Clin. Cardiol. 2, 257–263 (1979)

Approaches to Determination of Left Ventricular Volume and Ejection Fraction by Real-Time Two-Dimensional Echocardiography

A. F. Parisi, M.D., P. F. Moynihan, B. S., C. L. Feldman, D. SC., E. D. Folland, M. D.

From the Department of Medicine (Cardiology Section), V. A. Medical Center, West Roxbury, MA and Peter Bent Brigham Hospital and Harvard Medical School, Boston, MA, USA

Summary: Left ventricular volumes and ejection fraction were derived from real time two-dimensional echocardiographic images (2 DE) and single plane (RAO) left ventricular cineangiograms in a series of 50 patients. Prospective application of a series of 6 alternate algorithms showed that a modified Simpson's rule approach using mitral and papillary muscle cross sections and an apical four chamber view provided the best 2 DE – angiographic correlations: for end-diastolic volume r = 0.82, SEE = 39 ml; for end-systolic volume r = 0.90, SEE = 29 ml and for ejection fraction r = 0.80, SEE = 0.09. The large SEE for volume determination indicates that further refinements are necessary to predict left ventricular volumes adequately; however, ejection fraction can be derived with an accuracy which allows practical clinical decisions in patients with satisfactory 2 DE images.

Keywords: end-diastolic volume, end-systolic volume, ejection fraction, two-dimensional echocardiography, echocardiography, left ventricle

Supported by the Medical Research Service of the U. S. Veterans Administration.

Address for reprints:

Alfred F. Parisi, M. D.
V. A. Medical Center
1400 VFW Parkway
West Roxbury, MA 02132, USA

Received: March 26, 1979
Accepted: May 2, 1979

Introduction

Determination of left ventricular (LV) diastolic and systolic volume provides a quantitative measure of the effects of disease on cardiac function. Volume assessments document the degree of LV enlargement and allow derivation of indices which describe its diastolic filling properties (e.g. – compliance) and systolic pumping properties (e.g. – ejection fraction).

Historically volume measurements have been determined invasively from biplane and single plane (RAO) angiography (3, 9). The ability of M-mode echocardiography to determine internal left ventricular dimensions has stimulated interest in non-invasive volume measurements (4, 6, 12). Because M-mode techniques extrapolate volume from a single transverse measurement assumed to represent the LV minor axis diameter, they are subject to sampling error in ventricles which have irregular geometric shapes in diastole and/or in systole (10). An early study with gated B-scan ultrasonography indicated that two-dimensional (2D) techniques could minimize this sampling error (16). To date, however, there have only been preliminary reports of ventricular volume and ejection fraction determination by real time 2D echocardiographic systems (1, 2, 11, 13, 14, 17). We report herein our initial attempts to assess left ventricular volumes and ejection fraction from multiplane real-time 2D echocardiographic images in a series of patients who underwent left ventricular cineangiography.

Methods

Imaging Methods and Processing

Echocardiographic and cineangiographic images were processed by independent observers who were unfamiliar

with each other's results. In all instances echocardiographic images were traced before cineangiography. Beats immediately succeeding premature ventricular contractions were excluded from consideration.

Echocardiographic Images: Two dimensional echocardiograms were recorded using a commercially available phased array sector scanner (Varian V-3000) within 24–48 h of cardiac catheterization. On each patient two parasternal cross-sectional images – the first at the level of the mitral valve leaflet tips, and the second at the level of the mid-papillary muscles – and one apical view were obtained (Fig. 1 and 2). The mitral valve view was usually obtained from the third left interspace; the transducer was then placed 1–3 cm inferior and lateral from this point to obtain the papillary muscle level image. The apical view was directed to include all four cardiac chambers in the plane of both mitral and tricuspid valves. All studies were performed in the semi-recumbent position with varying degrees of left lateral rotation to optimize image quality. Two-dimensional images were stored on a ½" reel type magnetic videotape recorder (Panasonic NV-3160) and played back using a high resolution monitor (Conrac SNA-14/C).

