Estimation of Left Ventricular Volume by One-Plane Cineangiography

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SUMMARY

One-plane cineangiographic measurement of left ventricular volume uses angiocardiograms taken in the right anterior oblique view. Its basic assumption is that the third (unvisualized) dimension, depth from septum to free wall, is of the same magnitude and behaves in the same way as the visualized short axis. Examination of this assumption with biplane x-ray equipment revealed that the unmeasured length averages 7% less and varies directly with the length of the measured short axis. Volumes measured correlate well with consecutive studies using serial biplane x-rays and are systematically somewhat larger than volumes obtained in autopsy specimens injected with barium sulfate paste. The method is tolerant of variations in positioning of the patient, is convenient, yields repeatable analyses from one experienced observer to another, allows 60 volume measurements per second so that rapid cardiac events can be studied, and the small doses of x-rays and contrast medium permit several observations at one catheterization session. This means that effects of drugs and other interventions can be studied by the informative techniques of semi-continuous volume measurement and pressure-volume analysis.

ADDITIONAL INDEXING WORDS:
Biplane angiography
Angiotensin

LEFT ventricular volume can be measured by the somewhat cumbersome technique of biplane angiography \(^1\) and can be estimated conveniently by the often misleading \(^2\) indicator washout techniques. \(^3\) Both groups of methods have produced a growing appreciation of the importance of volume studies in evaluating left ventricular function, and of the frequent disparity between left ventricular end-diastolic pressure and end-diastolic volume. \(^4\) \(^5\) This report describes and validates a convenient cineangiographic method for measuring left ventricular volume in man. \(^6\) It is an elaboration of a method applied for the same purpose in dogs. \(^7\) Its validity has been examined in five ways: by comparison with the established biplane angiographic method, by study of observer variation, by biplane examination of the short axes of the ventricular ellipsoid, by study of postmortem hearts filled with contrast medium, and by a comparison of length measurements with area measurements. An important advantage of the one-plane cine method described herein is that multiple studies become feasible at a single clinical catheterization session, so that various drugs and maneuvers can be assessed in regard to their effect on ventricular function.

Methods

Angiocardiograms were performed in patients with valvular heart disease and in a few subjects with substantially normal circulation usually studied because of a systolic murmur. Cineangiograms in the right anterior oblique projection were made...
at 60 frames per second as 25 to 50 ml of 76% methylglucamine diatrizoate (Renografin) were injected into the left atrium through a transseptal catheter. In 18 subjects these were followed in 15 to 30 minutes by biplane 30 by 30-cm angiocardiograms with injection of 40 to 80 ml of the same material into the left atrium. Aside from rotating the patient from one projection to the other and sliding the x-ray table to a new position, there were no changes in the experimental conditions between the two consecutive sets of measurements of left ventricular volume. Volumes were calculated from the biplane films by a slightly modified Arvidsson technique as described previously.\(^7\)

Left ventricular volume was calculated from the one-plane cine pictures using the ellipsoid-type model developed by Arvidsson for his biplane technique. In the biplane method the long axis of the ventricle, \(L\), and two mutually perpendicular short axes at its midpoint, \(M\) and \(N\), are measured, and the volume is calculated from the formula for the volume of an ellipsoid,

\[
V = \frac{\pi}{6} \cdot LMN
\]

where \(V\) is equal to left ventricular volume.

In the one-plane cine picture, \(L\), the long axis of the ventricle, and \(M\), a short axis at right angles to it at its midpoint, are both directly measurable. The assumption is made that the short axis which is not visible, \(N\), perpendicular to both \(L\) and \(M\), is equal to \(M\). The formula then becomes

\[
V = \frac{\pi}{6} \cdot LM^2.
\]

**Technique of Measurement of the Cine Film**

This technique needs detailed description. The image of the opacified left ventricle on cine film in the right anterior oblique projection is viewed under standard conditions, and the best cycle is picked from the sequence of contractions. Appropriate reference is made to the simultaneous graphic records of electrocardiogram and ventricular pressure to avoid premature contractions and post-extrasystolic beats. A review of the sequence at cine speed allows an image of the ventricle to be remembered so that individual frames may be measured with more confidence. A coupled frame counter is of help in identifying frames.

