Measurement of Ventricular Volumes, Ejection Fraction, Mass, Wall Stress, and Regional Wall Motion

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Cardiac angiography was introduced initially to provide qualitative information regarding anatomic abnormalities of the cardiovascular system. Subsequently, it became apparent that quantitative information derived from cineangiography could provide insight into functional abnormalities of the heart as well. Direct measurements of ventricular dimension, area, and wall thickness allow calculation of volume, ejection fraction, mass, and wall stress. Assessment of pressure-volume relationships provides additional information regarding systolic and diastolic function of the ventricular chambers. Finally, techniques developed to assess regional left ventricular wall motion have proved useful in the evaluation of patients with coronary artery disease. Therefore, the ventricular angiograms obtained by the techniques described in Chapter 12 can be used to derive quantitative descriptors of geometry and function.

VOLUMES

Technical Considerations

As discussed in detail in Chapter 12, ventriculograms are generally recorded on cine film or in digital format at 15 to 60 frames per second (fps), and radiographic contrast material is usually injected into the left ventricle at rates of 7 to 15 mL/sec for a total volume of 30 to 50 mL. Alternatively, the left ventricle may be visualized from contrast injections into the pulmonary artery, the left atrium (by the transseptal technique), or, in cases of severe aortic insufficiency, the aortic root. Attention to catheter position and injection rate minimizes the occurrence of ventricular ectopy during contrast studies; this is important because analysis of extrasystoles and postextrasystolic beats cannot be used for proper assessment of basal ventricular function.

With the widespread availability of computer systems, the technique of determining ventricular volumes has evolved from a handheld planimeter with pencil and paper (or a calculator) to semiautomated software packages. The principles important in accurate volume determination, however, apply equally to manual and computer-based techniques. For example, the need for magnification correction applies to both manual and automated techniques of volume determination.

In the first step in assessing left ventricular chamber volume, the left ventricular outline or silhouette is traced. The ventricular silhouette should be traced at the outermost margin of visible radiographic contrast so as to include trabeculations and papillary muscles within the perimeter (Fig. 16.1). The aortic valve border is defined as a line connecting the inferior aspects of the sinuses of Valsalva. Some computer-based systems require that the entire ventricular silhouette be traced manually; others incorporate a semiautomated edge-detection algorithm, wherein some points on the ventricular silhouette are entered manually and others are “supplied” by the computer software.

FIG. 16.1.

Left ventriculogram in the 30° right anterior oblique projection. The ventricular outline has been traced, as indicated by the broken line.

To facilitate the calculation of left ventricular volume, the ventricle is usually approximated by an ellipsoid (1), (2). Alternatively, techniques based on Simpson’s rule, which is independent of assumptions regarding ventricular shape, may be used (3). Because the x-rays emanate from a point source, they are nonparallel; correction must therefore be made for magnification of the ventricular image onto the image intensifier. A further complicating factor is so-called pincushion distortion, which causes greater magnification at the periphery than in the center of the image, as a result of spherical distortion.
aberration of the electromagnetic lens system (4). Finally, ventricular volumes calculated by most mathematical techniques overestimate true ventricular chamber volume, so that regression equations must be used to correct for the overestimation.

**Biplane Formula**

Biplane left ventriculography may be performed in the anteroposterior (AP) and lateral projections (2), the 30° right anterior oblique (RAO) and 60° left anterior oblique (LAO) projections (5), or angulated projections (e.g., 45° RAO and 60° LAO–25° cranial) (6). Although it is a complex geometric shape, the left ventricle can be approximated with considerable accuracy by an ellipsoid (2) (Fig. 16.2). The volume of an ellipsoid is given by the equation

\[ V = \frac{4}{3} \pi \frac{L \times M \times N}{2 \times 2 \times 2} = \frac{\pi}{6} LMN \]  

