An Automated Method for the Measurement of Ventricular Volume


SUMMARY
Several important indices of myocardial performance depend upon accurate and frequent measurement of ventricular volume. Studies employing such measurements have been limited because of the difficulty of manually measuring and calculating volumes frequently enough to obtain meaningful data. We, therefore, have developed an automated method for determination of ventricular volume in man. Left ventricular cineangiograms taken in the right anterior oblique position at 60 frames/sec are projected with a flickerless projector onto a Plumbicon television camera. A second television camera is used by a skilled operator for masking out noncontributory portions of the film and for shading selected areas to facilitate accurate recognition of the opacified chamber. An electronic video-tracking device then simultaneously determines the area and the maximum length of the opacified chamber in each cine frame. These data are recorded as analog signals on magnetic tape. Volumes are calculated by computer and plotted against time. When volumes determined by this automated method are compared with those obtained by manual planimetry, the correlation coefficient is 0.96. Aluminum prolate spheroids, left ventricular casts, and left ventricular cineangiograms were studied. This automated technic permits rapid and accurate measurement of ventricular volume in patients having diagnostic left ventriculograms.

Additional Indexing Words:
Prolate spheroid Video tracking Ventricular casts Cineangiogram

In 1960 Dodge and associates\(^1\) demonstrated in man that left ventricular volume could be determined with reasonable accuracy from biplane angiograms. This method, however, is laborious, and many hours are often required to analyze the changes in ventricular volume that occur during the cardiac cycle. In the past decade several improvements in the method have decreased the effort required to analyze the angiographic data without significantly decreasing the accuracy of the method. The three principal improvements have been the use of computers in the required arithmetical calculations,\(^2\) the use of specialized planimetric devices,\(^3\) and the demonstration that only a single-plane left ventricular angiogram is required.\(^4\)\(^-\)\(^6\) Even if all of the latest advances were utilized however, the determination of ventricular volume at frequent intervals during the cardiac cycle remains a formidable task and requires considerable effort on the part of a skilled individual. The purpose of this paper is to describe a method for determining left ventricular volume that requires so little effort that volume can be determined in patients undergoing left ventriculography.

Method

Filming Technic
At the time of diagnostic cardiac catheterization, single-plane left ventricular cineangiography
is performed with the patient placed in the right anterior oblique position (15° to 40°) so that the adipose tissue in the atrioventricular groove appears as a radiolucent line and the long axis of the left ventricle is approximately perpendicular to the vertical X-ray beam. Before filming, the image of the catheter tip within the left ventricle is obtained by a second fluoroscope positioned in the horizontal plane so that the distances from the left ventricular cavity to the vertical X-ray tube and image intensifier can be measured. Approximately 1 cc/kg of contrast material* then is injected at a pressure of 400 to 800 lb/in² through a retrograde or transseptal catheter into the left ventricular cavity, and the 35-mm cine film is exposed at a rate of 60 frames/sec. After the study a 1-cm² cross-hatched grid is filmed at the same distance from the X-ray tube and image intensifier as the left ventricular cavity was. Because an adequate 35-mm flickerless projector is not available currently, the film is reduced to 16 mm.

The Flickerless Projector and the Primary Television Camera

The 16-mm film is threaded into a flickerless projector† that is equipped with a constant-speed shutter specifically designed for use with a television system. The projector is close-coupled

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*Hypaque-M, 75%, or Renografin, 76%. 
†Model 16N/T.V. Selectra-Frame; TRAID Corporation, Glendale, California.
Diagram of the video-tracking system. A synchronizing generator provides signals to the two cameras to insure stability of their common signals. The images from the two cameras are previewed on television monitors. The film camera image is attenuated by 10% by a distribution amplifier. The image of the key camera is superimposed upon the film camera image by a video insert keyer. Local shading within the key can then be added via a video mixer. The composite signal is then sent to the video planimeters. The composite image and the area estimates of the planimeters are visualized on a television monitor. The area and length analog signals are recorded either on a strip chart or magnetic tape.

