# Prospective Study Comparing Different Echocardiographic Measurements of Pulmonary Capillary Wedge Pressure in Patients With Organic Heart Disease Other Than Mitral Stenosis

JOSEPH ASKENAZI, MD, FACC, DAVID I. KOENIGSBERG, MD, FACC, HILLEL S. RIBNER, MD, FACC, DOMINIC PLUCINSKI, MD, IRWIN M. SILVERMAN, MD, MICHAEL LESCH, MD, FACC

*Chicago, Illinois*

**In 25 patients with cardiac disease, but free of left ventricular inflow obstruction, the electrocardiogram and M-mode echocardiogram of the aortic root, left atrium and both the mitral and the aortic valves were obtained simultaneously with the pulmonary artery wedge pressure (PAWP) during right heart catheterization. The echocardiographic measurements of the left atrial size, PR-AC interval, left atrial emptying index and the ratio between the electrocardiographic Q wave to mitral valve closure (Q-MVC) and between aortic valve closure to the mitral E point (AVC-E) were correlated to the pulmonary artery wedge pressure by means of linear regression analysis. A formula in which PAWP = 36.6 (Q-MVC/AVC-E) − 2 was prospectively used to study the measured pressure in the current group of patients. The pulmonary artery wedge pressure derived from these latter measurements correlated well with the invasive measurement of this pressure (r = 0.91). The pulmonary artery wedge pressure calculated by echocardiography differed from the pulmonary artery wedge pressure measured by catheterization by 3 mm Hg or less in 19 of the 25 patients, by 4 mm Hg or less in 22 patients and by 6 mm Hg or less in 24 patients. Although the correlation between the (Q-MVC/AVC-E) ratio and measured pulmonary artery wedge pressure was highly significant (r = 0.91, probability [p] < 0.001, n = 25), the left atrial emptying index, PR-AC and left atrial size revealed poor correlation coefficients (r = 0.45, r = 0.45 and r = 0.56 [p < 0.05]), respectively.**

**In conclusion, in patients in stable condition with left ventricular dysfunction but without mitral valve obstruction, M-mode echocardiography using a ratio of the intervals (Q-MVC/AVC-E) provides a useful and reliable noninvasive method to predict pulmonary artery wedge pressure. Other M-mode echocardiographic measurements, PR-AC interval, left atrial emptying index and left atrial size, have limited use as a noninvasive method to predict pulmonary artery wedge pressure.**

In recent years, two techniques have been reported for obtaining from M-mode echocardiographic data estimates of left ventricular filling pressure as reflected by pulmonary artery wedge pressure in patients free of mitral valve obstruction. In the initial study (1), an atrial emptying index was utilized, while in the second (2), the ratio of Q wave to echographic mitral valve closure interval (Q-MVC) to aortic valve closure to mitral E point interval (AVC-E) was used. Others have correlated left ventricular end-diastolic pressure with the PR-AC interval (3,4) and the pulmonary artery wedge pressure with left atrial size (5). The ability to assess left ventricular filling pressure by a noninvasive technique such as M-mode echocardiography would be of obvious potential benefit in the management of patients with cardiac disease. Unfortunately, the prospective validity of these different echocardiographic methods in unselected patients with a variety of cardiac illness has not been established. In the present study, we prospectively compared the different echocardiographic measurements of pulmonary artery wedge pressure with simultaneously obtained catheterization measurements of this variable in patients with stable cardiac disease.

From the Department of Medicine, Section of Cardiology, Veterans Administration Lakeside Medical Center and Northwestern Memorial Hospital, Northwestern University Medical School, Chicago, Illinois. Manuscript received March 3, 1983; revised manuscript received May 23, 1983, accepted May 25, 1983.

Address for reprints: Joseph Askenazi, MD, Section of Cardiology, Veterans Administration Lakeside Medical Center, 333 East Huron Street, Chicago, Illinois 60611.

## Methods

**Study patients.** The study group consisted of 25 men with an average age of 56 years (range 41 to 70) undergoing simultaneous bedside flow-directed right heart catheteriza-



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tion and echocardiographic study (8 patients) or diagnostic cardiac catheterization and echocardiographic study (17 patients) (Table 1). Four patients were studied twice, first in a control state and then after intravenous administration of hydralazine. Coronary artery disease was present in 11 patients, congestive cardiomyopathy in 6, mitral regurgitation in 3 and chronic aortic regurgitation in 1 patient.

