Determination of Left Ventricular Preload and Afterload by Quantitative Echocardiography in Man

CALIBRATION OF THE METHOD


ABSTRACT

Left ventricular circumferential wall stress at end-diastole (preload) and at the end of isovolumic left ventricular contraction (afterload) was calculated in 48 subjects with chronic myocardial and valvular heart disease by using left ventricular internal dimensions and wall thickness measured by quantitative echocardiography, left ventricular end-diastolic pressure, and aortic end-diastolic pressure. These calculations were then compared with similar determinations made using quantitative angiocardiography. Left ventricular preload and afterload determined by quantitative echocardiography and quantitative angiocardiography correlated significantly (r = 0.978 and 0.864, respectively). Left ventricular preloads of $30 \times 10^3$ dynes/cm$^2$ in subjects with mitral stenosis and $39 \times 10^3$ dynes/cm$^2$ in subjects with coronary artery disease unassociated with left ventricular dysfunction or mitral regurgitation were close to or within the normal range ($32 \times 10^3 \pm 4 \times 10^3$ dynes/cm$^2$). Left ventricular preload in subjects with compensated volume overload was comparable with the angiographically calculated values of $63 \times 10^3$, $57 \times 10^3$, and $53 \times 10^3$ dynes/cm$^2$ in subjects with coronary artery disease plus mitral regurgitation, mitral regurgitation, and aortic regurgitation, respectively. Left ventricular preload was most elevated in subjects with coronary artery disease associated with segmental left ventricular dyskinesis or akinesis. No significant differences in left ventricular afterload were noted between subject groups, although those with hypertrophic cardiac disease had the lowest calculated values. Quantitative echocardiography is an accurate technique for measuring left ventricular circumferential wall stress (preload and afterload) when left ventricular end-diastolic pressure and aortic end-diastolic pressure can be obtained.

KEY WORDS

- circumferential wall stress
- ultrasound
- left ventricular geometry
- left ventricular wall thickness
- valvular heart disease
- coronary artery disease

The adaptive anatomic and functional alterations of the left ventricle produced by chronic myocardial or valvular heart disease can be evaluated by measuring ventricular volume, intracavitary pressure, and mass. Quantitative angiocardiography (1) has facilitated description of the mechanical function of the ventricle in the normal state (2) and in a variety of abnormal conditions (3, 4). However, evaluation of ventricular function from ventricular volume, pressure, and mass (5) has always required cardiac catheterization. The limitations of angiocardiography have stimulated evaluation of quantitative echocardiography as a noninvasive method for assessing ventricular geometry and performance. The reliability of echocardiographic measurements of ventricular volume (6–9), wall thickness (10), and mass (10) has been documented by demonstrating a significant correlation between the ultrasound and the angiocardiographic measurements.

Angiocardiographic studies in subjects with chronic cardiac disease have demonstrated that adaptive changes in left ventricular volume, pressure, and mass are associated with alterations in the forces acting within the ventricular wall. Circumferential wall stress has been calculated using ventricular chamber dimensions, pressure, and wall thickness. Formulas derived from the basic Laplace expression for thin-walled structures have been modified so that angiocardiographically determined wall thickness can be used to calculate average

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circumferential wall stress across the ventricular wall at its equator (11). More recently, equations have been developed which permit calculation of the stress distribution across a thick-walled ellipsoidal shell (12). Stress calculations from both thin- and thick-walled models have compared favorably (13).

Peak systolic circumferential wall stress has been used to evaluate the significance of myocardial hypertrophy in chronic heart disease (14) and to provide a measure of ventricular wall force so that the force-velocity concept can be employed to define the contractile state of the left ventricle in man (15). Moreover, circumferential wall stress developed during isovolumic contraction is an important determinant of myocardial oxygen consumption (16). Measurement of left ventricular preload as circumferential wall stress at end-diastole and of left ventricular afterload as circumferential wall stress at the time of aortic valve opening permits further quantification of the interrelationship among changes in ventricular geometry, pressure, and wall thickness at specific points in the cardiac cycle.

The present study was undertaken (1) to compare the results of angiocardiographic and echocardiographic measurements of left ventricular circumferential wall stress and (2) to assess the validity of the assumptions made in the quantification of wall stress measured by echocardiography.

Methods

The 48 subjects included in this study were referred for routine diagnostic cardiac catheterization. Left ventricular biplane angiocardiograms and quantitative echocardiograms were obtained in each subject so that left ventricular dimensions and wall thickness could be quantified.