Diastolic images were identified from the QRS complex of the simultaneously recorded electrocardiogram; systolic images of the same beat were identified from the first high frequency component of S_2 in a concomitantly recorded

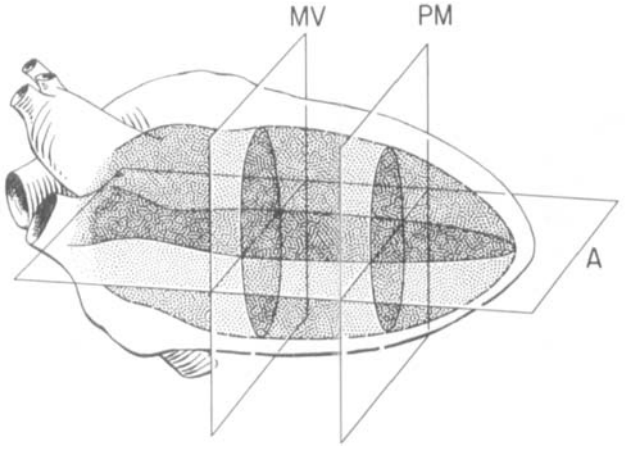

Fig. 1 Schematic of the heart illustrating the orientation of the sections utilized: stippling represents the left ventricle. MV = transverse section at mitral valve level, PM = transverse section at papillary muscle level, A = apical four-chamber view.

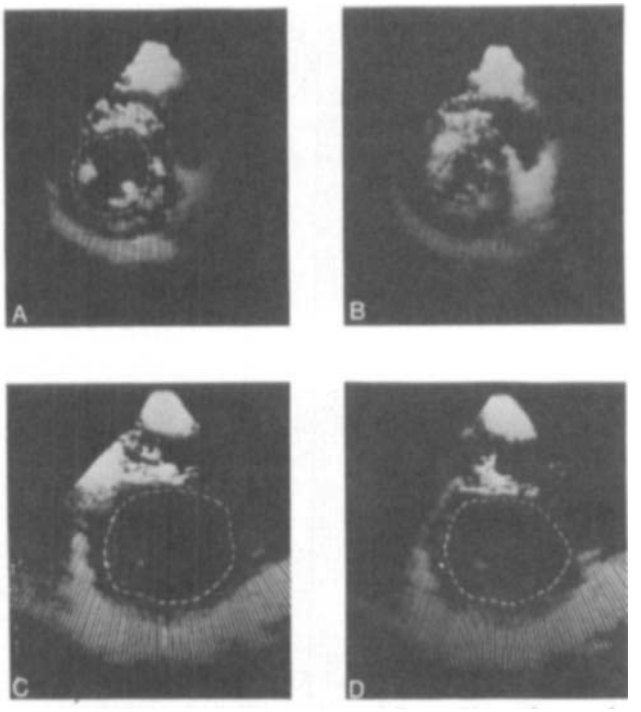

Fig. 3 Examples of transverse echocardiographic sections at the papillary muscle level for a normal-sized and a markedly enlarged ventricle demonstrating the technique of outlining the left ventricular endocardium. A. End-diastolic image of a patient with coronary heart disease and a normal-sized ventricle (angiographic EDV = 159 ml), B. end-systolic image corresponding to A (angiographic ESV = 70 ml), C. end-diastolic image of a patient with severe congestive cardiomyopathy and a large ventricle (angiographic EDV = 393 ml), D. end-systolic image corresponding to C (angiographic ESV = 335 ml). The scale represents five centimeters along each axis.