*Criteria for inclusion in the study included* the existence of a technically adequate echocardiogram, normal sinus rhythm with normal PR interval and the absence of left bundle branch block. Patients with acute aortic regurgitation, flail aortic or mitral leaflet or those thought to have an unstable cardiac state (that is, patients with unstable angina and those receiving pressor amines or intravenous nitrates or nitroprusside) were excluded. Only three patients were excluded from the study because the echocardiograms were not technically suitable.

**Hemodynamic studies.** Pulmonary artery wedge pressure was obtained in all patients in the supine position during standard right heart catheterization. The reference zero pressure level was arbitrarily set at the midpoint of the chest diameter. The pulmonary wedge position was confirmed by the presence of a characteristic phasic pressure waveform, by blood gas analysis from the wedge position and by fluoroscopy in the 18 patients undergoing diagnostic catheterization. The phasic pressure from the pulmonary artery wedge position was recorded at a paper speed of 50 mm/s, and the mean pressure was recorded at 10 mm/s. Pressure calibration and rezeroing to atmospheric pressure was performed before, during and at the end of the study.

**Echocardiographic studies.** M-mode echocardiography was obtained with standard single channel echocardiographic equipment: an Irex 101 or Electronics for Medicine machine using a 2.25 MHz transducer. All examinations were conducted with the patient in the supine position. Recordings from along the left sternal border were made of the aortic root and valve and the left atrium and mitral valve at sites where closure of these valves could be clearly defined. The echocardiographic tracings of the heart structures were recorded simultaneously with an electrocardiographic lead (bipolar chest or unipolar $V_5$ or $V_6$) that demonstrated a clear initial deflection of the QRS complex with a strip chart recording at a proper speed of 100 to 200 mm/s and longitudinal time lines of 10 ms. The echocardiograms were obtained at the time of right heart catheterization.

**Echocardiographic variables.** All echocardiographic intervals were obtained by averaging data from at least 3 cardiac cycles in which the preceding RR interval on the

**Table 1.** Summary of Data in 25 Patients

| Case | Heart Rate (beats/min) | Q-MVC / AVC-E | LAEI | PR-AC (ms) | LA (mm) | PAWP (mm Hg) Predicted | PAWP (mm Hg) Measured |
|---|---|---|---|---|---|---|---|
| 1 | 59 | 0.43 | 1.00 | 45 | 29 | 14 | 14 |
| 2 | 68 | 0.22 | 1.00 | 70 | 29 | 6 | 4 |
| 3 | 67 | 0.19 | 0.79 | 92 | 24 | 5 | 9 |
| 4* | 91 | 0.60 | 0.57 | 25 | 41 | 20 | 22 |
| 5† | 79 | 0.46 | 0.42 | 70 | 33 | 15 | 9 |
| 6 | 63 | 0.49 | 1.00 | 40 | 40 | 16 | 11 |
| 7 | 98 | 0.42 | 0.43 | 95 | 31 | 13 | 10 |
| 8* | 95 | 0.65 | 0.07 | 70 | 56 | 22 | 20 |
| 9† | 96 | 0.56 | 0.77 | 90 | 56 | 18 | 14 |
| 10 | 66 | 0.79 | 0.60 | 95 | 53 | 27 | 27 |
| 11 | 73 | 0.40 | 1.00 | 60 | 39 | 13 | 11 |
| 12 | 67 | 0.45 | 1.00 | 73 | 42 | 14 | 15 |
| 13 | 84 | 0.25 | 1.00 | 50 | 36 | 7 | 9 |
| 14 | 74 | 0.36 | 0.84 | 65 | 43 | 11 | 8 |
| 15* | 96 | 0.85 | 0.60 | 9 | 52 | 29 | 32 |
| 16† | 89 | 0.51 | 0.60 | 17 | 47 | 17 | 18 |
| 17 | 60 | 0.24 | 1.00 | 80 | 34 | 7 | 4 |
| 18 | 70 | 0.81 | 0.81 | 35 | 42 | 27 | 26 |
| 19 | 106 | 0.77 | 0.58 | 55 | 41 | 26 | 22 |
| 20* | 107 | 0.89 | 0.72 | 20 | 39 | 30 | 28 |
| 21† | 113 | 0.59 | 0 48 | 60 | 43 | 20 | 18 |
| 22 | 79 | 0.69 | 0.58 | 44 | 36 | 23 | 14 |
| 23 | 112 | 0.48 | 0.41 | 52 | 46 | 15 | 18 |
| 24 | 88 | 0.57 | 0 43 | 85 | 31 | 19 | 20 |
| 25 | 59 | 0.40 | 1 00 | 35 | 32 | 13 | 12 |

