{2}P_1 - P_2 \ (0)
\]

As stated above, we have at any time \(t\) during diastole:

\[
P_1 - P_2 \ (t) = 4v^2 \ (t)
\]

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Substituting equation (2) into equation (1):

\[ 4v^2 (t_v) = \frac{1}{2} 4v^2 (0) \]

or

\[ v (t_v) = \frac{1}{\sqrt{2}} (0) \]

Thus, the pressure half-time is the same as the time required for the maximum velocity curve to fall from peak velocity to peak velocity divided by 2 \( \cong 1.4 \). Pressure half-time varied slightly from beat to beat, and the mean of 10 beats was used.

With maximal velocities below 1.7 m/sec, mitral flow was measured by pulsed ultrasound while the continuous mode was used with higher velocities. Ultrasonic measurement of atrioventricular pressure half-time was done in 40 normal subjects (20 children and 20 adults), in 17 patients with isolated mitral regurgitation, in 32 patients with mitral stenosis and in 12 with combined stenosis and regurgitation. In 19 patients with mitral stenosis or combined stenosis and regurgitation, it was measured both at rest and during exercise, bicycling in the supine position. In 15 patients measurements were repeated one or more times within weeks, in some cases after 1-1½ years.

Heart Catheterization

Right- and left-heart catheterizations were done percutaneously from an antecubital (or femoral) vein and femoral artery, respectively. Pressures were measured simultaneously in the left ventricle and the pulmonary wedge position using an Elema-Schoenander transducer, type EMT 35, and recorded on a Minograph 81. The zero level for pressure measurement was the anterior axillary line in the fourth intercostal space. Cardiac output was determined by the Fick method (breathing into a Douglas bag for 3 minutes while blood tests were taken from the femoral and pulmonary arteries in the middle of the period). MVA was calculated using the revised Gorlin formula. In patients with combined mitral stenosis and regurgitation, MVA was calculated using the same formula, but cardiac output was determined by angiography. Left ventricular angiography was done in the 30° right anterior oblique position. Left ventricular volumes were calculated using the method of Dodge, modified by Kasser. Only cases with regular heart rate during angiography were included in the study. The correlation coefficient between cardiac output determined by the Fick method and by left ventricular angiography in our laboratory was 0.85 in 18 patients without valvular regurgitation or dyskinesia.

Heart catheterization was done in 32 patients for evaluation of mitral valve surgery. In 25, the pressure recording was done simultaneously with ultrasonic measurement and in seven, ultrasonic measurement was done the day before catheterization. Twenty-five had mitral stenosis and seven had combined stenosis and regurgitation. There were 26 women and six men. Ages ranged from 41-72 years (mean 56.1 years). Sixteen were in sinus rhythm and 16 had atrial fibrillation. All the patients with combined stenosis and regurgitation were in sinus rhythm. Seven were in functional class II, 16 in III, while nine had just recovered from pulmonary edema or right heart failure.

Results

Normal Subjects

Figure 1 shows ultrasonic recording of mitral flow in a normal subject. Flow is biphasic, with an initial peak early in diastole and a second peak after atrial contraction. Mean velocity is only slightly lower than maximal velocity, indicating a nearly flat velocity profile in the absence of mitral valve stenosis. Pressure half-time is measured from the decline in maximal

\[ \text{FIGURE 1. Ultrasonic recording of mitral flow in a normal subject from the fourth left intercostal space. Mean velocity is directional, flow is toward the transducer (positive) in diastole, while mitral valve closure is away from the transducer (negative). Maximal velocity is nondirectional. Pressure half-time is 45 msec.} \]
velocity before atrial contraction. Pressure half-time in 20 adults ages 21-72 years was 25-55 msec (mean 43 msec). In 20 children ages 1-16 years, pressure half-time was 20-60 msec (mean 49 msec). The mean for all 40 normal subjects was 46 msec. Mean pressure drop calculated from the maximal velocity curve was less than 1-2 mm Hg, except in small children with rapid heart rate, who had a mean pressure drop of 2-3.5 mm Hg.