The outline of the ventricle and adjacent atrial border is traced on a sheet of paper marked with an identifying frame number. Where indentations in the ventricular outline are caused by papillary muscles or trabeculations, these are ignored and the outline is drawn to include all the opacified areas. A typical frame and the tracing from it are shown in figure 1.

**Figure 1**

Right anterior oblique cine frame of opacified left atrium and left ventricle, left, and line drawing of the ventricular outline, right, with its long axis (\(L\)) and short axis (\(M\)). The base of the long axis is taken at the intersection of the left borders of the left atrial and left ventricular shadows, and its opposite end is the farthest point of the apex. \(M\) is perpendicular to \(L\) at its midpoint and extends to the limit of the ventricular shadow in each direction. The indentation made by the papillary muscle in the inferomedial margin of the ventricular shadow is ignored in drawing the ventricular outline. The left ventricular catheter is for simultaneous measurement of pressure. The left atrial catheter is for contrast injection.
With left atrial injection the base of the left ventricle and the aortic valve are obscured. Therefore, the long axis of the ventricular cavity is measured from its apex to the intersection of its left anterior margin with the corresponding margin of the left atrium (or in a few patients, of the aorta). This point is nearly as far from the apex as the center of the aortic valve, which is obscured. In each subject a decision was made whether to use one or the other intersection in drawing the long axis and this was then used in all studies on the subject. Figure 1 shows measurements made using the atriyoventricular intersection. The long axis, L, is drawn from the intersection of the left ventricular margin and the left atrial margin to the apex of the ventricle. It is bisected, and the transverse diameter, M, of the ventricle at the midpoint of its long diameter, L, is measured.

Both measurements must be corrected for magnification and distortion. Since there is "pincushion" distortion in the field as viewed through the image amplifier, we allow for both distortion and magnification by routinely photographing a metal grid of 1-cm squares placed at the level of the left ventricle (10 cm above the mattress top). Pincushion distortion is spherical aberration of the electromagnetic lens system, with more magnification at the periphery than in the central field. It is so-called because of the appearance of the straight lines of the metal grid, which appear to be curved convex to the center of the field. When the film is subsequently projected, the magnification of image and grid will be the same. In the Tage Arnö projector the magnification is about 1.5 at the center of the field and 1.6 at the periphery. Both magnification and distortion are corrected with a single factor (f) in the equation actually used:

\[ V = KLM^2 \]

where

\[ K = \frac{\pi}{6} \cdot \frac{1}{f^3} \]

Distortion in the image amplifier depends upon the distance of the line being measured from the center of the picture. Radii and tangents are affected slightly differently. A satisfactory compromise is achieved by using a factor dependent upon the mean distance from the center of the picture of the line being measured. One might calculate the magnification and distortion factor, f, separately for each frame. In practice the ventricle changes position in the field so little that the factor changes only in the third decimal place throughout the cycle. It is sufficient, therefore, to calculate f once for a frame in mid-systole or mid-diastole and to use that value throughout the cycle.

Testing the Assumption that \( N \) Equals \( M \)

To test the assumption that the short axis not measured, N, is equal to the measured short axis, M, biplane films at six exposures per second were made in the two oblique projections. These paired pictures permitted measurement of N and M simultaneously. Satisfactory measurements were obtained in eight patients, and 19 or more consecutive frames were obtained in each study. Accordingly the middle 19 consecutive pairs of frames were measured on each of the eight subjects, and these 152 values for M and N were analyzed statistically.