QUANTITATIVE ANGIOCARDIOGRAPHY

All subjects were studied in the postprandial state under local anesthesia without premedication. Intravascular and intracardiac pressures were measured with Statham P23Db strain-gauge transducers positioned at the midpoint of the chest. Left ventricular end-diastolic pressure was measured at the plateau following atrial systole (after the a wave) prior to ventricular contraction. In subjects with atrial fibrillation in whom no a wave could be identified, end-diastolic pressure was measured 0.05 seconds after the onset of the QRS complex (17). In these subjects as well as in those with sinus rhythm, end-diastolic pressure was averaged from a series of at least five representative cardiac cycles. Following the injection of contrast material into the left ventricle, biplane ventricular angiocardiograms were recorded using an Elema-Schonander roll film changer operating at 6-12 frames/sec. Left ventricular volumes were calculated by the area-length method of Dodge et al. (1) and were corrected by a standard radiographic magnification factor. Regression data and calculations were made using a computer program similar to one previously reported (18). The left ventricular minor diameter was determined from paired anteroposterior and lateral films; the values were averaged to obtain the short axis of a prolate ellipsoid. Average left ventricular wall thickness corrected for X-ray distortion was measured as described by Rackley et al. (5). Left ventricular circumferential wall stress was calculated by the method of Sandler and Dodge (11) from left ventricular and aortic end-diastolic pressures and angiocardiographically determined diastolic ventricular dimensions.

QUANTITATIVE ECHOCARDIOGRAPHY

Crowded conditions in the catheterization laboratory prevented simultaneous performance of both studies. Therefore, within 24 hours of cardiac catheterization angiocardiograms were performed using a Smith-Kline Ekoline-20 ultrasonoscope with 2.25-MHz transducers 0.50 inches in diameter focused at 5 or 10 cm. The echocardiographically determined minor axis was measured by the technique described by Feigenbaum et al. (9), Popp and Harrison (19), and others (6, 7). Subjects were recumbent with their heads elevated 30°. An aquasonic gel was applied to the skin area where the transducers were placed to ensure optimum contact. The transducer was positioned in the fourth or fifth intercostal space just to the left of the sternum and was directed posteriorly and medially until the characteristic pattern of mitral valve motion was discerned. The ultrasonic beam was then directed laterally and slightly inferiorly to locate a plane in which the motion of the interventricular septum and the left ventricular posterior wall components (endocardium and epicardium) could be detected simultaneously. The gain, damping, and reject controls of the ultrasonoscope were adjusted to optimally resolve echoes from these structures, which produce highly characteristic patterns of motion (Fig. 1). These movements were displayed in a B- or time-motion mode and were recorded on Polaroid film or by an Electronics-for-Medicine recorder (DR-S) with an ultrasonoscope interface (UDA) to obtain continuous strip charts.

To standardize the ultrasonoscope, the echo from the mitral valve was used as the reference point from which the ultrasonic beam was directed to a plane in which septal and posterior wall echoes could be observed simultaneously. The left ventricular internal dimensions were echocardiographically measured at end-diastole simultaneously with R wave of the electrocardiogram and at end-systole when the posterior wall and septum maximally approached each other. Ventricular internal dimensions were determined as the distance from the endocardial echo of the posterior left ventricular wall to the echo of the left side of the interventricular septum. Left ventricular...
LEFT VENTRICULAR WALL STRESS BY ECHOCARDIOGRAPHY

FIGURE 1

Left: Echocardiogram obtained from a normal patient to demonstrate techniques of measuring diastolic ventricular internal dimension (Dd) and posterior wall thickness (WT). Middle: Diagrammatic representation of left ventricular cavity and walls to further define measurements made from quantitative echocardiograms and angiocardiograms. Right: Schematic representation of aortic, left ventricular (LV), and pulmonary arterial (PA) pressure tracings for a single cardiac cycle. Asterisks define the times when pressure measurements should be made to determine left ventricular preload and afterload. EDP = end-diastolic pressure.

Wall thickness at end-diastole was estimated by measuring the distance between the left ventricular posterior wall endocardial and epicardial echoes at end-diastole. In subjects with atrial fibrillation, measurements of ventricular internal dimensions were averaged for at least five cardiac cycles. One or two observers made the echocardiographic measurements; the reproducibility of such measurements between observers has been documented.