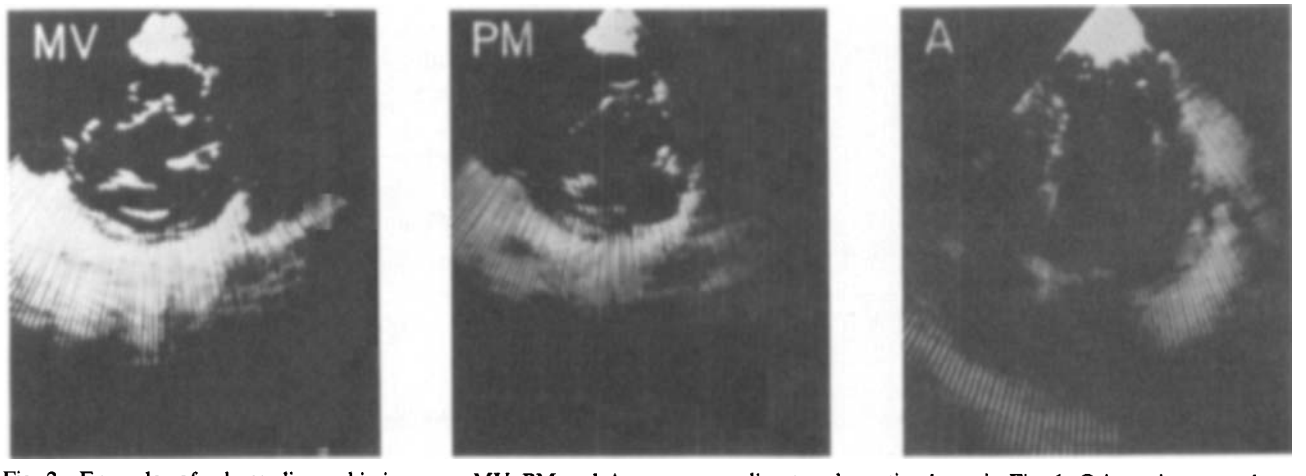

Fig. 2 Examples of echocardiographic images – MV, PM and A – corresponding to schematic planes in Fig. 1. Orientation accords to ASE standards (ASE Communicator, Vol. 4, No. 2, 1978).

phonocardiogram. With stop frame techniques outlines of diastolic and systolic images were traced with a light pen (Fig. 3) and subsequently analyzed using a computerized digitizing system adapted for echocardiographic analysis (Electronics for Medicine VVF). Slow and fast speed playback of the contraction pattern of preceding and succeeding beats provided further confirmation of endocardial targets. All images were traced along the innermost edge of endocardial echoes as they abutted the left ventricular cavity.

The parasternal image at the level of the mitral valve was divided by an axis constructed from the mid-point of the septum to the postero-lateral wall so as to divide the diastolic image into two equal halves. This was maintained as a fixed reference for systolic images. The diastolic and systolic length of this axis (D) and the diastolic and systolic areas of the mitral valve (Am) and papillary muscle level (Ap) images were determined by the computer system mentioned above.

The long axis of the apical image was constructed from the middle of the mitral valve to the cardiac apex in diastole and was also kept as a fixed reference for the systolic image. The diastolic and systolic length of the apical image long axis (L) and its diastolic and systolic area (A_l) were measured.

Diastolic and systolic left ventricular volumes, were assessed prospectively using six different algorithms (Fig. 4).

a) Modified Simpson's Rule: The length of the left ventricle was divided into thirds and its volume modeled as the sum of a cylinder from the base of the heart to the mitral valve, $V = A_m \frac{L}{3}$, a truncated cone from the level of the mitral valve to the level of the papillary muscles,

$$V = \left[\frac{A_m + A_p}{2}\right]\frac{L}{3},$$

and below this another cone to the cardiac apex

$$V = {}^1/_3\,[A_p]\frac{L}{3}.$$

b) A hemisphere-cylinder model using biplane data: The cross-sectional area at the mitral valve level (A_m) and long axis from the apical view (L) were used to solve for the volume of a cylinder

$$V = A_m \frac{L}{2}$$

capped on one end by a hemisphere with a base area and length equal to that of the cylinder

