Calculation of Right and Left Cardiac Ventricular Volumes

Method Using Standard Computer Equipment and Biplane Angiocardiograms

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A method has been described for the digital computer calculation of intracardiac ventricular volumes from orthogonal biplane x-ray images. It is directly applicable to both left and right ventricles and uses equipment commonly found in medium size computer centers. Validation of the method is presented using data from geometrical shapes and casts of human ventricular cavities.

SOME PREVIOUS ATTEMPTS TO ESTIMATE VOLumes of heart chambers by angiographic methods have been documented by Dodge et al.,[8] Chapman et al.[6] and Sanmarco and Bartle.[12] A number of recent publications have shown the ease and accuracy with which these calculations of volume can be applied to the measurement of the left ventricle. It is our purpose to describe a biplane angiocardiographic method for calculating both left and right cardiac ventricular volumes. Other angiographic approaches have generally neglected the latter chamber.

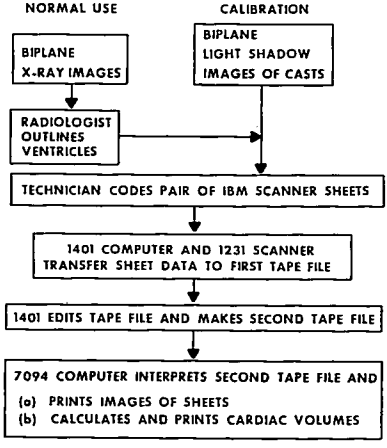

FIG. 1. *Processing scheme diagram.*

Methods

General: Fig. 1 illustrates the general scheme used in processing the data. Casts of cardiac ventricles were placed in a light-shadow device and the cast images traced onto IBM scanner sheets 8.5 × 11 inches. These sheets were originally designed for use in multiple-choice tests and can be read directly by a digital computer equipped with an IBM 1231 scanner. Our computer program transformed the data into volumes by effectively creating a model of the heart as a stack of elliptical cylinders positioned at the calculated center of mass (Fig. 2).

Cast preparation and image shadow: The 60 ventricular casts for calibrating were made from human hearts obtained at autopsy from subjects without known cardiac disease and were prepared within 24 hours after death. Both ventricular cavities were injected under low pressure with a silicone plastic via their atria as described by Carlsson.[4] The plastic mass was allowed to extrude from the cavities during setting and the material appearing in the aorta, pulmonary artery and atria was

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* Work done while a United States Public Health Service Special Fellow, Cardiovascular Research Institute.

This study was aided in part by United States Public Health Service grants HE-06285, HE-10318-01, and FR-01122.

The authors are indebted to Miss Laura Schmidt for assistance in programming.

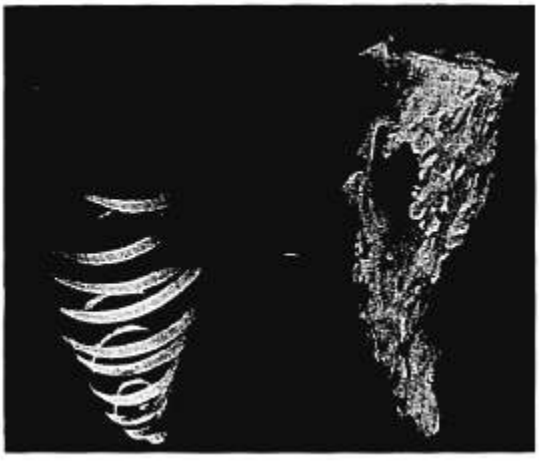

FIG. 2. *Representations of left ventricular cavities from computer data and silicone-plastic cast.*

later cut away. The ventricular casts were placed on an adjustable stand in a device (Fig. 3) containing two pinhole sources of light, each 90 cm from one of a pair of perpendicular plane surfaces representing the film in angiographic systems. Perpendicular lines (beam axes) from the light sources to the planes intersected at a point 19.6 cm from