The projected image measures 12.8 by 17.1 mm. A constant-speed shutter pulses a light through the film 120 times/sec, irrespective of the rate at which the film moves through the film gate; the rate of the film can be varied between 1 and 24...
Figure 3

Rotation of the television image. (Left) Usual position. (Right) Position following rotation of the primary camera. The long axis of the opacified ventricular cavity is now parallel to the television lines.

frames/sec. Each cine frame is illuminated twice during each television scan. The film is advanced only while the shutter is closed, and consequently the instantaneous light level received by the television camera is unaffected by film motion. An adjustable iris on the projection lens compensates for films of various densities. Since the signal-processing system is sensitive to total light quanta, the standard projector lamp was replaced with a 12.8-volt, 0.94-ampere, 15-candle-power lamp powered by a well-regulated direct-current supply with constant voltage output regulated to ± 0.05% for step-line voltage changes of ± 10%. A frame counter provides frame numbers to facili-

Figure 4

Area and length tracking by the video planimeters. (Left) Opacified left ventricular cavity is seen by the operator. (Right) Superimposed light-gray zone represents the area of the identical left ventricular silhouette as determined by the video planimeters. The narrow white band between the aortic valve and apex is the position of a second video planimeter which is used to measure changes in length.
Insertion of a mask by the key camera. (Left) Opacified ventricle as seen by the operator. (Right) The dashed line outlines the mask, which is superimposed on the same frame of the left ventricular cineangiogram.

Figure 5

A mount was constructed to allow 360° rotation of the television camera about the optical axis. This permits the long axis of the opacified left ventricle to be aligned horizontally on the television screen (fig. 3). The television cameras and camera control units* are of solid-state circuitry and modular construction and were selected because of excellent stability and functional control.

The Video Planimetering System

The left ventricular cineangiogram is viewed by the operator on a television monitor. The video planimeter is then activated. The area of the left ventricle determined by the video planimeter appears on the television monitor as a light-gray area superimposed on the opacified ventricle. The video planimeter has a variable threshold level that can be adjusted by the operator so that an accurate fit is obtained between the opacified area and the left ventricular cavity.

Figure 6

Original tracing of the areas and lengths of the left ventricular cavity as determined by the video planimeters for 48 frames of a cineangiogram.
estimated by the video planimeter and the area actually visualized (fig. 4).

Three additional technics aid in obtaining an accurate fit. (1) The extraneous background is eliminated by a mask that consists of a gray-on-black silhouette constructed slightly larger than the greatest area of the opacified ventricle in diastole. The mask is superimposed on the primary camera image by the key camera (figs. 1, 2, and 5) via a video keyer.* A synchronizing generator provides driving signals to the two cameras to ensure stability of their common signals. The video keyer also generates keying signals which serve as a gate for the video planimetering system, thereby eliminating the extraneous background. (2) The operator can compensate for unequal distribution of contrast material in the ventricle by shading the television image either horizontally or vertically. (3) In any local area within the mask, density can be added or subtracted from the video image by blackening or whitening areas and superimposing these densities on the film camera image via a video mixer.† This last technic is used to compensate for markedly uneven distribution of contrast material that sometimes occurs when unopacified blood from the left atrium enters the left ventricle.

The video planimeter determines the area of the opacified left ventricle on each cine frame by integrating the time that the gated television signal spends above the preset density threshold. A gated video comparator circuit determines when the video signal exceeds the threshold level. The output voltage of the comparator is summed during each scan by a gated analog integrator that is reset at the beginning of every vertical scan. The maximum voltage reached by the integrator is proportional to the area of the television picture above the threshold level. The analog output voltage of the integrator is processed by a sample-and-hold circuit and then recorded.

A second video planimeter determines the maximum length of the left ventricle on each cine frame by measuring a gated horizontal band between the aortic valve and the left ventricular apex (fig. 4). The height of the band is fixed at eight video lines so that changes in the area of the band are proportional to changes in its length. The position of the aortic valve is set by the position of the mask.

