Comparison of Echocardiographic Methods for Assessment of Left Ventricular Shortening and Wall Stress

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M-mode echocardiographic measurement of left ventricular fractional shortening and meridional wall stress has been used extensively alone and in combination to describe left ventricular systolic function. To determine whether the improved dimensional information afforded by two-dimensional echocardiography might result in shortening and stress calculations yielding a different view of left ventricular function, we compared two-dimensional and M-mode echocardiograms in 69 subjects (19 normal, 13 with aortic stenosis, 22 with aortic regurgitation and 15 with congestive cardiomyopathy).

Fractional shortening was greater with M-mode than with two-dimensional echocardiography in all subjects, especially in those with cardiomyopathy (\(p < 0.05\)). In aortic stenosis, two-dimensional shortening, at \(24 \pm 5\%\), was reduced (\(p < 0.05\) versus normal), but M-mode shortening, at \(34 \pm 5\%\), was not. M-mode estimates of meridional stress were higher than two-dimensional values, again especially in cardiomyopathy. Two-dimensional echocardiography enabled determination of long- and short-axis ratios, circumferential stress and the ratio of circumferential to meridional stresses. Circumferential stress was elevated in aortic stenosis at \(302 \pm 65 \times 10^3\) dynes/cm\(^2\), suggesting afterload excess as the cause for the observed reduction in two-dimensional shortening. The more spherical cardiomyopathic hearts had a meridional to circumferential stress ratio closer to 1, such that use of meridional stress alone would overestimate effective afterload.

It is concluded that M-mode and two-dimensional echocardiographic analyses of left ventricular shortening and stress produce different results. Two-dimensional echocardiographic methods may enhance the assessment of ventricular function, especially in patients with aortic stenosis and cardiomyopathy.

Methods

Study patients. M-mode and two-dimensional echocardiograms were performed in 69 subjects. There were 19 normal volunteers, without historic or echocardiographic evidence of cardiac disease, including 11 men and 8 women with a mean age of 28 years (range 25 to 35). Among 50
subjects with heart disease recruited from a clinical echocardiographic laboratory there were 13 with catheterization-documented critical aortic stenosis (8 male, 5 female; mean age 64 years, range 39 to 82); 22 with pure 3 to 4 + aortic regurgitation (18 men, 4 women; mean age 35, range 18 to 55); and 15 with congestive cardiomyopathy who were in functional class III or IV (8 men, 7 women; mean age 54 years, range 28 to 71). Because of the differing age range in each of the patient groups, a single group of normal subjects could not be matched to all patient groups simultaneously. Instead, normal subjects were similar in age to those with aortic regurgitation.

All subjects with aortic stenosis underwent cardiac catheterization to determine hemodynamics and exclude the presence of coronary disease, significant aortic regurgitation and mitral valve disease. Subjects with aortic regurgitation or cardiomyopathy had no historic, physical, electrocardiographic or echocardiographic evidence of ischemic heart disease, other valvular disease or segmental contraction abnormalities.

M-Mode echocardiography. M-mode echocardiograms were performed using either a Varian 3000, two-dimensionally guided echocardiograph (68% of subjects) or a SmithKline Ekoline echocardiograph (stand alone, 32% of subjects) and either 2.4 or 2.25 MHz transducers at 50 mm/s paper speed. M-mode data obtained from stand-alone equipment and obtained using two-dimensional guidance showed similar relations to two-dimensional results; therefore all M-mode results were analyzed as one group. Left ventricular images were evaluated at the chordal level just below the mitral valve leaflet tips when simultaneous visualization of septum and posterior wall was optimal. Three to five cardiac cycles were measured at end-diastole, taken at the maximal posterior wall endocardial echocardiogram. Posterior wall thickness was measured from leading edge of the posterior wall endocardium to leading edge of the epicardium, and left ventricular internal dimension was determined from the trailing edge of the left septal echocardiogram to the leading edge of the posterior wall endocardial echocardiogram. Measurements were performed on a Hewlett-Packard 9825 programmable calculator interfaced to a high resolution digitizer (resolution 0.01 inch [0.025 cm]). Meridional stress was calculated by the method of Mirsky (14) as

\[ \frac{2D \text{LVID}_{d} - 2D \text{LVID}_{s}}{2D \text{LVID}_{d}} \times 100. \]

where LVIDd and LVIDs = left ventricular internal dimension at end-diastole and end-systole, respectively.

