Brief Reviews

Determination of Left Ventricular Size and Shape

By Harold Sandler and Edwin Alderman

The importance of ventricular size and shape in determining cardiac function has been recognized for over 80 years; the concept is embodied in the Frank-Starling mechanism and in Laplace's law of the heart. However, over this same period, chamber pressure and cardiac output rather than ventricular dimensions have been measured to assess cardiac function, largely because cardiac catheterization procedures have made these hemodynamic measurements readily obtainable. Moreover, measurements of individual atrial and ventricular dimensions have been difficult to accomplish and have not been obtainable on a regular basis until relatively recently. During the past 15 years, an increasing number of investigators have begun to correlate the traditional hemodynamic measurements of cardiac performance with the parameters that measure the mechanical properties of the heart wall. Such studies have required strict attention to changes in chamber geometry and their correlation with simultaneously occurring pressure and flow events. Dimensional studies involving isolated papillary muscles or the intact heart have demonstrated the importance of initial fiber length and velocity of shortening in defining contractile state (1-3). Physical properties of the intact ventricular wall such as tension or stress, elasticity, viscosity, and compliance have been defined from pressure-volume relationships (4-8). Measurements of left ventricular volumes have allowed the determination of beat-by-beat stroke volume, the quantification of regurgitant flow in valvular heart disease, the calculation of ejection fraction, and the in vivo estimation of left ventricular mass (9-15).

The methods presently being used to measure cardiac chamber dimensions and volume in animals or man have been summarized in several recent reviews and symposia (16-20); they are listed in Table 1. Those methods listed as direct require surgery and associated thoracotomy for observation of or transducer attachment to a cardiac chamber. Indirect methods provide dimensional information without thoracotomy and utilize noninvasive or minimally invasive nondestructive procedures.

TABLE 1

Methods for Measuring Cardiac Chamber Dimensions and Cardiac Volume

<table>
<thead>
<tr>
<th>Animals</th>
<th>Man</th>
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<tbody>
<tr>
<td>Direct (Requires Thoracotomy)</td>
<td>Direct (Requires Thoracotomy)</td>
</tr>
<tr>
<td>(1) Resistance (strain) gauges</td>
<td>(1) Resistance (strain) gauges</td>
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<tr>
<td>Walton Brodie</td>
<td>Walton Brodie</td>
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<tr>
<td>Mercury-in-Silastic (Whitney)</td>
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<tr>
<td>Wall thickness</td>
<td>Wall force</td>
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<tr>
<td>(2) Mutual inductance</td>
<td>(2) Mutual inductance</td>
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<tr>
<td>(3) Impedance</td>
<td>(3) Impedance</td>
</tr>
<tr>
<td>(4) Ultrasonic crystals (transit time)</td>
<td>(4) Ultrasonic crystals (transit time)</td>
</tr>
<tr>
<td>(5) Accelerometers</td>
<td>(5) Accelerometers</td>
</tr>
<tr>
<td>(6) Radiographic (clips, beads, or both)</td>
<td>(6) Radiographic (clips, beads, or both)</td>
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<tr>
<td>(7) Models or casts of chambers</td>
<td>(7) Models or casts of chambers</td>
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<tr>
<td>Indirect (without Thoracotomy)</td>
<td>Indirect (without Thoracotomy)</td>
</tr>
<tr>
<td>(1) Radiographic</td>
<td>(1) Radiographic</td>
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<tr>
<td>Single plane</td>
<td>Single plane</td>
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<tr>
<td>Biplane</td>
<td>Biplane</td>
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<tr>
<td>Videometry, video densitometry</td>
<td>Videometry, video densitometry</td>
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<tr>
<td>Coronary branch points</td>
<td>Coronary branch points</td>
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<td>Particulate and adhesive contrast material</td>
<td>Particulate and adhesive contrast material</td>
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<tr>
<td>Tantalum screws</td>
<td>Tantalum screws</td>
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<tr>
<td>(2) Catheters (ultrasound, Peiper, resistance gauges)</td>
<td>(2) Catheters (ultrasound, resistance gauges)</td>
</tr>
<tr>
<td>(3) Echo ultrasound</td>
<td>(3) Echo ultrasound</td>
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<tr>
<td>(4) Indicator dilution</td>
<td>(4) Indicator dilution</td>
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<tr>
<td>(5) Radioisotopes</td>
<td>(5) Radioisotopes</td>
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Much has been learned concerning cardiac physiology from open-chested animals and isolated heart preparations. By their nature, such experiments represent acute observations; they require surgery with associated anesthesia and thoracotomy which alter control mechanisms present in the awake conscious animal (21-24). With continued technologic advances, most direct methods for dimensional analysis are now usable in chronic animal studies. Despite these advances, direct methods for measuring dimensions cannot be used without producing certain problems or raising certain questions. Primary among these problems are the unknown effects of the associated surgery or the presence of the transducers on normal cardiac dynamic geometry. All proposed direct methods for obtaining dimensional data require procedures for calibration and verification of measurement accuracy over the period of experimentation. In addition, the requirements for surgery and thoracotomy limit the clinical applications of these methods. Finally, the great majority of the methods listed in Table 1, whether direct or indirect, measure only a single chamber dimension or an isolated segment or area of such a dimension; others, such as the indicator-dilution methods, measure only a single parameter such as end-diastolic volume. Few methods provide information concerning the overall dynamic geometry of the atria or ventricles. Radiography, particularly angiocardiography, has proven with time to be the most readily available, reliable method for these purposes (7, 17, 20). Information obtained from radiographic procedures has been used to describe the patterns of chamber filling and contraction (25-30), the effects of injuries such as myocardial infarction and valvular disease or dysfunction (31-33), and the effects of interventions such as surgery, drugs, or pacing on cardiac function (34-37), to detect the presence of ventricular hypertrophy (38), and to calibrate various transducers or methods used to measure chamber dimensions. Other newer methods which may be used for these purposes, such as radioisotope angiography (39, 40), echo ultrasound (41-44), and endocardial labeling with tantalum screws (45, 46), are under development and will be discussed briefly later.