Mitral Regurgitation

In 17 patients with isolated mitral regurgitation, ages 11-69 years, pressure half-time varied from 35-80 msec (mean 50 msec). An example of mitral flow in a case of moderate mitral regurgitation is shown in figure 2. Peak maximal velocity (and peak pressure drop) is higher than in figure 1, but pressure half-time is within the range found in normal subjects. Mean pressure drop in the 17 patients calculated from the maximal velocity curve was 1-5 mm Hg (mean 3 mm Hg), and the highest values were observed when the regurgitation was large and the heart rate rapid.

Mitral Stenosis

Figure 3 shows ultrasonic recording of maximal velocity with calculated pressure drop and pressure half-time in a patient with severe mitral stenosis. A linear fall in velocity is seen throughout diastole. Because of atrial fibrillation a second peak due to atrial contraction is absent. Mean pressure drop varies with the length of diastole, while pressure half-time is similar from beat to beat.

Figure 4 shows ultrasonic recording of maximal velocity in a patient with mitral stenosis in sinus rhythm. In this case pressure half-time varied a little more from beat to beat, but was within the range shown. Mitral stenosis was less severe in this case than in the previous one and pressure half-time was considerably shorter. Mean pressure drop, however, was much higher, 23 mm Hg, due to a higher cardiac output and a more rapid heart rate.

In a few patients with mitral stenosis, decline in maximal velocity was linear only during the first part of diastole; only this was then used for the measurements. A slower decline in maximal velocity in the last part of diastole (fig. 5, left) has so far been noted only at velocities well below 1 m/sec (i.e., at a pressure drop less than 4 mm Hg).

Pressure half-time in the patients with mitral stenosis ranged from 90-383 msec. Individual results are shown in table 1, together with MVA and mean pressure drop by pressure recording and by ultrasonography. In the patients with simultaneous measurements, average mean pressure drop was 15.1 mm Hg by pressure recording and 14.2 mm Hg calculated from ultrasonic recording. The correlation coefficient was 0.92. In the patients in whom ultrasonic recording was done on the day before catheterization the correlation was less, but heart rate varied on the two recordings.
Mitral Stenosis and Regurgitation

In the 12 patients with combined mitral stenosis and regurgitation pressure half-time varied from 95–280 msec and mean pressure drop calculated from ultrasonic recording of maximal velocity from 4–23 mm Hg. Table 1 shows results in the seven patients in whom simultaneous pressure and ultrasonic recordings were done and satisfactory left ventricular angiograms and the presence of sinus rhythm made calculation of MVA possible. Average mean pressure drop on catheterization was 13.5 mm Hg and on ultrasonic recording 12.6 mm Hg. The correlation coefficient was 0.82.

Figure 5 (middle) shows maximal velocity in a patient with combined mitral stenosis and regurgitation and (below) pressure half-time and calculated pressure drop. The mitral stenosis was of similar severity as in the case on the left in figure 5, and pressure half-time was almost the same, while maximal velocity and pressure drop were much higher due to larger blood flow across the valve.

Recordings from a patient with severe isolated mitral regurgitation are shown on the right in figure 5. Initial maximal velocity and peak pressure drop were as high as in the patient with mitral stenosis, but decline in velocity was more rapid and pressure half-time much shorter. When comparing the three cases the maximal velocity curve indicates whether the increased maximal velocity and pressure drop are caused by the presence of stenosis or increased flow or both.

Exercise and Repeat Studies

On exercise the mean increase in heart rate in the 19 patients was 39% (from 67.1 to 93.4 beats/min) and the mean increase in pressure drop was 90% (from 6.8 to 12.9 mm Hg). Pressure half-time decreased slightly (4.6%), from 174.8 to 162.8 msec (NS).