(16.1)

where \( V \) is volume, \( L \) is the long axis, and \( M \) and \( N \) are the short axes of the ellipsoid. The long axis, \( L \), is taken practically to be \( L_{\text{max}} \), the longest chord that can be drawn within the ventricular silhouette in either projection. To determine \( M \) and \( N \), each of the biplane projections of the left ventricle is approximated by an ellipse. \( M \) and \( N \) are taken to be the minor axes of these ellipses. They are calculated by the *area-length method*, as introduced by Dodge et al. (2) from the silhouette areas and long-axis lengths in each projection, using the standard geometric formula for the area of an ellipse as a function of its major and minor axes. For biplane oblique (RAO/LAO) left ventriculography, for example, the areas of the two ventricular silhouettes are given as

\[ A_{\text{RAO}} = \pi \frac{L_{\text{RAO}}}{2} \frac{M}{2} \text{ and} \]  

\[ A_{\text{LAO}} = \pi \frac{L_{\text{LAO}}}{2} \frac{N}{2} \]  

(16.2)

\( L_{\text{RAO}} \) and \( L_{\text{LAO}} \) are the longest chords that can be drawn in the RAO and LAO silhouettes, respectively. The area of each traced silhouette (Fig. 16.1) is obtained by planimetry, and \( M \) and \( N \) are calculated by rearrangement as follows:

\[ M = \frac{4A_{\text{RAO}}}{\pi L_{\text{RAO}}} \text{ and } N = \frac{4A_{\text{LAO}}}{\pi L_{\text{LAO}}} \]  

(16.3)

Combining Equations (16.1), (16.2), and (16.3),
where $L_{\text{min}}$ is the shorter of $L_{\text{RAO}}$ and $L_{\text{LAO}}$. Because $L_{\text{RAO}}$ is almost always greater than $L_{\text{LAO}}$, $L_{\text{LAO}}$ is usually substituted for $L_{\text{min}}$.

Equation (16.4) is derived for projections at right angles, or orthogonal projections, and is applicable to biplane oblique ventriculography in the 30° RAO and 60° LAO views, as just described, or for the older AP and lateral format. Although it is not valid theoretically for nonorthogonal projections (e.g., RAO and angulated LAO), it has been demonstrated empirically to be useful in those situations as well (6).

Right ventricular volumes have been calculated from biplane AP and lateral films using [a modification of the Dodge area-length technique (7), (8) or Simpson’s rule (8–10). Because right ventricular volumes are rarely calculated from cineangiographic studies today, the reader is referred elsewhere for methodologic details (7–10).

**Single-plane Formula**

The area-length ellipsoid method for estimating left ventricular chamber volume has been modified for use when only single-plane measurements obtained in the AP or RAO projection are available (4,11–13). Inherent in single-plane methods is the assumption that the left ventricular shape may be approximated by a prolate spheroid—that is, an ellipsoid in which the two minor axes are equal (12). It is assumed that the minor axis of the ventricle in the projection used is equal to the minor axis in the orthogonal plane, which was not filmed. Recalling Eq. (1) for the general case of an ellipsoid:

$$V = \frac{\pi}{6} MNL$$  \hspace{1cm} (16.5)

If only single-plane (e.g., RAO) ventriculography is done, we assume that $M = N$ and that $L$ in the plane presented is the true long axis of the ellipsoid. $M$ is calculated from the single-plane silhouette area ($A$) and $L$ by the area-length method as $M = 4A/\pi L$. Therefore, the single-plane volume calculation becomes

$$V = \frac{\pi}{6} LM^2 = \frac{\pi}{6} L \left(\frac{4A}{\pi L}\right)^2 = \frac{8A^2}{3\pi L}$$  \hspace{1cm} (16.6)

**Magnification Correction: Single-Plane**

Correction accomplished by filming a calibrated grid at the estimated level of the ventricle (11) and submitting the grid to the same magnification process as the ventricle accounts for both linear magnification and pincushion distortion. Use of x-ray systems in which the center of the ventricle can be positioned at a fixed point (isocenter), around which the x-ray tubes and image intensifiers rotate, allows for magnification correction without the use of grids but does not correct for pincushion distortion.

The use of grids and other means of calculating magnification correction factors has been reassessed by Sheehan and Mitten-Lewis (14). They found that the error introduced by considering a large central square area of the grid rather than the
portion encompassing a particular ventricular silhouette was negligibly small. Replacement of the grid by a circular disk did not significantly alter the calculated correction factor. Alternatively, the use of catheters with radiopaque markers separated by 1 cm also yielded accurate correction factors.