$$V = {}^2/_3\,A_m \frac{L}{2}.$$

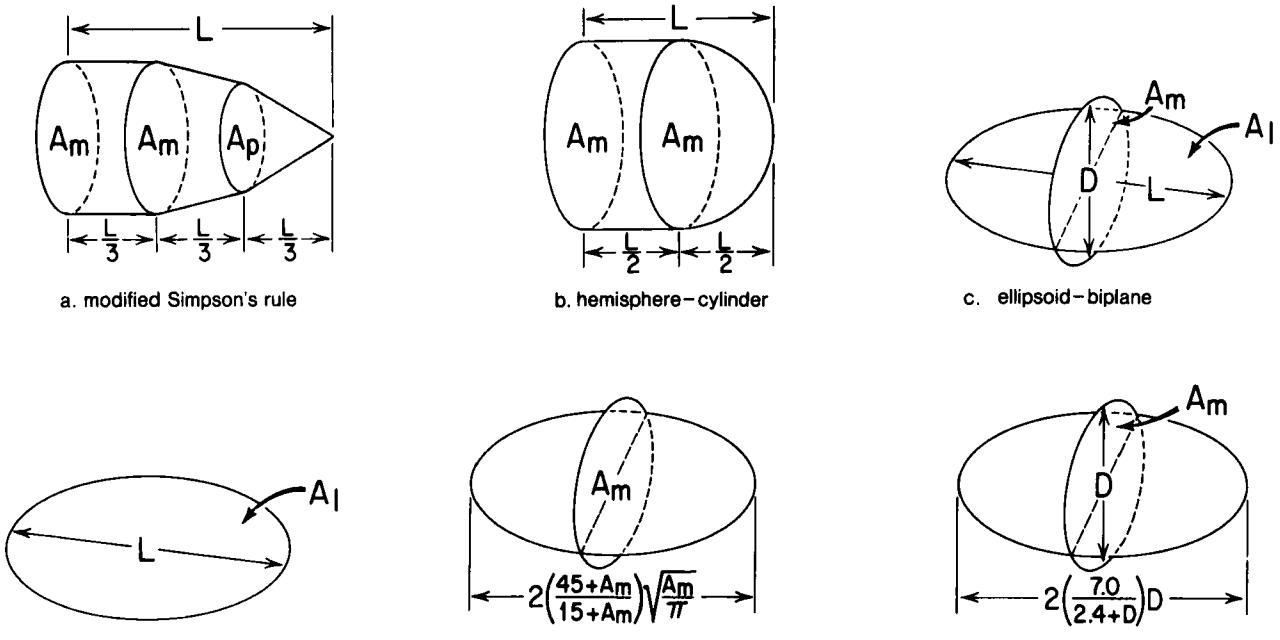

Fig. 4 Summary of the geometric models utilized to generate left ventricular volumes from two-dimensional echo data. A denotes area measurements, L is the long-axis length of the left ventricle from the apical section, and D is the septal-lateral diameter from the high cross-section of the ventricle. The subscripts m, p, and l refer to the mitral valve, papillary muscle, and long-axis (apical) sections, respectively.

c) An ellipsoid model using biplane data (after *Sandler* and *Dodge* (3)): Two perpendicular echo planes (the mitral valve (A_m) and apical view (A_l) were substituted for two angiographic projections

$$V = \frac{\pi}{6} L \left(\frac{4A_m}{\pi D}\right) \left(\frac{4A_l}{\pi L}\right).$$

d) An ellipsoid model using single plane data (8): Area (A_l) and length (L) from the apical echocardiographic image were substituted into the standard single plane area length equation (9)

$$V = \frac{8\,[A_l]^2}{3\pi L}.$$

e) A modified ellipsoid model using single plane data: The cross-sectional area at the mitral valve level was assumed to be at the middle of an ellipsoid ventricle

$$V = \left(\frac{45 + A_m}{15 + A_m}\right) A_m^{3/2}$$

whose major axis,

$$L = 2 \left(\frac{45 + A_m}{15 + A_m}\right) \sqrt{\frac{A_m}{\pi}}$$

is a function of the cross-sectional area which varies such that the ratio of major to minor axis length is approximately 2 : 1 for ventricles in the normal size range, becoming more elongate for smaller ventricles and more nearly spherical for larger ones. This formula is intended to compensate for the deviation from typical ellipsoid proportions which occurs in both unusually large and small ventricles, as well as the fact that the left ventricle typically contracts more circumferentially than longitudinally.