Two-dimensional echocardiography. Two-dimensional echocardiograms were obtained using a commercially available phased array echocardiograph and 2.25 MHz transducers. Left ventricular short-axis images were recorded for measurement at the high papillary muscle level, when simultaneous visualization of the entire left ventricular perimeter was optimal. Subjects whose endocardium could not be seen around the entire ventricular cavity were excluded from study. Three to five cardiac cycles were selected for analysis at end-diastole (R wave peak) and end-systole (time of smallest cavity area). Left ventricular endocardium, epicardium and the right side of the interventricular septum were traced from a video monitor onto clear plastic overlays with a fine felt tip pen. Three to five left ventricular long-axis images were recorded and traced from the apical four chamber view for measurement of left ventricular length at end-systole. Length was measured from the midpoint of the mitral anulus to the apical endocardium.

Calibrated tracings were digitized on a Hewlett-Packard 9825 microcomputer equipped with a high resolution digitizer to determine total left ventricular area (At) and left ventricular cavity area (Ac). The protruding portions of the papillary muscles were arbitrarily assigned to the left ventricular cavity. Myocardial area was determined by subtraction (Am = At - Ac). Interobserver variability for these methods have been previously characterized and shown to be acceptable (r = 0.98 for total left ventricular area, r = 0.96 for left ventricular cavity area) (11). Further, this method of overlay tracing and digitization produced results nearly identical to direct measurements of area by light pen (r = 0.98; slope = 0.96, intercept = 1.96 cm²).

Because we have previously demonstrated that two-dimensional images overestimate myocardial area (Am) and underestimate cavity area (Ac) in a predictable, instrument-specific fashion (11–13), results were regression corrected to provide accurate absolute values for cavity area and myocardial area.

To permit comparison of M-mode and two-dimensional data more directly we calculated two-dimensional left ventricular interval dimension (LVID) = \( 2\sqrt{\frac{Am}{\pi}} \) and two-dimensional mean wall thickness as \( \sqrt{\frac{4}{\pi}} \). Percent shortening was calculated as

\[ \sigma_m = 1.33 \frac{P \text{Am}}{\text{10}^3 \text{ dynes/cm}^2}, \]

where P = peak left ventricular pressure. End-systolic circumferential stress was calculated by the method of Mirsky (14) as

\[ \sigma_c = \frac{(1.33) P \sqrt{Ac}}{\sqrt{A_m + A_c} - \sqrt{Ac}} \left( \frac{4(\pi)^{3/2}}{(\pi L)^2} \right), \]
where $P$ = peak left ventricular pressure and $L$ = left ventricular long-axis length.

**Pressure measurements.** Peak left ventricular pressure was estimated by systolic cuff pressure in patients without aortic stenosis and measured by standard methods at cardiac catheterization in patients with aortic stenosis. We (15) have previously demonstrated excellent correlations between estimates of end-systolic left ventricular pressure and wall stress based on peak cuff or sphygmomanometer pressure and those based on high fidelity invasive end-systolic pressure ($r = 0.89$ for pressure, $r = 0.97$ for stress). Because pressure determination was identical for both M-mode and two-dimensional echocardiograms, any possible error should not affect comparison of the two methods.

**Statistical methods.** Relations between M-mode and two-dimensional echocardiographic results were examined using least squares linear regression and paired $t$ testing and comparison of subject groups by diagnosis was performed by analysis of variance (16).

**Results**

**Systolic shortening.** M-mode left ventricular percent systolic shortening ranged from 1 to 37%; two-dimensionally derived values ranged from 2 to 38%. The regression equation relating the two was two-dimensional shortening $= 9.28 + 0.85$ M-mode shortening, with a correlation coefficient of $r = 0.81$ (Fig. 1A). Thus, M-mode measurement of shortening yielded higher values and correlated moderately with two-dimensional measures of shortening. To further examine the two methods, we compared M-mode and two-dimensional measures of chamber diameter. Left ventricular cavity dimensions by M-mode and two-dimensional methods correlated well at both end-diastole and end-systole with regression slopes of 1.01 and 1.06 and correlation coefficients of 0.89 and 0.92, respectively.