An approximation of the magnification correction may be obtained by considering the diameter of the catheter used for left ventriculography. However, there is a large potential percentage error in measurement of this small dimension, and the percentage error in volumes derived from it is roughly triple that in the linear correction factor. Furthermore, there is no correction for pincushion distortion. On the other hand, the error introduced into calculation of ejection fraction by this technique is much smaller than that in the calculation of ventricular volume; if it were not for the need for regression formulas (see later discussion), ejection fraction could be determined without regard to magnification.

In the single-plane formula, the cube of the linear correction factor adjusts the volume for magnification:

\[
V = \frac{8}{3\pi} \left( \frac{A^2}{L} \right) \quad (16.7)
\]

**Magnification Correction: Biplane**

In biplane studies, a correction factor (CF) must be calculated separately for each projection, yielding, in the case of biplane oblique cineangiography, \( CF_{RAO} \) and \( CF_{LAO} \). The linear correction factor is multiplied by the measured lengths, and the square of this correction factor is multiplied by planimetered areas to convert to true lengths and areas. Accordingly, the corrected volume of the ventricle is

\[
V = \frac{8}{3\pi} \frac{ \left( CF_{RAO} \right)^2 \left( CF_{LAO} \right)^2 }{ CF_{LAO} } \frac{A_{RAO}A_{LAO}}{L_{LAO}}
\]

\[
= \frac{8CF_{RAO}^2CF_{LAO}}{3\pi} \frac{A_{RAO}A_{LAO}}{L_{LAO}} \quad (16.8)
\]

Postmortem studies of hearts injected with contrast material have demonstrated that angiographic volumes calculated by Eq. (16.8) overestimate true left ventricular cavity volumes (2,4,5). This overestimation results in large part from the papillary muscles and trabeculae carneae, which do not contribute to blood volume but are nevertheless included within the traced left ventricular silhouette. Regression equations derived from these studies are used to adjust the calculated volumes. A list of the most commonly used regression equations is given in Table 16.1. For biplane studies in AP and lateral projections using large-film techniques, the regression equation of Dodge and Sandler (15) is used. For children (in whom this regression equation may yield a negative volume), another formula has been suggested (16). For cine studies in the 60° RAO/30° LAO projections, Wynne et al. (5) used postmortem casts, as shown in Fig. 16.3, to derive the regression equation shown in Table 16.1.

**FIG. 16.3.**

Left ventricular casts made from fresh postmortem specimens of human hearts, using an encapsulant mixed with barium sulfate powder. The shape of the left ventricle only roughly approximates an ellipsoid of revolution; nevertheless, amazingly good correlation was obtained between true volume of these casts (measured by water displacement of the actual cast) and calculated volume. (From Wynne J, Green LH, Grossman W, et al. Estimation of left ventricular volumes in man from biplane cineangiograms filmed in oblique projections. Am J Cardiol 1978;41:726, with permission.)

Single-plane techniques tend to overestimate volume significantly, compared with biplane methods, and this is reflected in the single-plane regression equations (Table 16.1). Regression equations are incorporated into commercial catheterization laboratory packages.
EJECTION FRACTION AND REGURGITANT FRACTION

Visual inspection of the cine film allows selection of frames depicting maximum (end-diastolic) and minimum (end-systolic) ventricular volumes. Ejection fraction (EF) is then calculated as follows (17),(18):

\[
EF = \frac{(EDV - ESV)}{EDV} = \frac{SV}{EDV} \quad (16.9)
\]

where EDV is end-diastolic ventricular volume, ESV is end-systolic ventricular volume, and SV is the angiographic stroke volume.

In patients with aortic and/or mitral regurgitation, comparison of the angiographically determined stroke volume with the forward stroke volume determined by the Fick technique or (in the absence of concomitant tricuspid regurgitation) the thermodilution technique yields the regurgitant stroke volume, that portion of the ejected volume that is regurgitated and therefore does not contribute to the net cardiac output (15). The regurgitant fraction (RF) is defined as follows (17–19):

\[
RF = \frac{\frac{SV_{angiographic}}{SV_{forward}} - SV_{forward}}{SV_{angiographic}} \quad (16.10)
\]

An assumption of this calculation is constancy of heart rate between the determination of forward cardiac output and the performance of left ventriculography. If the heart rate (HR) is substantially different at these two times, a modified method for calculating RF must be used, wherein the angiographic minute output (\(SV_{angiographic} \times HR\)) is substituted for angiographic stroke volume and the forward minute output or cardiac output is substituted for the forward stroke volume. This calculation is based on the assumption that cardiac output is independent of heart rate to a first approximation.