An alternative version of this model was also tested, using the papillary muscle cross-sectional area and, because A_p is typically smaller than A_m, different constants were employed.

$$V = \left(\frac{36 + A_p}{12 + A_p}\right) A_p^{3/2}.$$

f) A modified ellipsoid model using unidimensional data: The septal-posterior wall dimension (D) was substituted into a formula described by *Teichholz* based upon an ellipsoid model

$$V = \left(\frac{7.0}{2.4 + D}\right) D^3$$

where the major axis,

$$L = 2 \left(\frac{7.0}{2.4 + D}\right) D,$$

is a variable function derived from the measured minor axis D. Again, this formula is intended to compensate for variation in ellipsoid proportions seen in both unusually large and small ventricles (16).

For all formulations ejection fraction was derived as the quotient of end-diastolic volume minus end-systolic volume/end-diastolic volume.

X-ray Cineangiograms: Left ventricular cineangiograms were filmed at 60 frames/s using a 9-inch image intensifier in 30° right anterior oblique projection during injection of 40–60 ml of contrast material (Renografin-76). End-diastolic, end-systolic and grid images were traced on celluloid directly from a cine projection viewing screen (Vanguard XR-35). Ejection fraction and ventricular volumes were derived using the described light pen computerized system programmed to determine left ventricular volumes and ejection fraction from angiographic diastolic and systolic frames using the single plane area-length method and regression equations described by *Kennedy* et al (9).

Regional function was assessed using a modified Hermann-Gorlin axis system in which abnormally contracting segments were identified when they were more than 2 SD below the mean determined for each LV segment from a series of 10 patients with "normal" reference LV cineangiograms (7, 15).

Patient Selection

Fifty patients were selected from a consecutive catheterization series of patients on the basis of having had both 2 DE and x-ray cine studies of adequate quality for quantitative interpretation. The clinical status of all patients was unchanged between studies. Thirty-eight patients had coronary heart disease, 7 had valvular heart disease, 2 had combined valvular and coronary disease, 2 had cardiomyopathies, and one had constrictive pericarditis. Twenty-five patients had cineangiographic segmental contraction abnormalities.

Results

As an initial step in comparing two-dimensional echocardiographic images to angiographic images, linear dimensions measured from the former were compared to analogous dimensions obtained from the latter. The results of the first hundred consecutive measurements are shown in Fig. 5. A linear relationship (r = 0.92, SEE = 0.97 cm) was obtained. Echocardiographic linear dimensions consistently underpredicted angiographic linear dimensions.

The end-diastolic volumes in these patients ranged from 99 to 393 ml and end-systolic volumes from 23 to 335 ml. Two-dimensional echocardiograms from a patient with an abnormally enlarged ventricle were shown in Fig. 2. The figures are displayed at the same magnification and illustrate the difference in cross-sectional area images between a normal and a markedly enlarged ventricle.

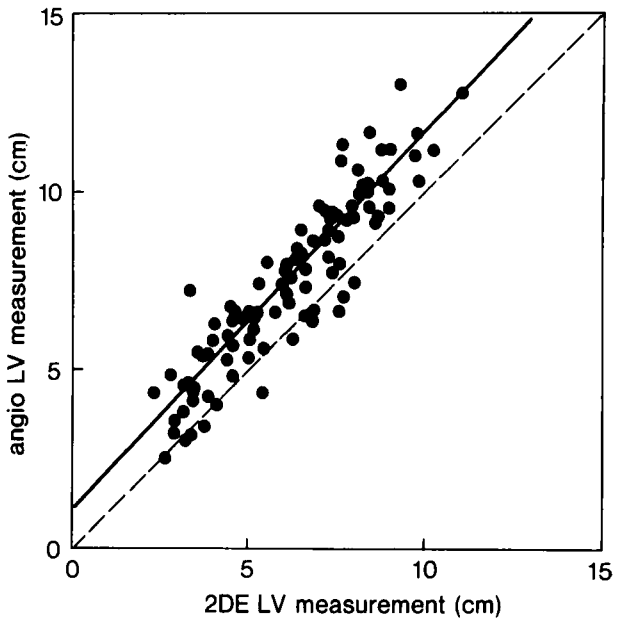

Fig. 5 Relationship of 100 corresponding linear measurements of the left ventricle (LV) made from two-dimensional echocardiograms (2DE) and x-ray cineangiograms (ANGIO). The regression equation (solid line) is y = 1.07 x + 0.83 cm. (r = 0.92, SEE = 0.97 cm). The dashed line is the line of identity.