Comparison of Calculated with Actual Cavity Volume

To compare the calculated volume with actual cavity volume, studies were made of barium-filled ventricles in hearts post mortem. The mitral valve orifices of seven fresh human hearts were closed by suturing the free edges of the mitral valves together. The left ventricular cavity was filled with measured increments of a thixotropic barium sulfate paste injected through a cannula fixed in the aortic valve orifice. The specimens were suspended in a position corresponding to that of the living heart in the right anterior oblique projection. Cine exposures were made after each increment of barium sulfate paste was injected into the left ventricular cavity.

A study was also made in the clinical angiograms to compare length-width data with planimetrically measured area to see whether these alternative measurements contained similar information or not. The area of the shadow of the left ventricle in the cine film was obtained by planimetric integration of the projected image. The product of length times width (length-width product) of the left ventricle was also measured and compared with the area. End-systolic and end-diastolic were studied in 15 subjects chosen to maximize the range of shapes and sizes.

In addition to the validation studies, drugs have been used to alter ventricular function. After a control angiogram, amyl nitrite (by inhalation) or isoproterenol or angiotensin (each by intravenous infusion) has been given. During administration of each drug, left ventricular pressure was monitored. When a pressure change occurred, a repeat cineangiogram was obtained. The objective in each of the drug studies was to produce a small change in ventricular parameters.

Results

The results are shown in figures 2 to 9.
Relationship of the One-Plane Volume to the Biplane Large-Film Volume (Figure 2)

In 18 patients the mean value for end-systolic volume over several cycles was determined by each technique, and similarly the mean value for end-diastolic volume.

The points are distributed linearly along the line of perfect agreement. The correlation coefficient for the comparison of the two methods is 0.988. The greatest disparity is a few points at end-systole, particularly end-systolic points less than 200 ml, where the cine volume is as small as 50% of the biplane volume, and points cluster below the line of identity. A possible explanation of this discrepancy is that, at six frames per second, it is possible to miss the time when the ventricle is smallest, while at 60 frames per second one records the smallest volume with greater accuracy. Otherwise the data give no indication of any systematic error. The lines connecting the end-systolic and end-diastolic points of a single case are in general parallel to the line of identity, so that absolute errors tend to cancel out in calculating stroke volume.

Observer Error

To test the influence of observer error two observers independently measured and calculated left ventricular volume, and correlated it with left ventricular pressure. The two pressure-volume loops were constructed, and then drawn on the same plot (fig. 3). There is disagreement on a few points, but the general shape is essentially similar. Other trials of this sort have given similar good agreement. Repeated measurements of a single dimension by one observer may differ by as much as 0.5 cm.

The Short Axes

The relationship of M, the measured short diameter, to N, the nonmeasurable short diameter (as measured in the special oblique biplane studies) is shown in figure 4, where the data are plotted in relation to the calculated regression line. The extreme values for the ratio of N to M were 0.79 and 1.02, with a mean of 0.93. The regression coefficient was 0.993.

The Postmortem Heart

Known amounts of barium sulfate paste were injected into postmortem hearts. The volume calculated from cineangiograms of these hearts suspended in the right anterior oblique projection was compared with the amount injected, as shown in figure 5. The mean volumes calculated at each increment injected and the standard error of the mean are

Figure 2

End-systolic and end-diastolic volumes of the left ventricle calculated from the cineangiogram (ordinate), and from biplane serial large films, taken 15 to 30 minutes later in 18 patients (abscissa). The dotted line represents perfect agreement.

Figure 3

Pressure-volume loop of a single ventricular contraction independently drawn by two observers. There is substantial agreement between the two loops.
Relationship of the two perpendicular short axes on simultaneous biplane oblique angiograms of the left ventricle. Different symbols are used for each of eight different patients.

The correlation coefficient between the two measurements was 0.975, showing that the length-width product contains virtually all the size information, and no material improvement would be obtained with a technique scissa). The Lars indicate the standard error of the observations. The numbers indicate number of observations at each volume. The dotted line represents perfect agreement.