Calculations

Calculation of left ventricular circumferential wall stress was based on the modified Laplace equation incorporated in the formula of Sandler and Dodge (11). This method utilizes a prolate ellipsoid figure and estimates mean circumferential wall stress (σ) across the ventricular wall at the equator:

\[ \sigma = \frac{Pb}{h} \left[ 1 - \frac{b^2}{a^2(2b + h)} \right], \tag{1} \]

where \( a \) is half the longest measured chamber axis (cm), \( b \) is half the mean minor axis (cm), \( P \) is left ventricular pressure (dynes/cm²), and \( h \) is left ventricular wall thickness (cm). Stress calculated by this formula represents a mean value across the thickness of the ventricular wall and therefore underestimates maximal stress at the endocardial layer and overestimates minimal stress at the epicardial surface.

The calculation of circumferential wall stress from echocardiographically determined ventricular dimensions and wall thickness with the Sandler and Dodge formula was based on previously validated assumptions (6). These assumptions are (1) that the ventricular internal dimension (D) measured by echocardiography is equivalent to the minor axis (2b) measured by angiocardiography and (2) that the angiocardiographically measured minor axis, which is an average of the measurements in the anteroposterior and lateral planes, is equal to half of the major axis (a). By substituting \( D = a \) and \( D/2 = b \) in Eq. 1, circumferential wall stress can be calculated from echocardiographic measurements. The equation becomes

\[ \sigma = \frac{PD/2}{h} \left[ 1 - \frac{D}{8(D + h)} \right], \tag{2} \]

where \( D \) is the ultrasonically measured ventricular internal dimension (cm), \( h \) is the ultrasonically measured ventricular wall thickness (cm), and \( P \) is the left ventricular end-diastolic or aortic end-diastolic pressure (dynes/cm²).

For both angiographic and echocardiographic calculations, the additional assumption was made that ventricular internal dimensions during isovolumic contraction did not change significantly and, thus, that end-diastolic dimensions and wall thickness could be substituted in Eq. 2 to calculate both preload and afterload. Left ventricular preload was calculated as circumferential wall stress at end-diastole and left ventricular afterload as circumferential wall stress at the time of aortic valve opening. Left ventricular and aortic pressures obtained during cardiac catheterization were used for both angiographic and echocardiographic calculations.

Results

A comparison of ventricular minor axis determinations at end-diastole by the two techniques is shown in Figure 2. The correlation coefficient was highly significant (r = 0.883), but a tendency toward slight underestimation of the ventricular minor axis by echocardiography, as previously noted (7), was observed. The angiographically measured end-diastolic major semiaxis and the echocardiographically measured ventricular end-diastolic internal dimension (Fig. 3) correlated less significantly (r = 0.574). The echocardiographically measured minor axis tended to exceed the angiographically measured major semiaxis by amounts that increased progressively as ventricular chamber size increased. Left ventricular end-diastolic wall thickness measured by angiography and echocardiography correlated significantly (r = 0.904, Fig. 4).

Comparisons of preload and afterload calculated by angiography and echocardiography are presented in Figure 5. The correlation coefficients (r = 0.978 and r = 0.864, respectively) were highly significant.

Mean left ventricular preload was elevated to 77.0 X 10^4 dynes/cm² according to quantitative echocardiography and to 71.5 X 10^4 dynes/cm² according to quantitative angiography.
13 subjects with chronic coronary artery disease associated with either mitral regurgitation or abnormally contracting (dyskinetic or akinetic) segments of left ventricular myocardium. Preload in the normal subjects ranged from \(19.1 \times 10^3\) to \(47.8 \times 10^3\) dynes/cm\(^2\) and agreed with values previously reported by Hood (20) (mean value of \(32 \times 10^3 \pm 4 \times 10^3\) dynes/cm\(^2\)). Mean ventricular preload was elevated to \(57.4 \times 10^3\) dynes/cm\(^2\) (quantitative echocardiography) and \(56.6 \times 10^3\) dynes/cm\(^2\) (angiocardiology) in 6 subjects with valvular mitral regurgitation unassociated with coronary artery disease, and to \(58.0 \times 10^3\) (echocardiography) and \(52.5 \times 10^3\) (angiocardiology) in three subjects with aortic regurgitation. Left ventricular after-
load in these subjects ranged from $141.9 \times 10^3$ to $523.3 \times 10^3$ dynes/cm$^2$ (echocardiography) and from $130.8 \times 10^3$ to $485.7 \times 10^3$ dynes/cm$^2$ (angiocardiology). No significant differences were noted in ventricular afterload among the various subject subgroups, although the subgroup with hypertrophic cardiac disease had the lowest calculated values.