Table I shows the correlations of each of the formulations used with angiographic volumes and ejection fraction. Modified Simpson's rule yielded the highest correlation coefficients and lowest SEE for volumes (r-EDV = 0.82; r-ESV = 0.90); the correlation remained in the same range (r = 0.80) when volumes were used to derive ejection fraction. The ellipsoid-biplane model had slightly poorer correlations for volume but maintained as reasonable a correlation with ejection fraction (r = 0.82). The remaining algorithms showed less satisfactory correlation. Of particular note is the lack of correlation of unidimensional (linear) data when ejection fraction is derived.

The ellipsoid-single plane formulation (based on the long axis view) and the area based modified ellipsoid (derived from the papillary muscle cross section), because they do not involve integration of data from multiple sections, offer the advantage of allowing beat-to-beat derivations of LV volume. In this regard the latter method had somewhat closer correlations with LV volumes than the former.

The modified Simpson's rule echocardiographic volumes are related to angiographic volumes in Fig. 6. As is the case with linear dimensions, echocardiographic volumes tended to underpredict angiographic volumes. Because the relationship was linear, a regression relationship defined by the formula ANGIO VOLUME = 1.08 (ECHO VOLUME) + 29.5 ml can be used to interrelate the echocardiographic and angiographic measurements more quantitatively.

Regional contraction abnormalities were identified in 25 of the 50 patients by cineangiography. In this subgroup

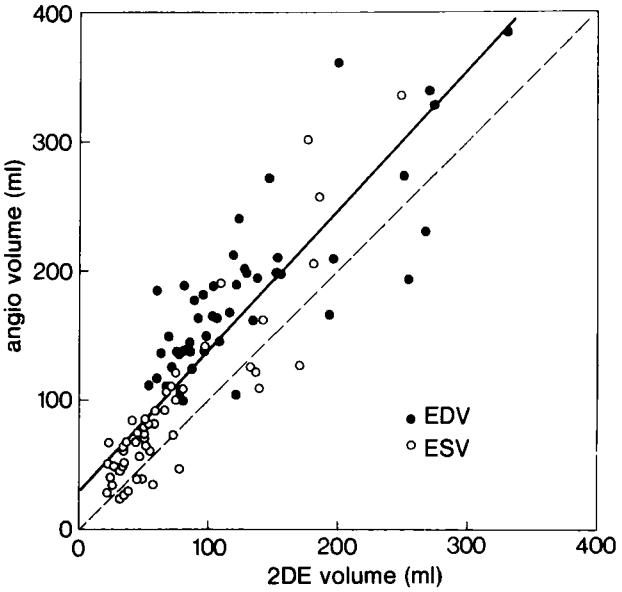

Fig. 6 Relationship of left ventricular end-diastolic (EDV) and end-systolic (ESV) volumes as determined by two dimensional echocardiography (2DE) and angiography (ANGIO). The regression equation (solid line) for all volumes is y = 1.08 x + 29.5 ml (r = 0.87, SEE = 39 ml). The dashed line is the line of identity.

Table I Correlation coefficients* comparing 2 DE algorithms tested with left ventricular cineangiography

	EDV	ESV	ALL V	EF
modified Simpson's rule	0.82 (39)	0.90 (29)	0.87 (39)	0.80 (0.09)
hemisphere-cylinder	0.69 (49)	0.74 (45)	0.77 (51)	0.62 (0.12)
ellipsoid-biplane	0.72 (47)	0.80 (40)	0.81 (47)	0.82 (0.09)
ellipsoid-single plane	0.69 (48)	0.74 (45)	0.79 (50)	0.76 (0.10)
modified ellipsoid (area based)	0.77 (43)	0.86 (34)	0.84 (44)	0.71 (0.11)
modified ellipsoid (linear based)	0.72 (47)	0.81 (39)	0.79 (49)	0.59 (0.12)

EDV = end-diastolic volume, ESV = end-systolic volume, EF = ejection fraction
* Standard error of the estimate in parantheses; for volume measurements these are expressed in ml.

modified Simpson's rule still provided the best correlation coefficients and lowest estimating errors – for all LV volumes r = 0.84, SEE = 45 ml; for ejection fraction r = 0.83, SEE = 0.08.