Because the derivation of RF involves the difference between the two stroke volume measurements, both of which contain some degree of error, the error in RF itself may be significant; interpretation of this number should be influenced by qualitative assessment of the degree of regurgitation seen on the angiogram. In cases of combined aortic and mitral regurgitation, estimation of the relative contribution of the two lesions must be made from the cineangiograms.

OTHER TECHNIQUES FOR MEASURING VENTRICULAR VOLUME AND EJECTION FRACTION

Image enhancement by computerized digital subtraction techniques can be used to obtain left ventriculograms after peripheral intravenous administration of contrast material (20),(21). Peripheral injection of the contrast agent eliminates the problem of ventricular extrasystoles sometimes associated with direct injection of contrast material into the ventricular chamber. Alternatively, the image enhancement provided by the digital subtraction process permits direct left ventricular injections with small volumes of contrast agents (20), possibly allowing multiple ventriculograms under varying conditions during a single catheterization procedure. Ventricular volume and ejection fraction may be calculated from digital subtraction ventriculograms using the area-length method (20), as described for standard ventriculograms. Alternatively, ejection fraction may be determined by computer analysis of the attenuation of x-rays by the contrast agent within the ventricle (21),(22). This technique is independent of geometric assumptions regarding the shape of the ventricle.

FIG. 16.4.

Multielectrode impedance catheter for measurement of instantaneous chamber blood volume. (See text for description.) (From McKay RG, et al. Instantaneous measurement of left and right ventricular stroke volume and pressure-volume relationships with an impedance catheter. Circulation 1984;69:703.)

A multielectrode catheter capable of measuring intracavitary electrical impedance has been introduced (23–25) and has proved useful for the measurement of ventricular volume and ejection fraction without the use of contrast agents. An early version of the catheter, consisting of 12 platinum ring electrodes mounted at 1-cm intervals along the distal end of an 8F or
9F end-hole catheter, is shown in Fig. 16.4. A 4-mA current flows through the blood of the ventricular chamber between selected ring electrodes, and the voltage needed to drive this current reflects the instantaneous electrical impedance of the blood, which has been shown to be a direct function of the blood volume. Newer catheters, only 6F in diameter, combine impedance, volume, and micromanometer pressure measurements. Validation studies (23),(24) indicate that both left and right ventricular volumes can be measured by this technique. An illustration of the potential usefulness of this catheter in assessing left ventricular pressure-volume relationships is shown in Fig. 16.5.

**FIG. 16.5.**

Use of multielectrode impedance catheter, shown in Fig. 16.4, to obtain left ventricular pressure-volume loops every fourth beat during inhalation of amyl nitrate. (From McKay RG, et al. Instantaneous measurement of left and right ventricular stroke volume and pressure-volume relationships with an impedance catheter. Circulation 1984;69:703, with permission.)

**LEFT VENTRICULAR MASS**

Measurement of left ventricular wall thickness, in addition to the parameters measured for volume determination, allows calculation of left ventricular wall volume and estimation of left ventricular mass (LVM). For these calculations, it is assumed that wall thickness is uniform throughout the ventricle. Wall thickness \( h \) is measured at end-diastole at the left ventricular free wall roughly two thirds of the distance from the aortic valve to the apex in the AP or RAO projection. Appropriate magnification correction is applied. For biplane methods, the total volume of left ventricular chamber and wall, \( V_{c+w} \), is approximated by that of the corresponding ellipsoid:

\[
V_{c+w} = \frac{4}{3} \pi \left( \frac{L + 2h}{2} \right) \left( \frac{M + 2h}{2} \right) \left( \frac{N + 2h}{2} \right)
\]

\[
= \frac{\pi}{6} (L + 2h) \left( \frac{4A_{RAO}}{\pi L_{RAO}} + 2h \right) (16.11)
\]

\[
\cdot \left( \frac{4A_{LAO}}{\pi L_{LAO}} + 2h \right)
\]