Data Recording, Calibration, and Analysis

The area and length video planimeters are calibrated by the operator using the appropriate grid. The areas and lengths on each cine frame

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*Model #930 Grass Valley Group, Grass Valley, California.
†Telechrome Model 3507.
‡Richmond-Hill EVS-7R.
(Left panels) The left ventricular areas, lengths, and volumes in one patient are plotted against time. The connected circles represent the estimates made by the traditional method of measuring (hand planimetry) and the continuous line represents the estimates made from identical cine frames by the video system. A total of 58 frames were studied. (Right panels) The same data are plotted on an X-Y plot. The lines drawn are regression lines. The correlation coefficients and the results of the regression analyses are shown. The standard errors of the estimates for the areas, lengths, and volumes are 1.3 cm², 0.2 cm, and 8.7 cc, respectively. The regression factor in the volume estimate did not differ from 1.0.
Figure 10

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and the frame pulse are recorded simultaneously as analog signals (fig. 6). The data are recorded on a direct-writing oscillograph and on magnetic tape.

The area and length signals are low pass filtered at 40 Hz, and the frame pulse signal is filtered at 150 Hz. Subsequently a hybrid computer* converts the analog signals to digital signals at 250 samples/sec. A program (IBM 360) accumulates the data points for each frame. Since the cineangiogram is played back through the video system at one-tenth real time (6 frames/sec), there are at least 40 data points/frame. The eleventh through the thirty-fifth data points are averaged to produce length and area values for each frame. This averaging acts as a digital filter to attenuate further the noise produced by the video system. The program then calculates the volume for each frame by using the formula: \( V = \pi LD^2/6 \); where \( V = \) volume, \( L = \) length, \( D = 4A/\pi L \), and \( A = \) area. The volume data are then plotted by an X-Y plotter.†

Results

Study of Prolate Spheroid Models

Five solid aluminum prolate spheroids with volumes of 20 cc, 40 cc, 80 cc, 160 cc, and 320 cc were constructed (tolerance = 0.005 in). Volumes were verified by Archimedes's principle. Cine films of the spheroids and the appropriate grids were analyzed with the video system just described. Figure 7 shows the volume data, the correlation coefficient, and the results of regression analysis. On the average, volumes measured by the video system are 8% less than the known volumes.

Study of Ventricular Casts

Left ventricular casts of five human hearts were made postmortem by filling the left

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*A Geospace Computer and a Control Data Computer Model 3100.

†Calcomp Plotter.

A comparison of left ventricular volumes measured by the video system with those measured by the traditional method in the other four patients (A, B, C, D). The format is similar to that in figure 9. The standard errors of the estimates for each of the cineangiograms are 3.9 cc, 8.9 cc, 11.1 cc, and 6.0 cc. (A, B, and C) In these three cases the regression factor did not differ significantly from 1.0; (D) In this case the regression factor did differ significantly from 1.0 at the 0.05 level of confidence.

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ventricles with silastic and barium sulfate. Volumes were determined by Archimedes's principle. Cine films of each cast in the right anterior oblique position and of appropriately placed grids were analyzed with the video system. Figure 8 shows the volume data, the correlation coefficient, and the results of a regression analysis. The volumes measured by the video system on the average are 10% greater than the known volumes.

**Study of Left Ventricular Cineangiograms**

Left ventricular cineangiograms of five patients were analyzed by the video system. One or two cardiac cycles from each of the five cineangiograms were also analyzed by the traditional method of measuring the area (by planimetry) and the maximum length of the opacified left ventricle on each cine frame. The lengths, areas, and volumes of identical cine frames determined by this method were then compared with those determined by the video system. Throughout the cardiac cycle, the areas, lengths and volumes measured by the video system agreed closely with those determined by the traditional method (figs. 9 and 10). Volumes measured by the video system tend to be slightly smaller than volumes determined by the traditional method.

**Study of the Recording-Computer System**

In two cineangiograms analyzed by the video system, the areas and lengths of the opacified left ventricle were recorded simultaneously on a magnetic tape recorder* and on an oscillographic recorder† at a paper speed of 125 cm/sec. The paper recording was read by the traditional method, and the magnetic tape, by the computer system. Volumes were then calculated from data obtained by the two methods and plotted both against time and on an X-Y plot (fig. 11). The correlation coefficient and regression analysis indicate that computer analysis does not introduce any significant error.

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*Ampex FR 1300.
†Brush Recorder.