Pressure half-time on exercise and on repeat examinations are shown in figure 6. On repeat studies only small changes in pressure half-time were seen, despite greater changes in heart rate and mean pressure drop on the different measurements. One patient was seen both in sinus rhythm and during atrial fibrillation, while another was observed during heart failure and after recovery. The small increase in pressure half-time (from 220.6 to 230.6 msec) from the first to the second examination was not statistically significant.
Table 1. Pressure Drop and Mitral Valve Area from Catheterization Data and Pressure Drop and Pressure Half-time from Ultrasonic Recording of Maximal Velocity in the Mitral Jet in 25 Patients with Mitral Stenosis and Seven with Combined Stenosis and Regurgitation

<table>
<thead>
<tr>
<th>Doppler estimates</th>
<th>Catheterization measurements</th>
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<tbody>
<tr>
<td>Pressure half-time</td>
<td>Mean pressure drop</td>
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<td>Mitral stenosis</td>
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Mitral stenosis and regurgitation recorded simultaneously

|                   |                   |                   |                  |
|                   | 280               | 23                | 23                | 1.09 |
|                   | 230               | 21                | 25                | 1.17 |
|                   | 216               | 9                 | 10                | 1.55 |
|                   | 174               | 9                 | 10.5              | 1.56 |
|                   | 120               | 4.5               | 6                 | 1.80 |
|                   | 112               | 16                | 13                | 3.00 |
|                   | 90                | 6                 | 7                 | 3.55 |

The correlation coefficient for pressure drops measured by the two methods when recorded simultaneously was 0.94 ± 0.204 (SEM). The correlation coefficient between pressure half-time and mitral valve area was −0.74 (SEM = 0.186). In parentheses, heart rate on the two occasions in patients with nonsimultaneous recording.

Mitral Valve Area

MVA calculated from catheterization data is shown in table 1. In two of the patients with combined stenosis and regurgitation the degree of stenosis was small, with values for MVA (3.55 and 3.0 cm²) and pressure half-times (90 and 112 msec) closest to the normal range. In the remaining patients, MVA ranged from 0.39–1.80 cm².

In figure 7 MVA is related to pressure half-time. With progressive reduction in valve area increasing pressure half-times are noted. There is a possible linear relationship between MVA and pressure half-time when values approximating the normal range are excluded. The correlation was significant in the 30 patients with MVA ≤ 1.80 cm² (r = −0.75) and in the 25 patients with isolated mitral stenosis (r = −0.72). In the five patients with combined mitral stenosis and regurgitation the correlation did not reach significance (r = −0.74).

In figure 8 pressure half-time is related to mean pressure drop and to MVA. Patients with a MVA less than 1.0 cm² have pressure half-times from 233–383 msec and mean pressure drops ranging from as low as 5 mm Hg to as high as 30 mm Hg. Those with a low pressure drop had reduced cardiac output and mitral flow; the severity of the stenosis, however, was indicated by the long pressure half-time. Those with a high pressure drop had normal or increased mitral flow (associated mitral regurgitation). In patients with MVA between 1.0 and 1.5 cm² pressure half-times ranged from 174–280 msec. With a MVA larger than 1.5 cm² pressure half-times were lower than 180 msec, except in one patient who had a half-time of 216 msec and a MVA of 1.55 cm². A high pressure drop can also be seen with MVA larger than 1.5 cm², as in the patient with a mean pressure drop of 16 mm Hg and a pressure half-time of 112 msec. The short pressure half-time indicates that the high pressure drop is mainly due to increased mitral flow and less to severity of mitral stenosis. (The patient had a large regurgitation and a MVA of 3.0 cm².)

Patients with isolated mitral regurgitation may have a mean pressure drop similar to that in patients with mild mitral stenosis, but the two groups are clearly separated when measurement of pressure half-time is added.

Limitations and Sources of Error

A nonlinear fall in maximal velocity at low velocities or nonlinearity at the beginning of diastole occasionally occurred, and pressure half-time was then measured as shown in figures 9A and B. When the PR interval is prolonged, resulting in an increase in velocity from atrial contraction early in diastole (fig. 9C), pressure half-time cannot be measured. The same problem may arise during exercise with high heart rates and sinus rhythm. In patients with atrial flutter or atrial tachycardia the frequent atrial contractions may prevent measurement of pressure half-time (fig. 9D).