As with \( h \), appropriate correction for magnification must be applied to \( A \) and \( L \) so that \( V_{c+w} \) represents the total volume of the left ventricular chamber and wall corrected for magnification. For single-plane methods, it is assumed that \( M = N \), yielding the single-plane formula:

\[
V_{c+w} = \frac{\pi}{6} (L + 2h) \left( \frac{4A}{\pi L} + 2h \right)^2 (16.12)
\]

The volume of the chamber is calculated by the biplane or single-plane technique. In order to exclude the volume of the papillary muscles and trabeculae from the chamber volume (and thus include their mass in LVM), the appropriate regression equation is applied, so that \( V_c \) is the regressed value for chamber volume. LVM, then, is calculated as follows:
where $V_w$ is wall volume, and 1.050 is the specific gravity of heart muscle. This method has been validated by postmortem examination of hearts (26), (27); however, it may not be accurate in the presence of marked right ventricular hypertrophy or pericardial effusion or thickening, where accurate measurement of wall thickness from the RAO silhouette may be impossible. The left ventricular wall thickness may sometimes be seen well in the LAO projection in the region of the posterior wall, or it may be measured accurately by echocardiography, computed tomography, or magnetic resonance imaging. Values obtained by any of these methods may be used for calculation of LVM.

**NORMAL VALUES**

A number of investigators have reported normal values in adults and children for left ventricular volume, ejection fraction, wall thickness, and mass (5, 16, 28–30). These are summarized in Table 16.2.

**WALL STRESS**

Whereas consideration of ventricular pressure and volume is useful for assessment of ventricular performance, direct evaluation of myocardial function requires attention to forces acting at the level of the individual myocardial fiber. In particular, correction must be made for differences in ventricular wall thickness and chamber radius ($R$), which modify the extent to which intraventricular pressure ($P$) is borne by the individual fiber; this is especially important in disease states characterized by ventricular hypertrophy or dilation or both. Such a correction may be achieved by consideration of wall stress ($\Sigma$) (29, 31–33). Several formulas are commonly used to calculate stress, all related to the basic Laplace relation:

$$\sigma = \frac{PR}{2h} \quad (16.14)$$

Assumptions of the shape of the ventricular chamber and the properties of the ventricular wall have led to a number of such formulas for wall stress components in the circumferential, meridional, and radial directions (Fig. 16.6). Consideration of circumferential and meridional stress has been particularly useful for clinical applications. A representative formula for calculation of circumferential stress, $\Sigma_c$, is

**FIG. 16.6.**

Circumferential ($\Sigma_c$), meridional ($\Sigma_m$), and radial ($\Sigma_r$) components of left ventricular wall stress for an ellipsoid model. The three components of wall stress are mutually perpendicular.

$$\sigma_c = \frac{Pb}{h} \left(1 - \frac{h}{2b}\right) \left(1 - \frac{hb}{2a^2}\right) \quad (16.15)$$

where $a$ and $b$ are the major and minor semiaxes, respectively, at the midwall. Meridional stress, $\Sigma_m$, may be calculated as follows (32):

$$LVM = 1.050 \, V_w \quad (16.13)$$

$$= 1.050(V_{c+w} - V_c)$$
\[ \sigma_m = \frac{PR}{2h(1 + h/2R)} \]  

(16.16)

where \( R \) is the internal chamber radius as bounded by the endocardial surface. For more detailed consideration of wall stress formulas, the reader is referred to reviews of the subject (33).

Calculation of wall stress in disease states has provided information not apparent from consideration of pressure and volume data alone. For example, it has been demonstrated that peak stress does not necessarily occur at the same time in the cardiac cycle as does peak pressure and that, in “compensated” pressure overload, the increase in ventricular pressure is offset by a proportional increase in wall thickness, so that wall stress remains normal (Fig. 16.7) (32).

**FIG. 16.7.**

A comparison of changes in left ventricular pressure, wall thickness, and meridional stress throughout the cardiac cycle for representative normal (A), pressure-overloaded (B), and volume-overloaded (C) ventricles. These parameters are plotted at 40-msec intervals. In all three types of ventricles, peak stress occurs earlier than peak pressure. In the pressure-overloaded ventricle, peak pressure is markedly elevated, but peak systolic stress and end-diastolic stress are normal. In the volume-overloaded ventricle, peak systolic stress is normal, but end-diastolic stress is elevated. (From Grossman W, Jones D, McLaurin LP. Wall stress and patterns of hypertrophy in the human left ventricle. *J Clin Invest* 1975;56:56, with permission.)