Many methods and equations have been developed for determining heart size and shape from x-ray photographs or films (7, 47). The first approaches were directed toward estimation of the volume of the entire heart. Methods for calculating specific chamber volumes did not appear until the late 1950s and have been used most commonly for determining left ventricular volume. At the present time, there is no method which allows a determination of the absolute amount of blood in a given cardiac chamber during life. The lack of such a standard for comparison has made calibration of various methods, including angiocardiography, difficult. This problem has been solved in part by the use of various models, usually postmortem casts of specific heart chambers (47). These casts have been used to justify the representation of chamber outlines on either single-plane or biplane recordings by various mathematical models or regular geometric figures. Resultant studies have shown that all radiographic methods for calculating volumes are unreliable unless they are corrected by appropriate regression equations to adjust for changes resulting from projection errors or choice.

**FIGURE 1**
Angiocardiographically derived left ventricular chamber dimensions and calculated shell mass over a cardiac cycle in man (right anterior oblique view). Chord represents measured midaortic-to-apex length, diameter is calculated from image area and chord, and wall thickness is measured along the posterior wall.
of specific mathematical models. The validity of x-ray volume calculations has also been checked by correlating stroke volume and cardiac output measured angiographically with flow measured by implanted transducers or Fick and indicator-dilution methods (10, 48). Recently, the ability to measure left ventricular chamber wall thickness on either anteroposterior or right anterior oblique film projections has provided an additional means of independently validating the accuracy of chamber outlines (14). Figure 1 illustrates data typically obtained by measurements made frame-by-frame over several heart cycles from a human cineangiographic study. Left ventricular dimensions (chord, diameter) are determined from image area and length; posterior wall thickness is directly measured from this single-plane right anterior oblique study. Left ventricular volume and shell mass, representing the amount of muscle in the left ventricular wall, can be calculated from these values using an ellipsoid reference figure (14, 15). Muscle mass is determined from the ellipsoid shell volume created by adding wall thickness to the respective chamber radii (chord, diameter) and multiplying by the specific gravity of heart muscle. If chamber margins are drawn accurately, calculated shell mass is assumed to change no more than 25% (the estimated maximal error resulting from volume measurement on the films) from the end-diastolic value (Fig. 1). When variations in mass greater than 25% occur (particularly during systole), such changes indicate that chamber margins have not been drawn correctly; reexamination of the films is in order (14, 49). Determination of shell mass in itself has been useful in assessing function in patients with valvular or coronary artery disease. Markedly increased masses have been found in subjects with valvular heart disease, primary myocardiopathies, and coronary artery disease (7, 14, 15, 50, 51). In evaluating clinical or laboratory findings in such subjects, it is becoming increasingly clear that the total amount of muscle present is an important factor in itself and should be included or accounted for in all evaluations of ventricular performance; in other words, it is not sufficient to rely on measurements of stroke volume, pressure, or hydraulic power alone. It must be noted, however, that checks or calculations of shell mass are invalid or require special interpretations in hearts with overt aneurysms or major akinetic areas, particularly at the site of wall thickness determination.