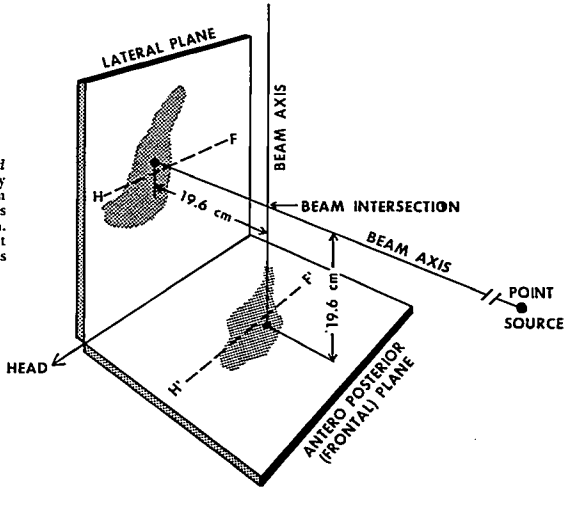

FIG. 3. *Geometry of light and x-ray system.* Light and x-ray point sources are 90 cm from their respective image planes where cast shadows are shown. Lines H-F and H'-F' represent the centers of area moments about a head-foot axis.

the center of each image plane. This arrangement thus duplicated the geometry of our biplane rollfilm changer and its x-ray tubes (Elema Schonander). Actual anteroposterior and lateral angiocardiographs of similarly shaped left or right ventricles were placed on the planes so that the beam centers of the x-ray images coincided with the light beam centers. Each cast was positioned so that the resulting shadow best fit the x-ray image, assuring a reasonably anatomical placement of the cast with respect to planes and light sources. The films were then removed, the outlines of the light shadows traced and the centers of the beams marked. Outlines of cardiac ventricles obtained from angiocardiograms would enter the process at this point and be treated in the same manner as the cast shadows hereafter.

IBM scanner sheets: The pair of traced outlines were transferred to IBM scanner sheets imprinted with a matrix of 1,000 markable cells consisting of 50 horizontal rows divided vertically into four groups of five columns each. Each cell is 0.51 cm deep by 0.84 cm wide. Fig. 4 shows one such sheet coded for an anteroposterior view. The criterion for marking an individual cell was that half or more of its area was within the outline of the shadow. The final matrix available for the image was 16.7 by 22.9 cm.

Digital computer phase: The data were processed through an IBM 1401 digital computer, followed by a final pass through an

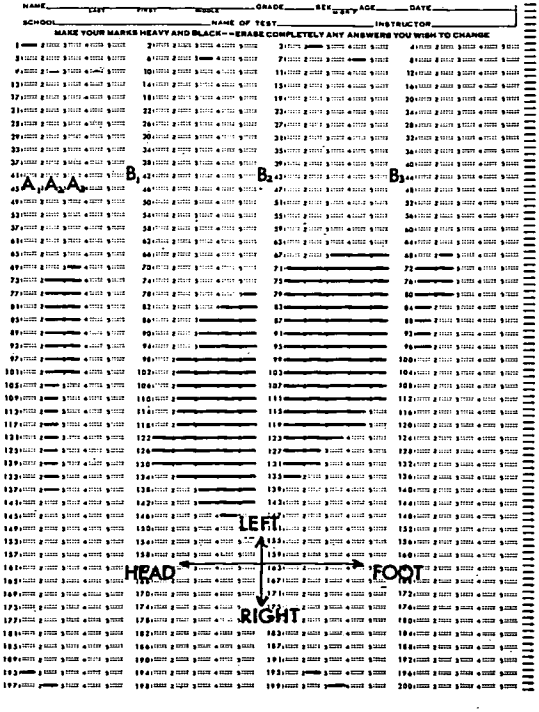

FIG. 4. *IBM scanner sheet coded for anteroposterior view.* The first three columns (A_1, A_2, A_3) represent the data not otherwise read in the blank columns (B_1, B_2, B_3). The upper three rows are used for identification and the lower two for beam center coding. The matrix was usually marked with a pencil, but was inked here for emphasis.

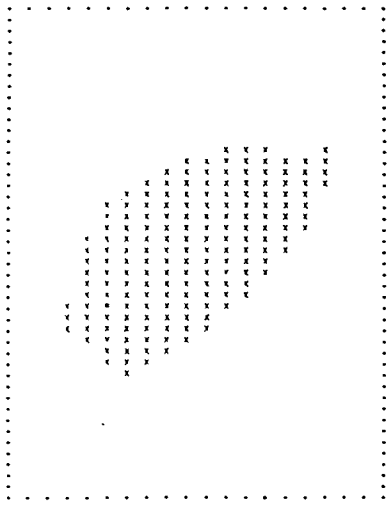

FIG. 5. *Part of computer printout.* The scanner sheet image of anteroposterior view of a left ventricle (head at left) indicates marked cells with (X) and beam center with (*). A beam center outside the shadow would be represented by (0). The extent of the reference grid is indicated by periods (.) on the periphery.