* Measurements taken before intervention and † after hydralazine administration.
LA = left atrial size; LAEI = left atrial emptying index; PAWP = mean pulmonary artery wedge pressure.

electrocardiogram did not vary by more than 10 ms. All measurements were performed in duplicate by two independent observers.

*1. The echocardiographic determinants of pulmonary artery wedge pressure* as recently described by us (2) included measurements of the following intervals (Fig. 1): *Q-MVC*: From the onset of the QRS complex to the echocardiographic C point of the systolic closure of the mitral valve leaflets. *Q-E*: From the onset of the QRS complex to the E point of the maximal early diastolic opening of the anterior mitral valve leaflet. *Q-AVC*: From the onset of the QRS complex to the closure point of the aortic valve. *AVC-E*: This interval was obtained by subtracting the Q-AVC interval from the Q-E interval. *Ratio Q-MVC/AVC-E*: This was obtained by averaging at least 3 cycles of the aforementioned intervals.

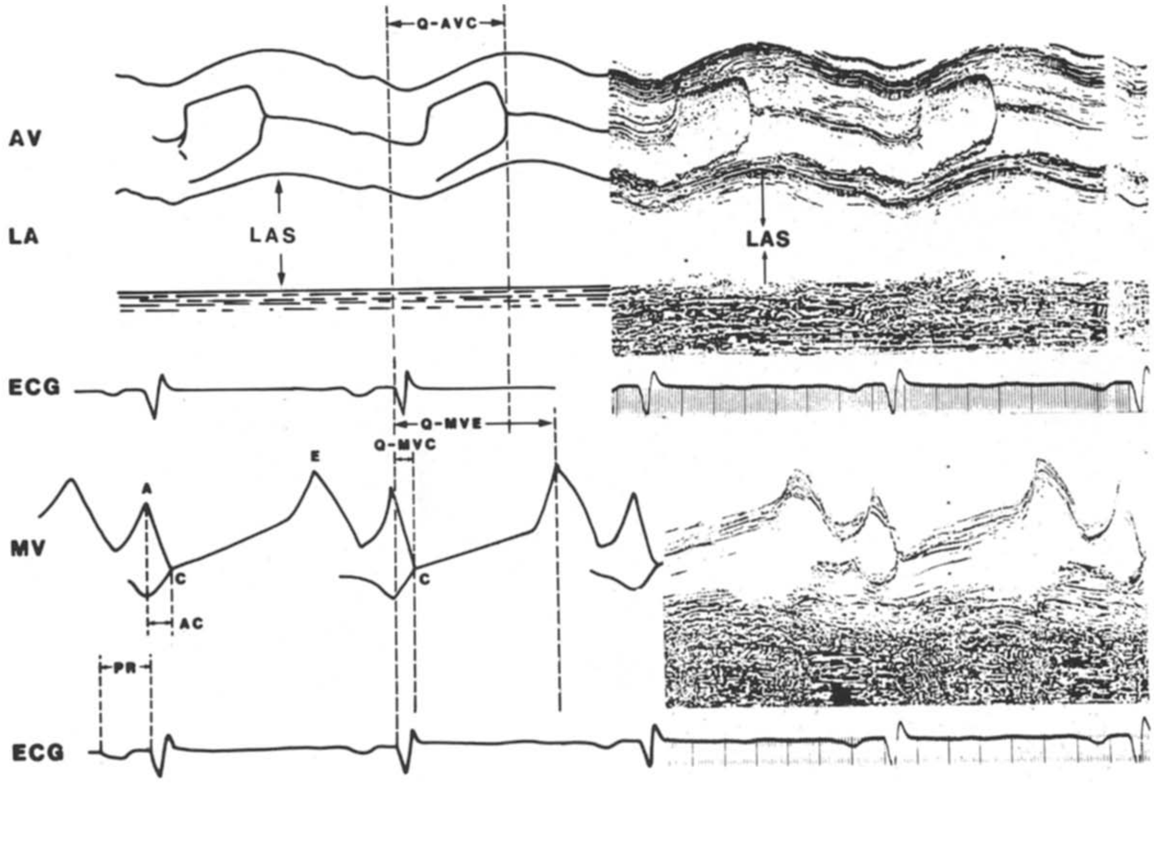
*2. The left atrial emptying index* was measured as described by Strunk et al. (6) and used by Wasserman et al. (1). The left atrial emptying index was defined by the fractional change in diastolic motion of the posterior aortic root in the first one-third of diastole (Fig. 2). The point where the posterior aortic wall begins its posterior motion is O, and the A point described a second abrupt posterior movement caused by atrial contraction. The left atrial emptying index (X/OA) is the ratio of the posterior aortic wall motion occurring in the first third of this passive emptying period (X) to the total passive emptying (OA).