Serious limitations still exist in making radiographic information concerning chamber size and shape available for clinical or investigative use within reasonable periods of time because of the tedious of associated calculations on angiographic films, the need for manual measurements, and the large volume of data requiring reduction if both the contraction and the relaxation phases of the cardiac cycle are to be evaluated. Original large-film x-ray studies recorded at 6 or 12 films/sec have been replaced over the past few years by motion picture studies recorded at 30-60 frames/sec. The latter studies have allowed for beat-by-beat analysis of recorded events; higher rates of 270 and 540 frames/sec have also been used experimentally for studies of flow patterns of particulate matter in arteries and veins and for motion studies of valve leaflets or ventricular wall segments (52, 53). The use of cine methods has resulted in a five- to thirtyfold increase in the volume of data requiring reduction and has stimulated the move toward partial or total use of automated computing techniques. Initially, information for such analyses was presented as prints or tracings of individual projected cine frames; more recently, stored single-plane or biplane television images have been used instead (54-56). Conversion to computer format has been accomplished by electronic planimeters, manual digitizers, light pens, or flying spot scanners. By these means, information concerning the margins of the chambers is stored or filed in the computer for subsequent display or analysis. Techniques for image enhancement, image subtraction, and totally unassisted analysis of masked portions of the original images are in progress but are still in need of further development.

At present, there is no agreement among various investigators as to the best method for image analysis or presentation of such information. Shape and shape alterations were initially assessed from changes in maximal or specific chamber diameters or characteristics (such as eccentricity or length-width ratios) of the various geometric models used for calculating ventricular volume (5, 7, 14, 36, 57). More recently, procedures based on slicing of opacified left ventricular images have been introduced by Herman and co-workers (58). The image is sectioned in this approach by at least three diameters drawn perpendicular to the long axis of the chamber: one diameter is placed at the midpoint and the other two divide the remaining halves into quarters. Changes in shape are determined from absolute measurements of length and
of the various constructed diameters, or their percent change from end-diastolic values is used. These descriptions have provided useful information about the presence or the absence of abnormal wall segment motion (30, 33, 36, 57-64). Images from successive frames have also been superimposed for detailed analysis of contours and compared with end-diastolic outlines (36, 51, 57-64). Analysis has been based on the assumption that the ventricle contracts in one of two ways: either concentrically about its center or with a fixed aortic valve plane. With the first assumption, images are superimposed using chamber length and midlength diameters. Contours from normal subjects show relatively concentric movement of all axes from end-diastole to end-systole (58, 64). Outlines from subjects with akinesis or aneurysm, however, show marked changes from such patterns with systolic contours that shift toward or extend beyond end-diastolic outlines. Analysis of images by the second assumption has been based on the use of a fixed cardiac structure such as a visualized cardiac catheter or a valve plane instead of an internal geometric center. Qualitative descriptions of chamber motion are similar whichever system is used. Quantitative studies of aortic and mitral valve plane motions, however, have demonstrated that the valves regularly move toward the cardiac apex during systole (65-67). Analyses of successive cine frames with the valve plane motion fixed would result in an accurate description of changes in chamber volume, but an accurate analysis of the changes in chamber contour or shape over the cardiac cycle would not be possible. In this regard, neither system is correct, since contour analysis can only be accomplished with a reference or coordinate system which is external to the chamber itself. In the past, reference points have been provided by beads or cross hairs attached to the image intensifier (7, 51); more recently, fixed noncardiac anatomic structures such as the diaphragm have been used when angiographic data are recorded during inspiration (68).