IBM 7094 computer. On the first pass data from pairs of scanner sheets were transferred to a file on magnetic tape by the IBM 1231 scanner and a program developed in our computer center. During the second pass the tape file was edited and checked for errors by an Autocoder language program and a second tape file was created. On the last pass the second tape file was used as input for calculations by a Fortran IV program. Printed output (Fig. 5) consisted of images of the scanner sheet matrices (adjusted for the missing columns and with beam center indicated), geometrical position and correction factors and the calculated ventricular volume. Execution time for the last pass was approximately 1.5 sec per volume, exclusive of off-line output printing. These programs have since been rewritten for an IBM 360 model 40 computer.

Calculation: The enlargement factors were computed according to the following scheme (Fig. 3): First, two head–foot lines were determined—a line in the lateral plane representing the center of front–back area moments about beam center and a line in the anteroposterior plane representing the center of left–right moments about beam center. In a horizontal section, these lines are represented by points. Fig. 6 is a schematic view of such a horizontal plane seen from above. Since the coordinates of S_{AP}, S_L, B_{AP} and B_L were fixed and the coordinates of the moment centers M_{AP} and M_L calculated, the intersection, C_H, of line $S_{AP}M_{AP}$ with S_LM_L could be directly determined. The axis of an ellipse or indeed any linear element positioned at C_H and parallel to the anteroposterior plane would be enlarged by projection onto that plane. The enlargement factor for the anteroposterior plane is given by the ratio of $S_{AP}B_{AP}$ to $S_{AP}C_{AP}$. A similar ratio gives the enlargement factor relating linear dimensions in the lateral image plane to their corresponding parallel sources positioned at C_H.

The head–foot diameters of the anteropos-

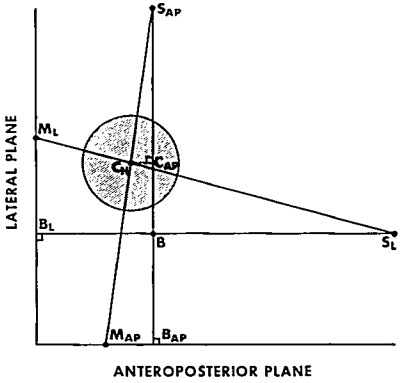

FIG. 6. *Calculation of enlargement factors.* The horizontal plane is depicted from above but not to scale. X-ray sources S_{AP} and S_L produce beams intersecting each other at B and intersecting the image planes at B_{AP} and B_L. M_{AP} and M_L represent the intersection of head–foot area moment lines with the horizontal plane. C_H is the calculated center of mass of the cardiac cavity. C_{AP} is the projection of C_H on the beam axis.

terior and lateral images were usually of different size, in which case they had been represented by a different number of units on the two scanner sheets. Therefore, to calculate ventricular volumes, we had to rescale the head–foot units of the shorter image by increasing their number so that each image when reduced and translated to the position of the center of mass contained the same number of units as its mate. The appropriate set of right–left or front–back measurements was scaled to conform with the new head–foot set in the adjusted image. Individual elliptical cylinder volumes were then obtained and summed to obtain the total volume according to the formula:

$$V = \sum_{i=1}^{h} v_i = \frac{f\pi}{4} \sum_{i=1}^{h} a_i b_i$$

where a_i is the right–left axis of the i^{th} cylinder; b_i is the front–back axis and h is the number of cylinders in head–foot units of the larger image. The factor f is given by:

$$f = f_1 f_2^2$$

where f_1 is the enlargement factor calculated for the smaller image and f_2 is the enlargement factor for the larger image. When the two images were of equal head–foot height, f was taken as:

$$f = f_1 f_2 (f_1 + f_2)/2$$

The validity of the assumptions involved in the preceding calculation was checked by substituting three spherical test objects and a cone-capped cylinder for models of the heart. The range of volumes tested was chosen to exceed the expected range of cardiac ventricular volumes. The objects were separately placed in the light–shadow device both near the beam intersection and at positions well outside the range thus far encountered in our clinical angiocardiographs. The volumes were calculated as before.