*3. The echocardiographic AC interval and electrocardiographic PR interval* were used for calculating the PR-AC interval (3).

*4. Left atrial size was measured at the level of the aortic root* as the distance from the anterior surface of the posterior aortic wall during end-systole to the anterior surface of the left atrial wall (7).

*The pulmonary artery wedge pressure, measured by catheterization technique, was related by means of linear regression analysis to*: a) left atrial size, b) PR-AC interval, c) left atrial emptying index, and d) Q-MVC/AVC-E ratio. The echocardiographic derived pulmonary artery wedge pressure (PAWP) by the previously reported formula (2) in which PAWP = 36.6 (Q-MVC/AVC-E)-2, was also related to the measured value.

**Figure 1.** M-mode echocardiograms of the mitral (MV) and aortic (AV) valves and left atrium (LA) recorded at a paper speed of 100 mm/s with time lines of 10 ms (**right panel**). Schematic representations (**left panel**) of left atrial size (LAS), electrocardiogram (ECG), PR and AC intervals and measurements of Q to mitral valve closure (Q-MVC), Q to aortic valve closure (Q-AVC) and Q to mitral valve E point (Q-MVE).



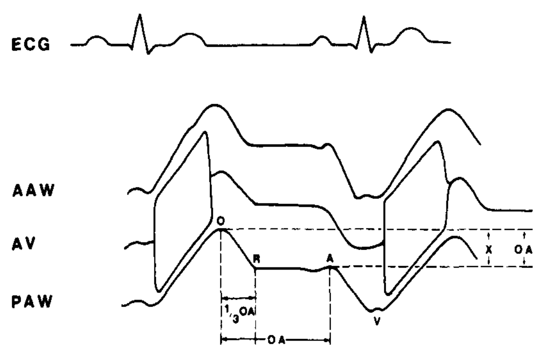
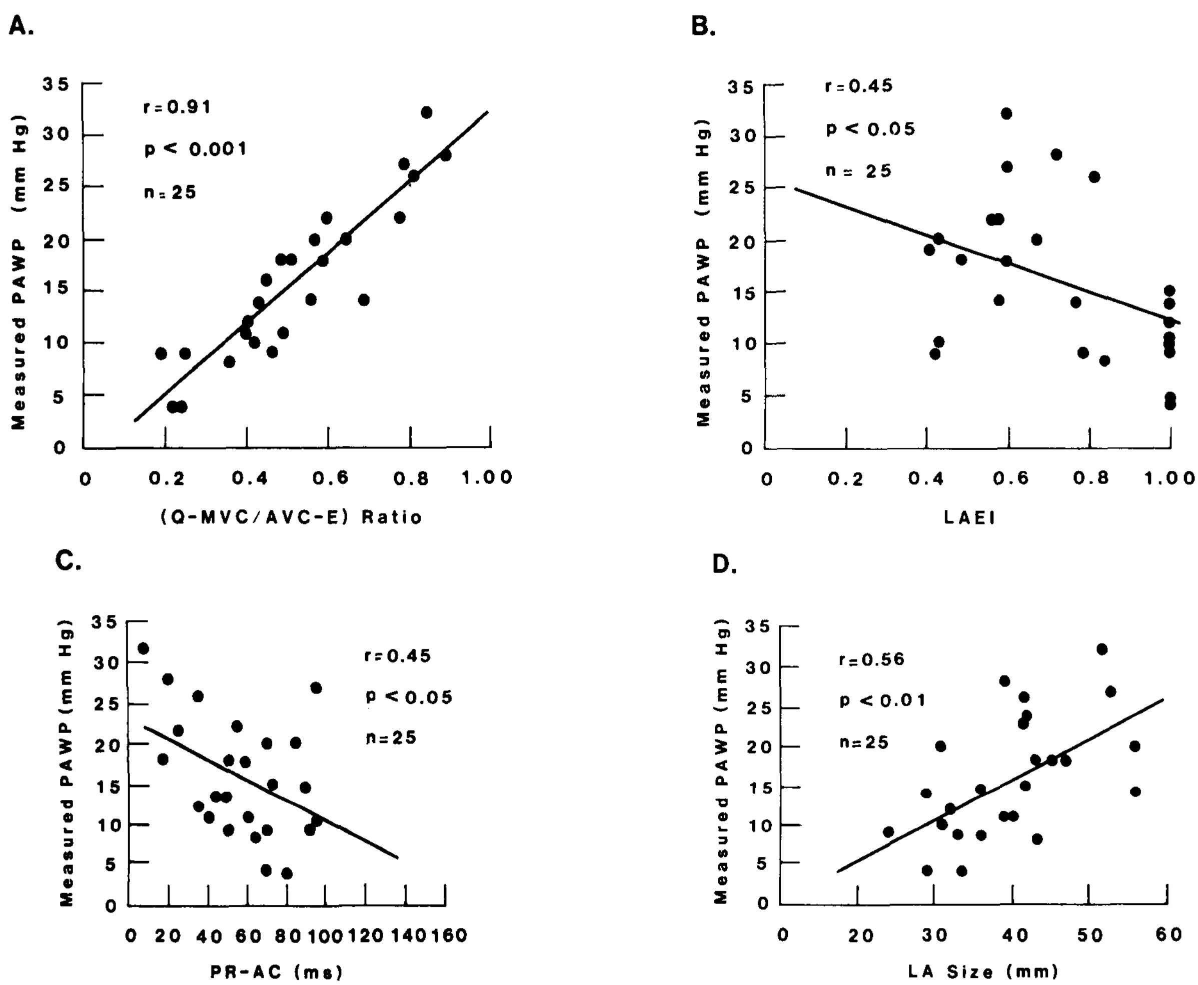