Discussion

Two-dimensional echocardiography and x-ray cineangiography are fundamentally different approaches for evaluating LV geometry. X-ray cine derives information from a two-dimensional LV silhouette. 2 DE is a tomographic method, producing slice-like LV images along the plane of orientation of the ultrasonic beam. In this regard it is not surprising that cine linear dimensions and volumes exceeded 2 DE dimensions and volumes. A silhouette of necessity portrays the largest dimensions of a figure orthogonal to the viewer; a tomogram does not necessarily coincide with this perception.

In theory selection of the most representative single 2 DE slice or integration of an appropriate series of 2 DE "slices" permits extrapolation to a three-dimensional reconstruction of LV anatomy. The approaches tested herein are a compromise between limitations of the current ultrasonic methodology and practicality. The beam generated by the phased array scanner utilized in this study approximates 1 cm in thickness in the region of the field where the heart is imaged, allowing only a finite number of slices in either transverse or apical orientations. Reproducibility of sampling is also limited by the number of ventricular landmarks, which are few. Imperfect lateral resolution distorts endocardial targets both as a function of depth of field and beam orientation. Considering these factors the methods herein represent the simplest initial approach we could find to the problem. Further refinement of ultrasonic imaging, different "slice" orientations and/or different algorithms may prove more highly satisfactory in the future.

The models tested also rest upon arbitrary and sometimes different assumptions about ventricular anatomy. For instance, 2 of 3 models using biplane sampling assume the mitral valve plane lies midway between the apex and base of the ventricle, while the area-based modified ellipsoid tests both cross-sections as being at the midpoint, achieving similar results each way. The modified Simpson's rule model assumes that the mitral and papillary muscle sections trisect the ventricle. Four of six models also assume that the relative position and/or geometry of the involved planes remains constant in systole and diastole. Also, two of the models employ empirical constants. The value of these models is therefore best judged pragmatically by their agreement with an independent reference standard, i.e. contrast angiography.

The data in Table I indicate that there is a predictable relationship between echo image areas and cineangiographic volumes. Modified Simpson's rule samples the most information; hence it is not surprising that it demonstrated the best relationship. For volume estimation the other formulations seem to offer little advantage over one another. When volumes are used to derive ejection fraction, modified Simpson's rule maintains a reasonable correlation as does the biplane algorithm. Other formulations are less impressive – in particular the method based on a single internal dimension (*Teichholz* formulation) is considerably poorer indicating that unidimensional sampling does not vary as systematically from diastole to systole as cross-sectional information.

While the modified Simpson's rule approach yielded the best relationship of the algorithms tested prospectively, this and the other multiple sampling methods do not allow beat-to-beat analysis of ventricular volume. For this purpose an approach using a single cross-sectional area or dimension is required. In this regard the area based modified ellipsoid appears to offer the most promise as a means of analyzing transient changes in LV volume and function.

While volumes derived from 2 DE and cine methods correlate reasonably, the scatter of measurements about the regression relationship is rather large (SEE = 39 ml for EDV and 29 ml for ESV) which for practical purposes are twice as large as the SEE noted when volumes derived from single plane cine are compared with direct biplane radiography (8). A 95 % confidence band for EDV of ± 78 ml limits the value of 2 DE volume determinations as a predictor of single plane cine volume for individual patients with normal to moderately increased ventricular size. The reproducibility of 2 DE volume measurements in the same subject has not been tested. Should they prove to be highly reproducible then they could be useful in serial studies of patients in spite of their variability compared to x-ray cine.