To estimate pressure drop and pressure half-time accurately, good Doppler signals must be obtained throughout diastole from a position where the angle between ultrasound beam and maximal velocity is not too large. Figure 10 shows the effect of increasing this angle, calculated from the Doppler equation, on max-
AV PRESSURE MEASURED BY DOPPLER/Hatle et al.

FIGURE 6. A) Pressure half-time measured from ultrasonic recording of maximal velocity in mitral flow at rest and during exercise in 19 patients with mitral stenosis; \( r = 0.91 \). B) Pressure half-time from repeat ultrasonic recordings (on different occasions) in 15 patients with mitral stenosis; \( r = 0.91 \) (first and second examination).

FIGURE 7. Pressure half-time obtained from ultrasonic recording of maximal velocity in mitral flow related to mitral valve area calculated from catheterization data; \( r = -0.74 \). \( \circ \) = mitral stenosis; \( \bullet \) = mitral stenosis and regurgitation.

FIGURE 8. Pressure half-time related to mean pressure drop and mitral valve area (MVA). \( \bullet \) = MVA < 1.0 cm\(^2\); \( \circ \) = MVA 1.0 - 1.5 cm\(^2\); \( x \) = MVA > 1.5 cm\(^2\); . = pure mitral regurgitation.
imal velocity and calculated pressure drop. Pressure half-time is independent of this angle.

If the ultrasound beam is not aimed at a central part of the mitral jet optimal Doppler signals may be obtained only during part of diastole due to movements of the heart. This may both underestimate pressure drop and change pressure half-time, which will be prolonged with insufficient signals in the first part of diastole. This possible source of error did not seem to be important, as pressure half-time on different occasions in the same patients varied very little. Figure 11 shows two measurements (A and B) in one patient 3 months apart with almost identical results. When the transducer was deliberately angled away from the optimal position, pressure drop was underestimated and pressure half-time prolonged (fig. 9C).

Discussion

The relationship between MVA and pressure half-time described by Libanoff and Rodbard3,4 was confirmed in the present study. Their pressure data were obtained at catheterization and compared with MVA at operation, while in the present study the pressure drop and pressure half-time obtained noninvasively by ultrasound were related to the MVA calculated from catheterization data. The results were similar with pressure half-times increasing from about 100 to 400 msec with increasing severity of mitral stenosis.

In both studies only a slight decrease in pressure half-time with exercise was associated with significant increases in pressure drop and, presumably, flow. This relative independence of flow is in agreement with the close correlation found between pressure half-time and MVA.

The same applies to mitral regurgitation, which did not influence the pressure half-time in any of the studies. A similar relationship to valve area was found as in pure mitral stenosis. This is useful because the clinical evaluation of severity of stenosis in the presence of mitral insufficiency may be difficult.
Askenazi\textsuperscript{10} has shown that a reliable estimate of MVA can be made in the presence of mitral regurgitation if a satisfactory left ventricular angiogram with correct calibration is obtained, heart rate is regular and there is no aortic regurgitation.

The relative independence of flow is also shown by the constancy of the pressure half-time on repeat examination despite great variations in the clinical situation, such as great changes in heart rate and pressure drop, change from sinus rhythm to atrial fibrillation and from heart failure to recovery.

By combining the noninvasive measurement of pressure drop and pressure half-time the severity of mitral stenosis can be better assessed than by pressure drop alone. Combination of the two measurements also makes deductions about mitral flow possible to some degree. With a long pressure half-time a high pressure drop would indicate severe stenosis with maintained or increased flow and a low pressure drop would indicate reduced flow. In a patient with mitral stenosis, increase in pressure half-time would indicate progressive stenosis, while a reduction in pressure drop would indicate decrease in mitral flow and cardiac output. When pressure half-time is short, a high pressure drop would indicate increased flow and in combined mitral stenosis and regurgitation, a high pressure drop in relation to the pressure half-time would indicate that the regurgitation was significant.

On exercise the increase in pressure drop related to change in heart rate and diastolic time might make it possible to judge whether flow can be significantly increased.