**Figure 2.** Schematic drawing illustrating the calculation of left atrial emptying index (LAEI) X/OA = 1.0. The total passive emptying period occurs between O to A point and the first third of this emptying (X) occurs between the points O and R. AAW = anterior aortic wall; AV = aortic valve; ECG = electrocardiogram; PAW = posterior aortic wall.

**Figure 3.** Relation of pulmonary artery wedge pressure (PAWP) to the (Q-MVC/AVC-E) ratio (**A**), left atrial emptying index (LAEI) (**B**), PR-AC interval (**C**) and left atrial (LA) size (**D**).

## Results

The echocardiographic variables and the pressure measurements from all patients are listed in Table 1. The 25 measurements obtained in this study of Q-MVC/AVC-E versus pulmonary artery wedge pressure are depicted in Figure 3A. A formula for pulmonary artery wedge pressure obtained from a linear regression analysis of these measurements equals 34.2 (Q-MVC/AVC-E) − 2.1, thus differing minimally from that described above from our previous retrospective study (2). In the 25 patients, the predicted pulmonary artery wedge pressure measured by echocardiogram, using the previously reported formula, differed from the pulmonary artery wedge pressure measured by catheterization by 3 mm Hg or less in 19 patients, 4 mm Hg or less in 22 patients and, 6 mm Hg or less in 24 patients with a correlation of r = 0.91 (Fig. 4). In all of the instances of a discrepancy between calculated and measured pulmonary artery wedge pressure of 5 mm Hg or more, the echocardiographically-derived predicted value was greater than the measured value. Retrospective analysis failed to define any common element that could explain the largest dis-