Figure 4

Figure 5

Volume of excised human left ventricles from right anterior oblique cineangiograms (ordinate) compared with injected volumes of barium sulfate paste (abscissa). The Lars indicate the standard error of the observations. The numbers indicate number of observations at each volume. The dotted line represents perfect agreement.
Figure 6

The product of the short axis and long axis of the ventricle, \( M \times L \), compared with the planimetrically measured area of the ventricular shadow. The linear distribution of the relationship indicates that the added information of the area measurement does not change the estimate obtained from the simpler measurement.

Based on the more laborious planimetric measurement.

Drugs

The effects of drugs on left ventricular function are illustrated in figures 7 to 9. Amyl nitrite usually lowered systolic pressure in the left ventricle, diminished end-systolic volume, and decreased end-diastolic volume and pressure. Stroke work was reduced (fig. 7). Angiotensin had opposite effects, increasing systolic and diastolic pressures, and increasing end-systolic and end-diastolic volume. Stroke work was unchanged (fig. 8). Both these drugs are thought to work primarily on the peripheral vascular bed, with reflex changes in heart rate. Isoproterenol on the other hand, with its inotropic effect on the ventricle, usually decreased left ventricular diastolic pressure, decreased end-systolic volume, increased end-diastolic volume, and resulted in an increase in stroke work (fig. 9).

Discussion

Left ventricular volumes as calculated from one-plane cineangiograms agree well with the biplane left ventricular volume data obtained from the same patient under substantially unchanged conditions a few minutes later. One source of systematic bias is that the cine volume was usually determined first, and may have influenced ventricular function during the subsequent observation. We do not believe that a significant error was thus introduced for two reasons. In one patient the

Figure 7

Representative pressure-volume loop of the left ventricle at rest, and similar loop after inhalation of amyl nitrite. With amyl nitrite, end-diastolic and end-systolic volume and pressure are less, as is stroke work. The patient had mitral stenosis and regurgitation and aortic regurgitation.

Figure 8

Representative pressure-volume loop of the left ventricle, at rest (control), and after an intravenous infusion of angiotensin. With angiotensin, end-diastolic and end-systolic volume and pressure are greater, but stroke work is unchanged. The patient had a calcified mitral valve with stenosis and regurgitation.
Representative pressure-volume loop of left ventricle at rest (control), and after an intravenous infusion of isoproterenol. With isoproterenol end-diastolic volume is larger. End-systolic volume and end-diastolic and end-systolic pressures are less. The stroke work is increased. The patient had mild mitral stenosis.

Precise measurement of the margin of the opacified ventricular shadow in the stationary projected cine frame is often more difficult than direct measurement on a 30 by 30-cm x-ray picture. That the problem can be overcome by practice is demonstrated by the good agreement of two experienced observers in constructing a pressure-volume loop from the same data. Part of the success comes from agreement on taking the widest extent of opacification and part from reviewing questionable frames in motion. Borders are more indistinct when seen in a still frame than when seen in motion because the signal (the shadow of the contrast) is reinforced, while the noise (random effects of film grain, and so forth) is largely cancelled.

The crucial assumption involved in calculating left ventricular volume from the right anterior oblique projection alone is that the two mutually perpendicular short diameters at the midpoint of the long axis of the ventricle are essentially equal. Direct measurement of these two diameters in simultaneous biplane oblique films shows that this is reasonable. The diameter not measured, N, is on the average 7% smaller than the measured diameter, and for some purposes it may be useful to make this correction. It should improve the agreement between calculated and actual left ventricular volumes (fig. 5). We have, however, chosen not to change the formula in the present series.

In a larger chamber the mechanical forces acting on the nonrigid myocardium are likely to make the cross-section of the ventricle more nearly round (cylindrical). M is more likely to equal N in a large cavity, and less likely to equal N in a small, contracted, irregular cavity. In the latter, the percentage error might become large, but the absolute error (ml) would not be great. In the eight subjects in whom M and N were directly measured and compared, the values ranged from less than 4 to more than 8 cm.