Results

Tables 1 and 2 compare the calculated volumes of three test spheres and a cone-capped cylinder with direct measurements. The agreement is generally good, lending credence to the geometrical approximations and the program logic. In trials 1 and 2 of Table 2 the cylinder was parallel to the head–foot axis and intercepted both beam axes. In trial 3 its orientation was the same but it was placed much closer to the lateral image plane. In trial 4 it was brought back to the beam intersection but directed perpendicular to the lateral plane.

TABLE 1. Volumes of Test Spheres, Measured and Computed

	Computed volumes (cc)				
	Position of test sphere				
Measured volume (cc)	At beam intersection	Near lat far from AP	Far from both AP and lat	Near both AP and lat	Mean
27.8	27.6	27.6	27.4	28.2	27.7
194	195	197	195	197	196
415	424	434	423	431	428

TABLE 2. Volumes Computed for a 170.5 cc Cone-capped Cylinder

Trial no.	Angle of cylinder axis with image planes		Computed volume
	AP	Lat	(cc)
1	0°	0°	169
2	0°	0°	168
3	0°	0°	164
4	0°	90°	161
5	22°	39°	177
6	29°	41°	175
7	45°	45°	249

None of these maneuvers produced a great variation in calculated volume. Even when appreciable angles were made with the image planes, as in trials 5 and 6, the results were quite accurate. In the extreme case of trial 7, wherein the cylinder was placed perpendicular to the head–foot axis and at an angle of 45° to both image planes, the computer overestimated the volume by almost 50%. The inaccuracy due to this orientation is geometrically predictable, of course, and would plague any scheme designed to calculate volumes from only two orthogonal views.

In Fig. 7 the computer-calculated volumes of 30 left and 30 right ventricular casts are plotted against corresponding volumes of casts measured by loss of weight in water. The data are given as points, and linear least-squares fits are indicated with 95% confidence limits for both the regression lines and for the samples. Correlation coefficients of 0.976 for the left ventricle and 0.953 for the right compare favorably with values given by Sanmarco and Bartle[12] and indicate that the equations shown can be used to predict cardiac volumes from computed volumes.

Discussion

This method of calculating intracardiac volumes has certain *a priori* advantages over some of those used in the past. First of all it adds information from the third dimension not accessible to monoplane angiographs. Since the time of Geigel[9] reasonable approximations to cardiac and intracardiac volumes have been obtained from the surface area of two dimensional heart shadows. Geigel used the projected area of the heart shadow in the frontal plane to calculate volumes of the whole heart and assumed that the heart could be represented by a sphere. Using F for Fläche (surface area) measured on a quarter centimeter grid, he calculated the volume from:

$$V = \frac{4\ F^{3/2}}{3\ \pi^{1/2}}$$

which relates the volume of a sphere and its projected surface area. This formula is misprinted in Chapman's article,[6] where F was incorrectly identified with diameter of the heart.

While a good approximation to the volume of cardiac models can be obtained using a minor modification of Geigel's method (P. Lee and E. Carlsson, unpublished observa-

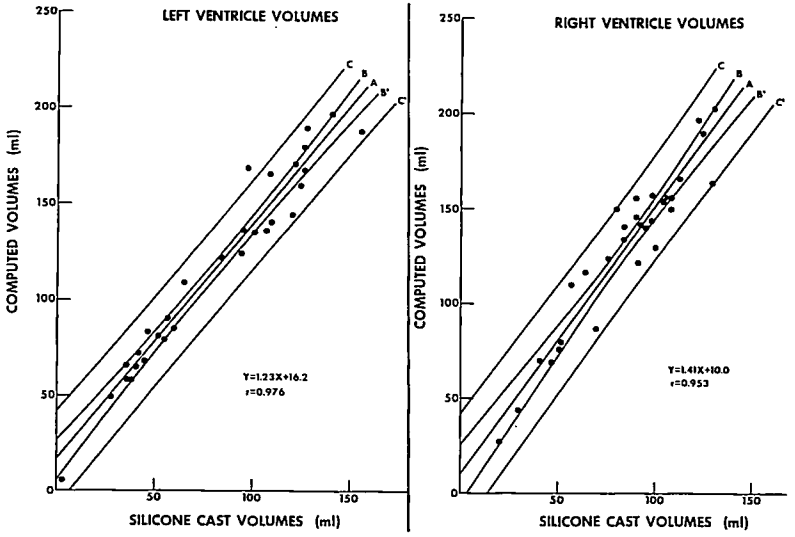

FIG. 7. *Computed volumes plotted against corresponding, directly measured, left and right ventricular volumes.* Equations for the regression lines (A) are given along with correlation coefficients (r). Ninety-five per cent confidence limits for the regression lines are indicated by the inner pair of curved lines (B, B'), and 95% confidence limits for individual measurements are indicated by the outer pair (C, C').