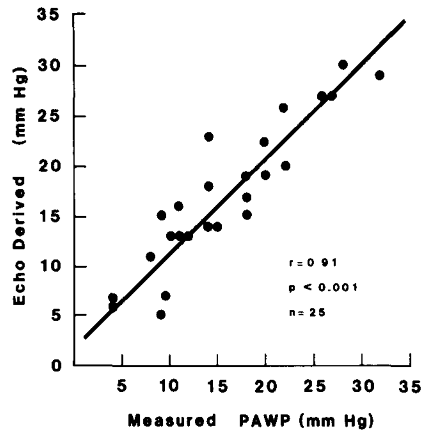



**Figure 4.** Measured mean pulmonary artery wedge pressure (PAWP) plotted against the echographically-derived valve.

crepancies between predicted and measured values (such as commonc cardiac disease).

Other echocardiographic methods designed to assess pulmonary artery wedge pressure (PR-AC interval, left atrial size and left atrial emptying index) did not accurately predict pulmonary artery wedge pressure by correlation coefficients of r = 0.45, 0.56 and 0.45, respectively (Fig. 3).

## Discussion

Previous attempts to define echocardiographic determinants of left ventricular filling pressure utilized highly selected groups of patients with relatively normal hemodynamic status studied retrospectively. In the present study, two independent observers prospectively compared four different echocardiographic estimates of pulmonary artery wedge pressure with a simultaneously obtained catheterization-measured value in a group of 25 patients with stable cardiac disease. Both the invasive and the noninvasive recordings were obtained simultaneously in the cardiac catheterization laboratory or the intensive care area. The relation of Q-mitral valve closure/aortic valve closure-E (Q-MVC/AVC-E) ratio to pulmonary artery wedge pressure in a group of 34 patients previously reported by us (2) revealed a highly significant correlation (r = 0.94). The pulmonary artery wedge pressure predicted by the linear regression equation, obtained in this latter study, was currently tested in a prospective manner in 25 patients and it correlated well with the measured pressure (r = 0.91). The relation of the Q-MVC/AVC-E ratio to the measured pulmonary artery wedge pressure, prospectively obtained in the present study, continues to show an excellent correlation (r = 0.91).

**Physiologic rationale for Q-MVC/AVC-E ratio as an estimate of pulmonary wedge pressure.** The physiologic rationale for relating the Q-MVC/AVC-E ratio to pulmonary artery wedge pressure is based on considerations derived from phonocardiographic measurements of these intervals in studies of mitral stenosis (8,9). The interval of Q wave to the mitral component of the first sound ($M_1$) is prolonged in severe mitral stenosis, while the interval between the aortic component of the second sound ($A_2$) and the mitral opening snap (OS) is shortened. The ratio of the phonocardiographic intervals $Q - M_1/A_2 - OS$ is equivalent to the echographic ratio of Q-MVC/AVC-E and it correlates closely with the mean pulmonary artery wedge pressure in mitral stenosis (10).

Because small variabilities always exist between the phonocardiographic and echocardiographic events (11,12), the formula derived from phonocardiographic measurements presumably differs somewhat from the echocardiographic formula. The high correlation we initially reported and subsequently documented herein between the Q-MVC/AVC-E ratio and measured pulmonary artery wedge pressure is somewhat surprising because multiple determinants govern the Q-MVC and AVC-E intervals. The Q to mitral valve closure (MVC) interval is influenced by heart rate (13), PR interval (14,15), electromechanical delay (16,17), first derivative of left ventricular pressure (dP/dt) and left atrial pressure at the time of crossover with the left ventricular pressure. The aortic valve closure to opening snap ($A_2$-OS) interval is similarly influenced by a number of variables: heart rate (13), systemic arterial pressure (17,18), rate of isovolumic relaxation and left atrial pressure. Despite this multiplicity of potentially discordant variables, combining the two intervals into a ratio in patients with a normal PR interval appears to cancel potential errors and yields an impressive positive correlation coefficient.

The linear regression equation for determination of pulmonary artery wedge pressure from echographic data in the groups of patients initially reported on and those studied herein remains quite identical. Though the formula may vary in different laboratories because of variation in techniques or measurement problems introduced when combining phonocardiography with echocardiography (19,20), the general validity of a linear relation between the described ratio of intervals and pulmonary artery wedge pressure seems established.