**Discussion**

A drawback of the angiographic method for determining ventricular volume has been the labor involved in measuring the cardiac dimensions from the films and in calculating the volumes. The video system described herein significantly decreases the work of measuring ventricular volume and eliminates the need for a skilled individual to measure the area and length of the opacified ventricle on every cine frame. It does require a skilled individual to adjust the mask, threshold level, and density shading of the video system so that an accurate fit is obtained between the area and length of the opacified ventricle as determined by the video planimeters and the area and length actually visualized by the operator.

The accuracy of the video system has been tested by several independent methods. The study of the prolate spheroid models demonstrates that the video system is accurate over a wide range of volumes and that the magnification and distortion introduced by the X-ray equipment can be compensated for adequately by appropriately placed grids. The video system underestimates volumes by approximately 8%. The reason for this is that the densitometers in the system require a certain minimal signal-to-noise ratio before any given density can be separated from surrounding subthreshold densities. At the very edge of the image the signal-to-noise ratio is inadequate. Consequently, a position just inside the actual edge is recognized as the border by the video system; this leads to a systematic underestimation of volume.

The study of the ventricular casts demonstrates that the video system can determine the volume of not only a spheroid but also an irregularly shaped ventricle with a reasonable degree of accuracy. Even though the video system systematically underestimated the volumes of the aluminum prolate spheroids, it slightly overestimated the volumes of all ventricular casts. This apparent paradox has an explanation. The shape of the left ventricular cavity is not that of a prolate spheroid or any other regular geometric figure, and when
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the formula for a prolate spheroid is used in the calculations, ventricular volume is overestimated considerably. Since the underestimation of volume by the video system is small by comparison, the net result of the two errors is that the volumes of the ventricular casts are slightly overestimated.

Although the studies of prolate spheroids and ventricular casts demonstrate that the video system can calculate the volumes of these objects with reasonable accuracy, the margins of the opacified left ventricular cavity during angiography are less sharply defined. Because of this potential problem and because the image actually analyzed by the video system is slightly modified by the various shading technics, we compared the volumes calculated by the video system with those calculated from the same cine frames by the traditional method. In general, volumes calculated by the two methods agreed closely. As expected, the volumes calculated by the video system were slightly less than those obtained by the traditional method. This error is small and partially corrects for the overestimate of volume resulting from the geometric assumptions.

Two specific problems are of special concern when this method is used. One is estimating the position of the aortic valve. The video planimeter cannot delineate the valve border since the densities above and below the aortic valve are virtually identical following the injection of contrast medium into the left ventricle. One approach to this problem is to assume that the aortic valve is fixed and to set its position with the mask. In those cineangiograms in which movement of the valve border appears to be minimal, this assumption does not lead to significant errors in the estimation of volume. In those cineangiograms in which the valve border appears to move appreciably, however, the edge of the mask that defines the position of the aortic valve can be changed during the course of the analysis by the operator so that it approximates the actual position of the aortic valve. Even when the ventricular silhouette is traced by hand, the position of the aortic valve occasionally can only be approximated because it is obscured by other opacified structures such as the descending aorta (anteroposterior projection) or the left atrium.

The second problem inherent in this method for determining ventricular volume is defining the border of the mitral valve when mitral regurgitation is present. When regurgitation is mild or moderate, the border of the mitral valve can be defined by the video planimeter since the density in the left atrium is less than that in the left ventricle. In the presence of gross mitral regurgitation, however, the border of the mitral valve cannot be delineated by the video planimeter. Under these circumstances, the analysis would have to be done much more slowly than 6 frames/sec so that the operator could alter this area of the mask on a frame-by-frame basis.

In summary, the video system described provides a method whereby changes in left ventricular volume can be analyzed from left ventricular cineangiograms in an automated fashion. The major advantage of the system is that the determinations of volume for an entire left ventricular cineangiogram can be made in 30 to 40 minutes. This system makes possible the routine determination of left ventricular volume changes throughout the cardiac cycle in patients who have left ventricular cineangiograms as part of their diagnostic cardiac catheterization.

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MELVIN L. MARCUS, WILLIAM H. SCHUETTE, WILLARD C. WHITEHOUSE, JAMES J. BAILEY and D. LUKE GLANCY

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