Discussion

The present study was undertaken to assess the validity of diagnostic ultrasonic measurements of left ventricular wall stress at end-diastole (preload) and at the end of isovolumic contraction (afterload). The techniques of quantitative echocardiography, developed by Feigenbaum et al. (9) and Popp and Harrison (19), are based on the principle that ultrasound signals directed through the chest will be reflected by tissues or fluids of different densities or acoustical impedance. The diastolic left ventricular internal dimension measured by this technique correlated well with the angiocardiographically determined diastolic ventricular minor axis in both this study and previous ones (6, 7).

The use of the diastolic ventricular internal dimension in the calculation of left ventricular circumferential wall stress required the assumptions that (1) the echocardiographically determined diastolic ventricular minor axis is an accurate estimate of the angiocardiographically determined diastolic minor axis, (2) the ventricular minor axes in both the anteroposterior and lateral planes are equivalent, and (3) the ventricular minor axis is equal to the major semiaxis. The first assumption has been validated by the present study and by previous investigations (6, 7); studies by Sandler and Dodge (21) have confirmed the second assumption. The validity of the third assumption relates to the changes that occur in ventricular dimensions with increasing volume. Presumably, the normal ventricle manifests the geometrical dimensions of a prolate ellipse; therefore, the ventricular minor axis and major semiaxis are equal or nearly equal. With increasing volume the ventricle becomes more spherical and the ratio of the major axis to the minor axis decreases to less than two (22). Thus, theoretically, an increasing distortion of calculations could be introduced by using quantitative echocardiographically determined ventricular dimensions from ventricles of large volume. In this study, the angiocardiographically determined major semiaxis and the echocardiographically determined ventricular internal dimension did not correlate significantly; however, left ventricular preload and afterload calculated by the echocardiographic technique correlated significantly with similar calculations derived from angiocardiographic measurements of ventricular major and minor axes over a wide range of ventricular volumes and wall thicknesses. Other investigations have also noted that, despite the
changes in ventricular geometry associated with increasing volume, correlation coefficients between ventricular volumes calculated by both the echocardiographic and the angiographic technique are high (7). In addition, the present investigation has confirmed the accuracy of previously reported (10) echocardiographic measurements of left ventricular wall thickness.

The calculation of circumferential wall stress using the echocardiographic measurements and the assumptions described in the present study relies on a relationship between the ventricular internal dimensions and wall thickness assessed by ultrasound, which is more complex than one of linear regression. In addition to the measurement of the ventricular minor semiaxis and wall thickness, the angiographic calculation of wall stress requires direct measurement of the ventricular major semiaxis, an assessment which is not obtainable with the present echocardiographic technique. In both the present investigation and previous studies (7, 10), ultrasound measurements tended to variably underestimate angiocardio graphic determinations of ventricular diastolic internal dimensions and wall thickness. Furthermore, major-minor axis ratios vary in ventricles of different sizes. Although ultrasound and angiographic measurements can vary, echocardiographic measurements allow accurate calculation of wall stress over a wide range of ventricular sizes and pressures: the SE of the ventricular preload calculation was $±7.544 \times 10^3$ dynes/cm$^2$ and that of the ventricular afterload calculation was $±41.145 \times 10^3$ dynes/cm$^2$.

Left ventricular circumferential wall stress at the time of aortic valve opening was calculated from angiographically and echocardiographically determined end-diastolic chamber dimensions and wall thickness and from aortic diastolic pressure. The calculation of afterload or wall stress at the time of aortic valve opening assumes that ventricular chamber dimensions and wall thickness do not change in the isovolumic contraction period. Previous experimental studies have noted changes in ventricular shape and in the ratio of the long to the short axis in the isovolumic phase (23, 24). A recent cineangiographic investigation in subjects with and without left heart disease has described reductions in ventricular shape and volume during isovolumic contraction; these reductions are due primarily to changes in equatorial diameter and range from 2.8% of end-diastolic volume in normal subjects to 8.0% of end-diastolic volume in subjects with mitral regurgitation (25). Although the precise measurement of changes in ventricular wall thickness in experimental animals is complicated by technical difficulties, thickening of the ventricular wall at the equator during isovolumic contraction has been reported to vary from 9% to 11% (26, 27). Furthermore, in subjects with coronary artery disease and localized dysfunction, ventricular wall movement and thickening in the isovolumic contraction phase may not be uniform. In subjects with mitral regurgitation, whether rheumatic or secondary to myocardial dysfunction, the isovolumic phase is shortened before aortic valve opening, and true afterload cannot be precisely calculated with the present techniques.