**Left atrial emptying index and pulmonary wedge pressure.** Originally, the echocardiographic analysis of the posterior aortic wall was thought to yield data as to left atrial volume (21). Changes of posterior aortic wall movement correlated with volume changes in the left atrium. Posterior aortic wall motion during diastole was subsequently quantified by a left atrial emptying index in an attempt to assess mitral valve obstruction in patients with mitral stenosis (6). The left atrial emptying index represents the fractional change in diastolic motion of the aortic posterior wall in the first one-third of diastole.

Recently, Wasserman et al. (1) evaluated the relation between the left atrial emptying index and pulmonary artery pressure. In 21 patients without mitral stenosis, they found a highly significant negative correlation (r = 0.91). The present study does not substantiate these observations; we found the correlation to be poor, although significant (r = 0.45, $p < 0.05$). Our inability to reproduce their results presumably relates to differences in design and patient selection. The study of Wasserman et al. excluded patients with valvular disease such as mitral regurgitation, because the aortic root excursion in this group has significantly increased motion (22). In 12 (57%) of their 21 patients, the pulmonary artery wedge pressure was 9 mm Hg or less, although in only 6 (24%) of our group of 25 patients the measured pressure was 9 mm Hg or less. This fact alone may account for their high negative correlation coefficient. It is also conceivable that the passive posterior aortic wall motion during the first third of diastole is not solely dependent on left atrial emptying; other factors include total aortic root excursion, compliance of the aortic root and systemic peripheral resistance (1,22,23).

**Left atrial size as an index of pulmonary wedge pressure.** Our study did confirm the previous observation in which the PR-AC interval and left atrial dimension correlate independently, but poorly, with pulmonary artery wedge pressure (r = 0.45 and 0.56, respectively) (5,24). However, a close correlation between left ventricular end-diastolic pressure and left atrial dimension as measured by two-dimensional echocardiography in an experimental animal study has been reported (25). The parallel clinical study in which left atrial size by M-mode echocardiogram was related to the pulmonary artery wedge pressure revealed a poor, but significant correlation in a recent study (5), although in another report published several years ago (26) the authors concluded that M-mode left atrial size cannot be used to satisfactorily assess pulmonary capillary pressure after intervention.

**PR-AC interval as an index of pulmonary wedge pressure.** A PR-AC interval of 60 ms or greater correctly predicted a pulmonary artery wedge pressure of 20 mm Hg or less in 12 (92%) of 13 patients; however, in only 4 (33%) of 12 with a PR-AC interval less than 60 ms was the pulmonary artery wedge pressure greater than 20 mm Hg. These data are essentially similar to those reported by Lewis et al. (24) wherein 15 (94%) of 16 patients with a PR-AC interval greater than 60 ms had a left ventricular end-diastolic pressure less than 20 mm Hg. Our results are somewhat different from those of Yow and Reicheck (27), who observed that all four patients with left ventricular end-diastolic pressure greater than 20 mm Hg demonstrated a PR-AC interval less than 60 ms.

**Clinical implications.** On the basis of the present study we conclude that in patients with diverse causes of left ventricular dysfunction, echocardiographic measurements of PR-AC interval, left atrial size and left atrial emptying index are of limited value in quantitating left ventricular filling pressure as reflected by mean pulmonary artery wedge pressure. Conversely, the echographic ratio of Q-mitral valve closure/aortic valve closure-E point (Q-MVC/AVC-E) seems validated prospectively in predicting pulmonary artery wedge pressure and appears to be the best available M-mode echocardiographic technique for assessment of this hemodynamic variable.