tions), a system that adds independent information from sagittal plane projections and takes enlargement into account might be expected to be more accurate. Both Arvidsson[1, 2] and Dodge et al.[7, 8] take these factors into account in their methods but use elliptical approximations early in their calculations and hence do not glean full information from the shadows.

Nelson and Lipchik[10] have presented a digital computer scheme to analyze such data; however it would seem more appropriate to put these powerful machines to work abstracting more of the information present before the calculation is performed. Baker, Khalaf and Chapman[3] do just this and hence bypass that phase of the calculation where the heart shadow must be represented as an ellipse. In use, this last method requires that an observer judge the position of the heart in each case and place a lead reference object in the proper position for calibration. The system uses a sophisticated specially built device which scans the traced heart shadows to provide computer input. The shape of the heart is then approximated by the same stack of elliptical right cylinders we have used.

Although our method is quite similar to that of Baker et al., it eliminates the use of their lead reference standard and calculates the position of the center of mass of the ventricle directly from information present in the images themselves. In addition, we employ a standard optical scanning device (IBM 1231), probably not available to these investigators in 1960 but now common in many computer centers.

The present system and all of the above angiographic methods are still limited by the geometrical fine structure illustrated in Fig. 2. The deep infoldings due to papillary muscles and trabeculae cannot be resolved by any biplane system in which only outline of shadow is considered. An image-scanning device capable of gray-scale discrimination could, if assisted by proper programming, come close to the goal of estimating the volume of these hidden structures. It would be limited, however, by the same mixing difficulties complicating dye-dilution curve determinations of volumes and cardiac outputs. Furthermore, the associated computer program would have to be extremely sophisticated. Lacking such refinements, one must be content with data scatter similar to that seen in Fig. 7. The spread remaining is apparently related to the variability in volumes of trabecular and papillary muscle and to the variability in chamber axes.

The reference grid of our system (5.1 $\times$ 5.1 $\times$ 8.4 mm, referred to the image planes) is quite a bit coarser than that of Chapman (1 $\times$ 1 $\times$ 1 mm) or even of Geigel (2.5 $\times$ 2.5 mm) but we believe it to be appropriate considering the lack of sharpness of the shadows encountered in angiograms and the total volumes concerned. In any case, the summation over many such unit-volume cells will give an answer inherently more accurate than could be obtained by the use of only three linear dimensions with the same linear indeterminacy.

Once the geometry of an angiographic system has been determined, our method can be applied in a straightforward manner to the biplane images for calculations of intracardiac volume. The dimensions of systems with fixed geometries such as the Elema Schonander would be incorporated into the computer program. With most cineangiographic apparatus, however, it would be necessary to measure the systems each time they are used and to supply these dimensions to the program at time of computation along with the scanner sheet input. Alternatively such magnification corrections could be incorporated in the projection-tracing phase.

This paper is the second development, to our knowledge, of an angiographic method purporting to measure right ventricular volume directly. Carlsson[4] has devised a method of measuring intracardiac volumes which involved the creation of a styrofoam model of the cavity from biplane angiocardiographs. The model study of Carlsson, Harrison and Wright[5] showed that right and left ventricular volume could be calculated equally well.

Reedy and Chapman[11] have estimated right

ventricular volume by subtracting a calculated left ventricular volume and an estimate of the "volume" of the ventricular septum from a measured figure for the whole heart which included the volumes of both ventricular cavities and the ventricular septum. They believed that the concave–convex right ventricular shape could not be represented by the stack-of-cylinders approximaton. Our data (Fig. 7), however, agree with those of Carlsson et al. in showing that the volumes of right ventricular casts can be estimated very nearly as well as can those of left ventricles. We submit that the direct Chapman method[6] could also be applied to right ventricles.

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