Ventricular afterload in these studies, calculated with the present technique, would tend to overestimate actual values, since chamber dimensions would decrease prior to aortic valve opening. These limitations must be considered when ultrasound techniques are used to calculate afterload or circumferential wall stress at the time of aortic valve opening. Since brachial arterial pressures and phonocardiograms were not recorded simultaneously with the echocardiograms, the isovolumic period of ventricular systole was not defined in the present study. Changes in ventricular geometry during this period were not assessed.

In the present study, calculated left ventricular preload was elevated in subjects with chronic coronary artery disease associated with mitral regurgitation or with segmental ventricular dysfunction. Moderate elevations in preload were noted in those subjects with compensated volume overload resulting from mitral or aortic valvular regurgitation. Values for ventricular preload in these two groups were comparable to those described for similar subjects in previously reported studies (11, 28).

Previous studies have noted an overlap between mean values for circumferential wall stress in subject subgroups (13, 14, 20) and between individual values from different subject subgroups (28). This overlap between values for wall stress in subjects from different subgroups, described in terms of compensated and decompensated chronic valvular and myocardial disease, is reasonable, since each subgroup includes a range of individuals whose ventricles
vary in both size and hemodynamic characteristics. Calculated wall stress is an expression of the geometric and hemodynamic characteristics of individual ventricles and does not necessarily discriminate between subgroups.

Calculations of ventricular preload reflected changes in left ventricular filling pressure, but calculations of left ventricular afterload showed no significant mean differences between subject subgroups. Although ventricular circumferential wall stress at the time of aortic valve opening may be similar in a variety of chronic cardiac disorders, subsequent changes in wall stress during the ejection phase of the cardiac cycle may further aid in characterizing normal and abnormal ventricular function. The continuous assessment of changes in afterload during systolic ejection would require a simultaneous analysis of intravascular pressure and ultrasonically determined ventricular dimensions (29); the capability for such an analysis was not available at the time of the present study.

Although recent investigations (30, 31) have questioned the existence of a linear relationship between pulmonary artery end-diastolic pressure and left ventricular end-diastolic pressure, the accuracy of pulmonary artery end-diastolic pressure as a reflection of left ventricular end-diastolic pressure described in previous studies (32, 33) has been reconfirmed in recent studies. Rahimtoola et al. (34) have demonstrated a relationship between pulmonary artery end-diastolic pressure and left ventricular end-diastolic pressure in subjects with acute myocardial infarction. Scheinman et al. (35) have more recently suggested that pulmonary artery end-diastolic pressure is an accurate reflection of left ventricular end-diastolic pressure in subjects in shock resulting from several primary etiologies including acute myocardial infarction and have noted that good correlations exist between the two pressures not only during the resting state but also during hypoxia, volume loading, and the administration of sympathomimetic agents. These investigations indicate that the use of pulmonary artery end-diastolic pressure together with quantitative echocardiography may allow the assessment of ventricular preload and, thus, provide a more detailed description of ventricular function during acute situations of hemodynamic deficit.

The present study has further validated the use of quantitative echocardiography in the evaluation of left ventricular function. The accuracy of echocardiographically determined ventricular dimensions and wall thickness has been reconfirmed, and a significant correlation between circumferential wall stress determined by ultrasound and by angiographic techniques has been described. When systemic arterial and pulmonary arterial pressures are monitored, access to left ventricular chamber dimensions and wall thickness should permit quantification of both ventricular performance during acute illness and ventricular response to pharmacologic intervention. In patients undergoing diagnostic catheterization, ventricular performance at rest and during exercise or pharmacologic intervention can be evaluated without the injection of radiopaque dye, which may alter ventricular hemodynamics. The use of diagnostic ultrasound requires experienced and meticulous technique to obtain echocardiograms of the quality needed for quantitative analysis of ventricular function. Although approximately 80–90% of patients with chronic cardiac disease can be adequately studied, the success rate of studies in acutely ill patients falls to 50–70% or less. Both the noninvasive methodology and the opportunity to repeat measurements in a serial fashion are features of echocardiographic examination that may enhance its clinical value. However, the application of quantitative echocardiography in the measurement of ventricular function will continue to require calibration against the established techniques of quantitative angiocardiography to validate its accuracy and reproducibility.

References


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