## References

1. Wasserman AG, Meyer JF, Ross AM. The relationship of pulmonary artery wedge pressure to the posterior aortic wall echocardiogram in patients free of obstructive mitral valve disease. Am Heart J 1980;100.500–5.
2. Askenazi J, Koenigsberg DI, Ziegler JH, Lesch M. Echocardiographic estimates of pulmonary artery wedge pressure. N Engl J Med 1981;305:1566–8.
3. Konecke LL, Feigenbaum H, Chang S, Corya BC, Fischer JC. Abnormal mitral valve motion in patients with elevated left ventricular diastolic pressure. Circulation 1973;47:989–96.
4. Corya BC, Rasmussen S, Knoebel SB, Feigenbaum H. M-mode echocardiography in evaluating left ventricular function and surgical risk in patients with coronary artery disease. Chest 1977;72:181–5.
5 Wilson JR, Robertson JF, Holford F, Reichek N. Evaluation of M-mode echocardiographic estimates of left ventricle function: relationship of selected ultrasonic and hemodynamic parameters. Am Heart J 1981;101:249–54.
6. Strunk B, London EJ, Fitzgerald J, Popp RL, Barry WH. The assessment of mitral stenosis and prosthetic mitral valve obstruction using the posterior aortic wall echocardiogram. Circulation 1977;55:885–91.
7. Hirato T, Wolfe SB, Popp RL, Helmen CH, Feigenbaum H. Estimation of left atrial size using ultrasound. Am Heart J 1969;78:43–53.
8. Wells B. The assessment of mitral stenosis by phonocardiography Br Heart J 1954,16:461–6
9. Bayer O, Loogen F, Wolter HH. The mitral opening snap in the quantitative diagnosis of mitral stenosis. Am Heart J 1956;51:234–45.
10. Yigitbasi O, Nalbantgil I, Birand A, Terek A. Q-I/IIA-OS formula for predicting left atrial pressure in mitral stenosis. Br Heart J 1970,32:547–50.
11. Chandraratna PAN, Lopez JM, Cohen LA. Echocardiographic observations on the mechanism of production of the second heart sound. Circulation 1975;51:292–6.
12. Anatassiades PC, Quinones MA, Gaasch WH, Adyanthaya AV, Waggoner AD, Alexander JK. Aortic valve closure:echocardiographic, phonocardiographic and hemodynamic assessment. Am Heart J 1976;91.228–32.
13. Wells BG. Prediction of mitral pressure gradient from heart sounds. Br Med J 1957;2:551–4.
14. Burggraf GW, Craig E. The first heart sound in complete heart block: phono-echocardiographic correlations. Circulation 1974;50:17–24.
15. Brooks N, Leech G, Leatham A. Factors responsible for normal splitting of first heart sound:high speed echo-phonocardiographic study of valve movement. Br Heart J 1979;42:695–702.
16. Kelly JJ Jr. Diagnostic value of phonocardiography in mitral stenosis: mode of production of first heart sound. Am J Med 1955;19:862–8.
17. Julian D, Davies LG Heart sounds and intracardiac pressures in mitral stenosis. Br Heart J 1957;19:486–94.
18. Oriol A, Palmer WH, Nakhjavan F, McGregor M. Prediction of left atrial pressure from the second sound-opening snap interval. Am J Cardiol 1965;16:184–8.
19. Abdulla AM, Kavouras T, Rivas F, Stefadouros MA. Determination of mean pulmonary capillary pressure by a noninvasive technique. JAMA 1980;243:1539–42.

20. Palomo AR, Quinones MA, Waggoner AD, Kumpuris AG, Miller RR. Echophonocardiographic determination of left atrial and left ventricular filling pressures with and without mitral stenosis Circulation 1976;54:744–50.

21. Strunk BL, Fitzgerald JW, Lipton M, Popp RL, Barry WH. The posterior aortic wall echocardiogram: its relationship to left atrial volume change. Circulation 1976;54:744–50.

22. Akgun G, Layton C. Aortic root and left atrial wall motion: an echocardiographic study Br Heart J 1977;39:1082

23. Pratt RC, Parisi AF, Harrington JJ, Sasahara AA. The influence of left ventricular stroke volume on aortic root motion Circulation 1976;53.947–53.

24. Lewis JR, Parker JO, Burggraf GW. Mitral valve motion and changes in left ventricular end-diastolic pressure: a correlative study of the PR-AC interval. Am J Cardiol 1978;42:383–7

25. Haendchen RV, Povzhitohov M, Meerbaum S, Maurer G, Corday E. Evaluation of changes in left ventricular end-diastolic pressure by left atrial two-dimensional echocardiography. Am Heart J 1982;104:740–5

26. Orlando J, Del Vicario M, Aronow WS, Cassidy J. Correlation of mean pulmonary wedge pressure, left atrial dimension and PTV-V in patients with acute myocardial infarction. Circulation 1977;55:750–2.

27. Yow MV, Reichek N. Left ventricular end-diastolic pressure and echocardiographic mitral valve closure. Circulation 1975:51,52(suppl II):II–51.