**Comparison of M-mode and two-dimensional shortening by diagnostic groups** revealed disease-specific differences between the two methods (Fig. 2). Values for percent systolic shortening by M-mode methods were: normal $34 \pm 5\%$; aortic stenosis $34 \pm 5\%$; aortic regurgitation $31 \pm 7\%$; congestive cardiomyopathy $12 \pm 7\%$. Using two-dimensional echocardiographic-derived percent change in diameter, patient group values were: normal $30 \pm 5\%$; aortic stenosis $24 \pm 5\%$; aortic regurgitation $25 \pm 7\%$; congestive cardiomyopathy $8 \pm 5\%$. Percent systolic shortening by two-dimensional methods was lower than by M-mode methods in each of the patient groups, with significance levels of probability ($p < 0.05$ in the normal group and $p < 0.01$ in the congestive cardiomyopathy, aortic stenosis and aortic regurgitation groups. The discrepancy between the two methods was examined by comparing the ratio of M-mode to two-dimensional results and found to be greater for congestive cardiomyopathy ($p < 0.05$) than for any other group. More importantly, two-dimensional methods detected reduced shortening in aortic stenosis ($p < 0.05$) but M-mode methods did not.

**Meridional stress.** M-mode meridional end-systolic stress ranged from 32 to $302 \times 10^3$ dyne/cm$^2$ in the study population, and two-dimensional meridional stress from 68 to $400 \times 10^3$ dyne/cm$^2$. The regression equation relating the two was two-dimensional stress $= 2.52 + 1.43$ M-mode stress, with a correlation coefficient of 0.71 (Fig. 1B). Thus, M-mode and two-dimensional meridional stress values correlated only moderately well, with M-mode values being systematically lower than those obtained using two-dimensional echocardiography.

To determine the source of disagreement between M-mode and two-dimensional meridional stress, we compared M-mode and two dimensional measures of wall thickness. In contrast to cavity diameter, M-mode posterior wall thickness correlated poorly with mean two-dimensional wall thickness and was larger at both end-diastole and end-systole. The regression equations relating the two echocardiographic methods had slopes of 0.39 at end-diastole and 0.61
at end-systole with correlation coefficients of only 0.37 and 0.57, respectively.

Comparison of stress calculations by subjects' diagnostic groups revealed an average value of M-mode meridional end-systolic stress in the normal group of $73 \pm 21 \times 10^3$ dynes/cm$^2$. In contrast, average values were $78 \pm 25$ in aortic stenosis, $97 \pm 37$ in aortic regurgitation and $136 \pm 39$ in congestive cardiomyopathy (Fig. 3). Only the congestive cardiomyopathy group differed significantly from the other patient groups ($p < 0.01$). The average values for two-dimensional meridional stress were: normal $86 \pm 16 \times 10^3$ dynes/cm$^2$; aortic stenosis $110 \pm 25$; aortic regurgitation $120 \pm 43$; congestive cardiomyopathy $252 \pm 78$ (Fig. 3). Only the congestive cardiomyopathy group differed significantly ($p < 0.01$) from other patient groups, although a trend toward higher wall stress in aortic stenosis and aortic regurgitation was noted. Further, the trend toward higher wall stress in aortic stenosis and aortic regurgitation was noted. Further, the trend toward higher wall stress in aortic stenosis was noted only by two-dimensional methods. Although M-mode stress was lower in all patient groups because of larger measured wall thickness, the differences between the two methods, expressed as the ratio of two-dimensional/M-mode meridional stress, were more marked in the congestive cardiomyopathy group ($p < 0.01$) than in any other groups.

Chamber shape and circumferential stress. Two-dimensional echocardiography permits direct measurement of left ventricular length and assessment of left ventricular shape by comparison of long- and short-axis dimensions. End-systolic left ventricular length ranged from 4.8 to 11.5 cm, whereas end-systolic short-axis dimension ranged from 2.6 to 9.1 cm by two-dimensional echocardiography. Mean long-axis lengths by diagnosis groups were: normal $7.4 \pm 1.0$ cm; aortic stenosis $7.3 \pm 1.1$; aortic regurgitation $9.0 \pm 1.2$; congestive cardiomyopathy $9.5 \pm 1.1$; there were significantly longer lengths in aortic regurgitation and congestive cardiomyopathy groups than in aortic stenosis or normal groups ($p < 0.01$). The ratio of short-to long-axis lengths ranged from 1.0 to 3.2. Average ratios by diagnosis were: normal $2.2 \pm 0.3$; aortic stenosis $2.2 \pm 0.5$; aortic regurgitation $1.9 \pm 0.3$; congestive cardiomyopathy $1.4 \pm 0.3$. The ratio of long-to short-axis lengths was higher in the normal and aortic stenosis groups indicating a more ellipsoidal left ventricular shape, than in the aortic regurgitation group ($p < 0.05$ versus normal) or the congestive cardiomyopathy group ($p < 0.01$ versus all groups). The volume-overloaded and cardiomyopathic hearts had a more spherical left ventricular shape, as well as larger chambers.