Calculation of both pressure drop and pressure half-time from the maximal velocity curve in mitral regurgitation also makes it clear whether additional stenosis is present or not. The pressure half-time in patients with isolated mitral regurgitation and in normals was slightly longer in this study than in that of Libanoff and Rodbard.\textsuperscript{3, 4} This may be due to the different method used. There was still clear separation between these and patients with mild mitral stenosis.

The possibility of underestimating the pressure drop in mitral stenosis if optimal Doppler signals are not found is discussed previously.\textsuperscript{2} However, satisfactory Doppler signals are easily found in almost all patients and underestimation was within 20% of the pressure drop obtained at catheterization and in most within 10%. Still, if significant underestimation of pressure drop should occur with inadequate Doppler signals or a large angle between ultrasound beam and mitral jet, pressure half-time would not underestimate the stenosis, as the values then will be unchanged or even prolonged.

Conclusion

Maximal velocity in the mitral jet can easily be measured noninvasively by Doppler ultrasound and both pressure drop and pressure half-time can be calculated. The latter is shown to be related to MVA and relatively independent of mitral flow. With both these measurements the degree of stenosis can be adequately assessed. In the follow-up of patients with mitral valve disease a progressive increase in pressure half-time indicates reduction in valve area and a decrease in the pressure drop indicates reduced mitral flow and cardiac output.

References

Cross-sectional Echocardiography
I. Analysis of Mathematical Models for Quantifying Mass of the Left Ventricle in Dogs

H. L. Wyatt, Ph.D., Ming K. Heng, M.D., Samuel Meerbaum, Ph.D., John D. Hestenes, Ph.D., Julio M. Cobo, M.D., Robert M. Davidson, M.D., and Eliot Corday, M.D.

SUMMARY  Cross-sectional echocardiography was used to quantify left ventricular mass noninvasively in 21 dogs. Short- and long-axis cross-sectional images of the left ventricle were reproducibly traced at endocardial and epicardial borders during stop-motion video-tape replay. We used area, length and diameter measurements to calculate left ventricular mass by seven mathematic models, including the standard formulas used with M-mode echocardiography and cineangiography. Calculated mass was compared with excised weight of the left ventricle by regression and percent error analyses. Formulas using short-axis areas and long-axis length resulted in higher correlation coefficients (0.94-0.95) and lower mean errors (6-7%) than for standard formulas. Since short-axis areas account for regional left ventricular irregularities, noninvasive quantification of left ventricular mass by cross-sectional echocardiography in dogs is most accurate with formulas using short-axis areas.

M-MODE ECHOCARDIOGRAPHY has been used to quantify left ventricular (LV) dimensions, yet the technique is limited by its one-dimensional approach. Cross-sectional echocardiography, with its two-dimensional visualization of the heart, has not only greatly enhanced the range of noninvasive cardiac diagnosis, but also provides new opportunities for quantification of LV volumes and mass. The primary source of errors in LV volume measurement by most of the currently available techniques is the inability to accurately assess endocardial asymmetries and irregularities such as those caused by the presence of papillary muscles and trabeculae carneae. Because good tomographic ultrasonic visualization of LV endocardial contours is possible in most dogs, quantification of cardiac size has become a distinct probability.

Cross-sectional echocardiographic quantification of LV dimensions and volumes has not been adequately validated, even though several preliminary clinical investigations suggested correlation with cineangiography. The lack of an absolute standard against which to compare echocardiographic measurements limits the implications of prior studies. Hence, techniques were developed in this laboratory for performing non-invasive cross-sectional echocardiography in closed-chest dogs. With this technique a variety of LV cross-sectional images may be recorded for detailed analysis of cardiac size, structure and function. The present study in closed-chest dogs was designed to determine the accuracy of LV mass assessment with

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6. Angelsen BAJ: Analog estimation of the maximum frequency of Doppler spectra in ultrasonic blood velocity measurements.

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Report 76-21-W, Division of Engineering Cybernetics, Norwegian Institute of Technology, University of Trondheim, Norway, 1976

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