Estimates of left ventricular volume by the one-plane cine technique and by the biplane technique are both larger than the volumes of barium sulfate paste injected into postmortem specimens. The injected volume includes only the fluid placed in the ventricular cavity, while the angioograms outline the greatest extent of the ventricular cavity. This latter measurement includes papillary muscles and trabeculations. This discrepancy is some measure of the volume of these structures. If one's objective is the study of ventricular muscle function, the larger volume, including trabeculations and papillary muscles, is of more significance, since a circular band of muscle at the ventricular waist is contracting on a non-compressible core which includes muscle as well as liquid contents.

In turning the patient into the right anterior oblique projection, it is not easy to be certain of the angle made by the long axis of the
heart and the central x-ray beam. True measurement of the long axis depends upon this angle being 90°. Deviations from a true perpendicular affect the measurement as the cosine of the angle of deviation, and for small angles they are negligible. The long axis must deviate by 25° in order to cause a 10% shortening in this measurement. The rounded shape of the ventricular apex further diminishes this error, since angulation shortens the shadow of a blunt object less than that of a thin line.

The assumption that the ventricle is 10 cm above the surface of the mattress is used in correcting for magnification. This vertical height is the approximate position for the average adult subject in the right anterior oblique projection. If the mean level of the ventricle varies 5 cm above or below, the maximal error introduced will be +9% or −7%, respectively.

The rough ellipse of the left ventricular outline contains much more information about ventricular dimensions than is utilized in making only two measurements, the length and the width. One might anticipate that better estimations could be obtained by using more information, for example, the area. Dodge and co-workers² have improved their data derived from use of the biplane technique by using a short axis determined from planimetric measurement of the area of the ventricular shadow. The high correlation between the product of the length and width of the ventricular shadow and its area in our data indicates that the simpler measurements are adequate indications of ventricular size.

The volume-time curve of the left ventricle can be studied by comparing it with records of such other simultaneous measurements as the ordinary intraventricular pressure-time curve. Such a display, however, is less immediately informative than the plot of intraventricular pressure against volume. This four-sided loop shows clearly end-diastolic volume, end-diastolic volume, stroke volume, residual volume, systolic and diastolic pressures, and stroke work (the area of the loop). Various valvular lesions lead to characteristic deformities of the pressure-volume loop, as have been described recently.⁷ The changes in the loop under the influence of drugs are currently being explored (figs. 7 to 9). The area of the pressure-volume loop equals the net stroke work of the left ventricle. Since intraventricular rather than aortic pressure is used, no assumptions are necessary concerning aortic cross-sectional area of kinetic work. The pressure-volume figure is currently the best method available clinically for measuring left ventricular stroke work and is indispensable where valvular regurgitation invalidates the simpler stroke work measurements.

The advantages of the one-plane cine method over the biplane technique are several, and include convenience, smaller dose of contrast medium, smaller dose of radiation, the potential for multiple serial observations, and volume measurements 60 times per second instead of a maximum of 12 times per second. Mechanically, it is easier to position a patient for one-plane cineangiography and to record in similar fashion the effect of a drug. Good definition of the adult ventricle is obtained with 30 to 40 ml of contrast injected into the left atrium. Such doses are well tolerated and may be repeated after 5 minutes without difficulty. The hypotension which usually follows such an injection into the left side of the heart does not appear until after the volume data have been collected, and has disappeared well before 5 minutes have elapsed, usually in 1 or 2 minutes. The use of an image amplifier in one plane requires much less radiation than biplane exposures by usual radiographic techniques. The recording of 60 frames per second allows one to calculate volume changes at that rate, to estimate the rate of ventricular ejection, and to fill in the pressure-volume loop in much greater detail. This is particularly helpful at the beginning of ventricular ejection and at the beginning of ventricular filling, two points in the cardiac cycle where volume is changing rapidly.

Addendum

Since this paper was submitted, Dodge and co-workers¹⁰ have described a method for determining left ventricular volume from angiocardiograms taken in a single anteroposterior projection on large films.
LEFT VENTRICULAR VOLUME

References


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