Circumferential end-systolic stress ranged from 174 to $573 \times 10^3$ dynes/cm$^2$ (Fig. 3). Analysis of circumferential stress by patient groups showed average values to be $213 \pm 29 \times 10^3$ dynes/cm$^2$ in normal, $302 \pm 65$ in aortic stenosis, $268 \pm 24$ in aortic regurgitation and $413 \pm 102$ in congestive cardiomyopathy groups. Again the value in congestive cardiomyopathy was higher than in other groups ($p < 0.01$); however, stress was also significantly higher in the aortic stenosis than the normal group ($p < 0.01$). This finding of increased circumferential stress in aortic stenosis confirms the trend toward higher stress noted by two-dimensional methods of calculating meridional stress. Together, the two-dimensional data suggest that the reduced two-dimensional echocardiographic shortening is likely due to afterload excess and not impaired myocardial function.

The differences between M-mode and two-dimensional assessment of ventricular function in aortic stenosis is emphasized by plotting stress against shortening (Fig. 4). Use of M-mode shortening and meridional stress (open square in Fig. 4) makes the aortic stenosis group indistinguishable from the normal group. In contrast, use of two-dimensional shortening and circumferential stress (closed square), the
physiologically correct comparison, shows increased stress and reduced shortening. Although not shown, comparison of two-dimensional and M-mode measures of the same variables, meridional stress and shortening, reveals a trend toward lower shortening and higher stress which reaches significance when circumferential stress is used.

The differences in chamber shape noted among subject groups were closely paralleled by differences in the ratios of circumferential to meridional stresses. The ratios of orthogonal stresses were: normal group 2.57 ± 0.33; aortic stenosis group 2.70 ± 0.34; aortic regurgitation group 2.31 ± 0.23; congestive cardiomyopathy group 1.71 ± 0.21. The two stresses were more nearly equal in congestive cardiomyopathy than in all other groups (p < 0.01) and in aortic regurgitation than in either the normal or aortic stenosis groups (p < 0.05). Thus, as expected, the more spherical hearts had stress ratios closer to 1. Because circumferential stress is the more important load, consideration of meridional stress alone would lead to an overestimation of afterload.

Effects of age. Because normal subjects could not be age matched to all patient groups, we examined the effects of age on our results in normal subjects. No systematic relation between age and either M-mode or two-dimensional echocardiographic stress or shortening determination were found in normal subjects. Similarly, the relation between data obtained using the two techniques were unaffected by subject age.

Discussion
The present study examines two echocardiographic techniques used for the evaluation of left ventricular shortening and wall stress. These variables vary markedly in different types of cardiovascular disease and both alone and together have been proposed as measures of ventricular function, useful for diagnostic and prognostic determinations (1–4,6–10). Left ventricular size and shape are known to be important considerations in the assessment of systolic function (4,6,17–19), and may in themselves alter results of stress and shortening calculations. Thus, the accuracy and completeness with which left ventricular geometry is defined may substantially affect determinations of function.

Echocardiography is currently the most widely accepted noninvasive tool used for assessment of left ventricular wall thickness and chamber size, with M-mode methods conventionally used for assessment of wall stress. Recently, we have described methods by which both meridional and circumferential stresses may be measured using two-dimensional echocardiography (10). Therefore, we sought to analyze the results obtained by the two methods to evaluate the assessment of ventricular function obtained by M-mode and two-dimensional echocardiographic techniques.

Comparison of M-mode and two-dimensional echocardiographic results. We found that descriptions of chamber architecture, as well as fractional shortening and wall stress by these two methods, differ systematically in a complex, disease-related pattern. M-mode data resulted in consistently higher values for shortening, but lower values for meridional stress than did two-dimensional methods. The two methods correlated somewhat better for shortening than for stress. The failure of M-mode recording to detect reduced shortening in patients with aortic stenosis is of special concern.

Perhaps the greatest difference between M-mode and two-dimensional methods is the ability to measure long-axis length. Because shape is known to be variably altered in cardiovascular disease states, (4,6,17) it cannot be determined by a fixed long- or short-axis ratio. Further, if shortening or end-systolic size and load are to be interrelated, it is important to consider the force acting on the plane in which shortening or size is observed. Because circumferential stress occurs in the same plane as minor axis dimension and shortening, it is the appropriate load to consider in the stress-shortening or stress-dimension relation. In addition to being physiologically correct, use of circumferential stress may yield a different picture of ventricular function than does meridional stress. For example, in a group of patients with dilated cardiomyopathy, Laskey et al. (6) noted no slope change from normal in the meridional stress–end-systolic dimension relation, whereas the circumferential stress–dimension relation demonstrated a reduced slope, suggesting impaired contractility.