It is possible that our correlations might have been improved were it possible for us to compare our 2 DE data with biplane rather than single plane cineangiography. Some preliminary clinical studies utilizing biplane cine data have reported closer correlations (1, 13, 14), but this has not consistently been the case (11). Our current data indicate that further refinements are necessary to predict left ventricular volumes with more accuracy using real time 2 DE. Choosing the appropriate formulation – in our hands modified Simpson's rule – allows a reasonable derivation of ejection fraction. In particular the SEE of 0.09 compares favorably with similar approaches using radionuclide angiography (5) and indicates that practical clinical decisions about LV function can be made in those patients with satisfactory 2 DE images.

Acknowledgment

The authors acknowledge with gratitude the excellent secretarial assistance of Ms. Elizabeth Gillam, Mrs. Donna Kantarges and Ms. Clare Smith.

References

1. Carr K, Engler R, Forsythe J: Measurement of left ventricular ejection fraction by mechanical cross-sectional echocardiography and comparison with angiography (abstract). Circulation 58, II – 40, (1978)
2. Chaudry KR, Ogawa S, Pauletto FJ: Biplane measurements of left ventricular volumes using wide angle, cross-sectional echocardiography (abstract). Am J Cardiol 41, 391 (1978)
3. Dodge NT, Sandler H, Ballew AM, Lord JA Jr: Use of biplane angiocardiography for the measurement of left ventricular volume in man. Am Heart J 60, 762 (1960)
4. Feigenbaum H, Popp RL, Wolfe SB, Haine CL, Dodge HT: Ultrasound measurements of the left ventricle: A correlative study with angiocardiography. Arch Int Med 129, 461 (1972)
5. Folland ED, Hamilton GW, Larson SM: The radionuclide ejection fraction: A comparison of three radionuclide techniques with contrast angiography. J Nucl Med 18, 1159 (1977)
6. Fortuin NJ, Hood WP Jr, Sherman ME, Craige E: Determination of left ventricular volumes by ultrasound. Circulation 44, 575 (1971)
7. Herman MV, Heinle RA, Klein MD: Localized disorders in myocardial contraction: asynergy and its role in congestive heart failure. N Engl J Med 277, 222 (1967)
8. Kasser IS, Kennedy JW: Measurement of left ventricular volumes in man by single-plane cineangiography. Invest Radio 4, 83 (1969)
9. Kennedy JW, Trenholme SE, Kasser IS: Left ventricular volume and mass from single-plane cineangiocardiogram. A comparison of anteroposterior and right anterior oblique methods. Am Heart J 80, 343 (1970)
10. Linhart JW, Mintz GS, Segal BL: Left ventricular volume measurement by echocardiography: Fact or Fiction. Am J Cardiol 36, 114 (1975)
11. Nixon JV, Saffer SI: Three dimensional echoventriculography (abstract). Circulation 58, II—157 (1978)
12. Pombo JF, Troy BL, Russell RO Jr: Left ventricular volumes and ejection fraction by echocardiography. Circulation 43, 480 (1971)
13. Schiller N, Botvinick E, Cogan J, Greenberg B, Acquatella H, Glantz S: Noninvasive methods are reliable predictions of angiographic left ventricular volumes (abstract). Circulation 56, III–221 (1977)
14. Silverman NM, Schiller NB, Yaeger RL: Left ventricular volume analysis by two dimensional echocardiography in children (abstract). Circulation 58, II–202 (1978)
15. Singer PJ, Feldman CL: An on-line, semi-automated video ventriculography system. Proc Computers in Cardiology (1976) p 261
16. Teichholz LE, Kreulen T, Herman MV, Gorlin R: Problems in echocardiographic volume determinations: echocardiographic-angiographic correlations in the presence or absence of asynergy. Am J Cardiol 37, 7 (1976)
17. Wyatt HL, Heng M, Murbaum S, Davidson R, Lee S, Corday E: Quantitative left ventricular analysis in dogs with the phased array sector scan (abstract). Circulation 56, III–152 (1977)