The use of right anterior oblique ventriculograms or other single-plane views, such as a posteroanterior projection, for analysis of localized abnormalities, although expeditious, yields incomplete data. Right anterior oblique methods do detect 60-70% of segmental contraction abnormalities which are noted using biplane techniques (69). However, significant segmental abnormalities may be missed completely or their true extent underestimated in the absence of other projections. Moreover, major segmental myocardial abnormalities introduce errors into the calculations of ventricular volume due to the use of a regular geometric reference figure (usually an ellipsoid) which has been validated by comparison with postmortem casts of normal left ventricles. In the presence of segmental akinesis and dyskinesis, single-plane calculations of volume, by either posteroanterior or right anterior oblique techniques, are particularly vulnerable to error, since the extent of inappropriateness of the assumed model for volume calculation cannot be appreciated in a single-plane view.

With biplane recordings, usually obtained in mutually perpendicular projections, it is possible to obtain spatial information for points that are identifiable on each pair of films (7). With motion pictures and television recording methods, it has been possible to track selected points and accurately describe their spatial motion over a cardiac cycle (54, 70, 71). In practice such points have been provided by markers (clips [26, 72], beads [73, 74], screws [46, 70]) attached to or embedded within the myocardium and by clearly identifiable anatomic structures such as valve planes (66, 67) or coronary vessel branch points (75, 76). The task has been laborious and tedious but has been eased tremendously by the ability to enter and store obtained information in the computer and use computer graphic techniques for analysis and display (27, 54, 70, 71). Most recently, computer graphic methods have also been used to create animated two- or three-dimensional cartoons of the left ventricular chamber (70, 71). The displays are based on the ability to record each image with respect to an external coordinate system such as cross hairs attached to the face of the image intensifier. The digitized outlines of images may be viewed on a television screen or an oscilloscope in real time or at various speeds. All cine or video information other than the margins of the chamber are eliminated by these procedures, allowing the viewer to concentrate solely on the dynamic motion of the chamber. For three-dimensional reconstructions (Fig. 2), the apex-to-midaortic valve length is used to construct multiple chamber diameters, and these diameters are used to create ellipsoidal or circular slices for the subsequently displayed model. The images can be rotated on the television screen so that they can be viewed from different perspectives, and isolated sections can be magnified or viewed apart from the rest of the image for intensive study. Finally, images can be dis-
Three-dimensional views of the left ventricle generated by computer graphics. AP—anteroposterior projection, and RAO—right anterior oblique projection. Each slice is a circular section created by a diameter constructed perpendicular to the midaortic-apex length. The numbers represent alpha-numeric instruction codes allowing investigator (light pen) interaction with the computer graphic unit.

played with simultaneously recorded hydraulic or mechanical information for dynamic correlations. Recently, it has been pointed out that the use of orthogonal silhouettes may result in ambiguities in characterizing changes in spatial size and shape for the ventricular chamber (77). Analysis of roentgen density over the entire opacified silhouette is proving to be of value in solving this problem.