Differences between M-mode and two-dimensional results are quite striking in the patients with cardiomyopathy. Use of M-mode data to construct a meridional stress-shortening relation would imply greater myocardial dysfunction and a lesser component of afterload excess than would con-
structing a circumferential stress–shortening relation. Thus, two-dimensional data provide an important rationale for afterload reduction in congestive cardiomyopathy: to the extent that pump function is depressed by excess load, reduction of that load will improve ventricular performance.

The two echocardiographic methods also resulted in quite different pictures of ventricular function in aortic stenosis. M-mode meridional stress and shortening were normal, whereas two-dimensional shortening was reduced, two-dimensional meridional stress tended to be higher and circumferential stress was clearly elevated. This combination implies afterload excess, or depression of pump function due to abnormal loading conditions, rather than impaired intrinsic myocardial performance. Others (7,8) have documented afterload excess in aortic stenosis, and found that it provides a powerful argument to proceed with valve replacement despite clinical heart failure.

**Limitations of M-mode and two-dimensional echocardiographic methods.** Although no absolute reference standard is available to determine the more reliable technique, each echocardiographic method has important limitations. M-mode data are derived from a single dimensional sampling of the left ventricle, and septal measurements are generally excluded from consideration (20). In addition, unlike the majority of echocardiograms in the present study, many previous reports have used stand-alone M-mode instrumentation, which may fail to recognize oblique views. However accepted in published data, these characteristics make M-mode echocardiography extremely sensitive to small errors in transducer angulation or endocardial identification. Such small errors are magnified by stress equations which include calculation of relative wall thickness. In contrast, the two-dimensional echocardiogram provides more accurate spatial orientation and extensive cross-sectional sampling with determination of dimensional information around the entire left ventricle border. Chance errors are more likely to be canceled out and true regional variability more likely to be accurately incorporated.

**Wall thickness.** We (21) and others (22) have demonstrated significant heterogeneity of wall thickness in both normal and cardiac disease states, such that the ventricular wall progressively thins from base to apex. Because M-mode information is recorded more basally than two-dimensional information, one might expect a discrepancy between M-mode and two-dimensional data, with greater wall thickness measured by the M-mode method. Indeed, we found wall thickness to be larger by the M-mode method.

Whereas the present study employed anatomically validated regression equations for correction of known systematic error in two-dimensional measurements (11,13), no equivalent corrective technique is available for M-mode methods. Instead, conventional measures of posterior wall thickness provide less accurate estimation of anatomic mass than two-dimensional measures (13,23). Further, because cavity measures are similar, the differences between M-mode and two-dimensional wall thickness measures are probably due to differences between the two techniques and not to the two-dimensional regression correction.

**Chamber dimensions.** Like measurement of wall thickness, two-dimensional measures of chamber dimensions are also found to better predict anatomic information (12,13). Further, two-dimensional left ventricular dimensions and shortening correlate more closely with ventriculographic volume and ejection fraction estimates than do M-mode data (24), which have been found by others to overestimate angiographic data, much as the M-mode data overestimated two-dimensional fractional shortening in the present study.

**Two-dimensional echocardiography also has some recognized inherent limitations (25).** Extreme lateral "drop-out" due to structures being parallel to the ultrasound beam may occur, although far more of the left ventricular perimenter is routinely visualized than by the M-mode technique, and therefore can be included in shortening and stress calculations. Because of the lower frequency frame rate and real-time display, quantitative analysis of two-dimensional echocardiograms may be difficult and tedious. However, any resultant errors have been shown in vivo to be corrected by the anatomically validated regression techniques used in the present study (13).

**Conclusion.** The marked disease-related variability in left ventricular size, shape, shortening and wall stresses appear to be reflected differently by M-mode and two-dimensional echocardiographic techniques. The ability of two-dimensional echocardiography to accurately detect and quantitate changes in cavity shape, assess the appropriate measure of afterload and calculate the relation of orthogonal stresses appears to have a direct impact on the determination of ventricular function in both aortic stenosis and congestive cardiomyopathy. Two-dimensional methods appear preferable for noninvasive determinations of left ventricular stress and shortening.

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### References