**PRESSURE-VOLUME CURVES**

Simultaneous measurement of ventricular pressure and volume allows construction of the pressure-volume diagram (Fig. 16.8) (34–37). The position and slope of the diastolic portion of the pressure-volume curve provides information regarding diastolic properties of the ventricle (35),(38). Construction of the systolic portion of the curve is useful for analysis of the end-systolic pressure-volume relation, a measure of ventricular contractile function (see Chapter 17).

**FIG. 16.8.**

Pressure-volume diagram for the left ventricle. In this example, the diagram derived from single-plane cineangiography is compared to that constructed from radionuclide volume data. (From McKay RG, et al. Left ventricular pressure-volume diagrams and end-systolic pressure-volume relations in human beings. *J Am Coll Cardiol* 1984;3:301, with permission.)

**REGIONAL LEFT VENTRICULAR WALL MOTION**

The recognition that left ventricular regional dyssynergy is a more sensitive marker of coronary artery disease than is depression of global function has led to attempts to quantify abnormalities of regional wall motion. Left ventriculography is performed in the RAO or RAO and LAO projections. The ventricle is divided into regions by one of two methods: (a) construction of lines perpendicular to the major axis that divide the major axis into equal segments (39),(40) or (b) construction of lines drawn from the midpoint of the major axis to the ventricular outline at intervals of a fixed number of degrees (39). Extent of inward (or outward) movement of individual segments can then be measured, usually with the aid of computer techniques, providing quantitative measures of hypokinesis, akinesis, and dyskinesis.

**FIG. 16.9.**

Assessment of regional wall motion in the control state (CON) and after induction of angina pectoris by atrial pacing tachycardia (PCG). Left ventricular pressure (LVP)–length loops are plotted for a myocardial region distal to a stenotic coronary artery (a and b) and for a normally perfused region (c and d). (From Sasayama S, et al. Changes in diastolic properties of the regional myocardium during pacing-induced ischemia in man. *J Am Coll Cardiol* 1985;5:599, with permission.)
An automated method of processing the left ventricular cineangiogram was reported by Sasayama et al. (41–43). End-diastolic and end-systolic ventricular silhouettes are superimposed (Fig. 16.9), and 128 radial grids are drawn from the center of gravity of the end-diastolic silhouette to the endocardial margins. Measurement of the length of each radial grid between end-diastolic and end-systolic silhouettes measures segmental systolic and diastolic function. Figure 16.9 illustrates this technique in a patient with coronary disease before and after induction of angina pectoris by rapid atrial pacing. Simultaneous measurements of left ventricular pressure permit construction of segmental left ventricular pressure-length loops for both normally perfused myocardial regions (Fig. 16.9, c and d), and regions perfused by stenotic coronary arteries (Fig. 16.9, a and b). Depressed wall motion develops during angina in the latter, and compensatory hyperkinesis develops in the former.

**FIG. 16.10.**

Wall motion as assessed by the center line method. The center line (A, dotted line) is constructed midway between the end-systolic and end-diastolic silhouettes. In panel B, chords are drawn at right angles to the center line. The percentage of systolic shortening along each chord is plotted (C, solid line) and compared with normal mean and standard deviation values (dashed and dotted lines). Deviation from normal is replotted in panel D. (From Sheehan FH, Bolson EL, Dodge HT, et al. Advantages and applications of the center line method for characterizing regional ventricular function. *Circulation* 1986;74:293, with permission.)

Another approach has been used by Sheehan et al. (44),(45). Wall motion is measured along 100 chords constructed as perpendiculars to a line drawn midway between the end-diastolic and end-systolic left ventricular contours (Fig. 16.10). The motion of each chord is compared with a normal range established from analysis of ventriculograms from patients without heart disease. Deviations from the normal range indicate hypokinesis or hyperkinesis. In studies of wall motion after thrombolysis, availability of the LAO in addition to the RAO projection proved particularly useful in patients with left circumflex coronary artery thrombosis (45).

Software for regional wall motion analysis is now available in commercial catheterization laboratory computer systems.