A variety of implanted transducers (Table 1) have been used for assessing wall motion and chamber configuration in experimental animals. Methods have ranged from mutual inductance or strain gauges to ultrasonic crystals (16, 18, 19). Wall motion and distance have been recorded by displacement between pairs of these transducers attached to the endocardial or the epicardial ventricular surfaces. Each pair of transducers measures only a single chamber dimension (length, width, or wall thickness) or a segment (chord or arc) of such a dimension. In the case of mercury-in-Silastic or other strain-gauge transducers, these displacements are sensed by a change in tubing length or distance between the gauge feet attached to the heart. The degree to which each measurement represents overall or actual geometric change for the ventricle must be determined by an independent means; in the past this calibration has usually been done before implantation or at the time of postmortem study. In vivo calibrations have been difficult to accomplish and have relied principally on the use of radiographic or angiographic studies (73). The high initial cost of the required x-ray equipment, the difficulties in making quantitative measurements from the films, and the need for catheterization, anesthetics, and restraint of the animals when the x-ray equipment is used have limited such comparisons. Certain of these problems have been remedied by the use of clips or beads implanted in or on the ventricular walls to allow for repeated radiographic observations of isolated wall segment movements without need for injections of contrast material or anesthesia (21, 26, 70, 73). Endocardial labeling with tantalum screws has allowed for x-ray observation of discrete wall motions without opening the chest, since the screws can be implanted through a cardiac catheter; this procedure shows great promise for future experimentation in animals and man (46). Marker studies or studies of clearly defined anatomic structures such as valve planes or coronary vessel branch points show that normal chamber wall motions are complex and will require further extensive study.

Recently, an increasing number of investigators have reported on the use of radioisotope angiocardiography for measurement of cardiac volume. One or two Angar cameras are used to record the scintillation images resulting from the injection of small doses of sodium pertechnetate into a peripheral vein. Data are recorded in real time on magnetic tape with the electrocardiogram which is used subsequently with a gating device to identify and display end-diastolic and end-systolic images (39). Gated images from multiple successive heart beats are displayed for viewing or analyses on an oscilloscope. Scintillation-derived values have shown close correlation with those from biplane angiocardiography (39, 40). The method has been used most frequently in pediatrics and with critically ill cardiac patients, since it allows repeated examinations and avoids the use of cardiac catheterization and central injections of large amounts of contrast materials. Presently, the quality of isotope-generated images is not sufficient to allow for size and shape analysis over a cardiac cycle, and the technique does not show promise for such use in the near future. Methods for radioisotope myocardiography, however, do show great promise and should prove more useful than angiocardiography for definition and quantification of ischemic areas associated with myocardial infarction or other lesions (78).

The need to make repeated measurements in living intact animals or man by methods that are innocuous and do not change the physiological state has produced increasing interest in the use of echo ultrasound for cardiac dimensional analyses. These more recent efforts have been an extension of
earlier experiments using implanted transducers or cardiac catheters (79, 80). Echoes, instead of pulse transit time, have been utilized to obtain transverse dimensions of the left ventricular chamber or motion of the posterior wall (41-44). A reasonably close correlation has been found in man between ultrasonic methods for calculating volume and stroke volume and angiocardiography when it is assumed that the left ventricle has a fixed length-to-width ratio which does not change significantly with contraction (41-44, 81). Recently, through technologic advances in integrated circuitry and image-processing methods, arrays of crystals have been placed on the anterior chest wall to enable visualization of cross-sectional areas of the ventricle or to produce images similar to those obtainable by cineradiography or cineangiography (82-83). Presently obtained silhouettes and structures suffer from the same limitations in definition seen with radioisotope angiography and will need considerable additional work and improvement.

In conclusion, significant advances have occurred over the past 15 years in the ability to measure ventricular dimensions. Angiocardiography still remains the most reliable method for overall determination of chamber size and shape and serves as a standard for calibration or comparison for newer methods. Improvements in the use of radiographic methods over the next few years are anticipated with more extensive use of multplane studies associated with repeated injections of improved contrast materials that produce fewer physiological effects or with substances that adhere to the endocardial surfaces (84-86). It is also anticipated that existing methods for automatically obtaining dimensional information from x-rays will be continued an improved (87). Increased use of methods such as echo ultrasound and isotope imaging is also anticipated. The latter methods will be used to replace more costly radiographic procedures and in addition will allow repeated observations in experimental subjects without concern for changing physiological state as part of the diagnostic procedures. It is anticipated that isotope imaging procedures will be used increasingly for measurements of regional blood flow to the myocardium.

References

VENTRICULAR DIMENSIONS


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