J AM COLL CARDIOL
1983,1(3) 863-8

Left Ventricular Volumes Determined by Two-Dimensional Echocardiography in a Normal Adult Population

DENNIS W. WAHR, MD, YIN SHI WANG, MD, NELSON B. SCHILLER, MD, FACC

San Francisco, California

The purpose of this study was to determine normal population volume variables of the left ventricle as determined by different algorithms currently available. Two-dimensional echocardiography was prospectively performed on 52 normal volunteers to determine normal left ventricular volume and ejection fraction as a prerequisite to their clinical application. All echocardiograms were performed using a commercially available two-dimensional phased array sector scanner. Three algorithms were applied to three views in various combinations. Ejection fraction calculations were found to be reliable, reproducible and independent of the algorithm employed. Left ventricular volumes were larger in men than in women (probability [p] < 0.005) despite correcting for body surface area, indicating the need for separating patients according to sex. The Simpson's rule algorithm resulted in smaller values for left ventricular volume than did any of the area-length algorithms and the data were the most reproducible as judged by intraobserver variation. The single plane area-length methods are clinically useful because they are simple, rapid to execute and reliable. Ejection fraction calculation was independent of the algorithm employed.

Knowledge of normal echographic measurements of left ventricular volumes is a prerequisite for the clinical application of quantitative echocardiography and these data have not been reported. It is appropriate to determine the normal volumes at this time because several studies have validated the relation between two-dimensional echocardiographic volume measurements and those of angiography, radionuclide and pathologic measurements (1–6). Although there seems to be a consistent underestimation of left ventricular volume using two-dimensional echocardiography, these measurements have proved reliable when tested by interobserver and intraobserver methods (1–6). Therefore, the purpose of this study was to determine normal population left ventricular volume values as calculated with various algorithms currently in clinical use.

Methods

Patient Selection

The study group consisted of 52 volunteers chosen randomly and prospectively from hospital employees. Prospective criteria for participation included no previous history of cardiovascular problems or symptoms and a normal electrocardiogram. Heart rates ranged from 45 to 100 beats/min. There were 29 men and 23 women aged 20 to 66 years. Five additional volunteers met all criteria for inclusion in the study but were excluded because their echocardiogram was technically inadequate. Three subjects claimed to be trained endurance athletes, but their left ventricular volumes did not differ significantly from those of the general population.

Equipment

All two-dimensional echocardiograms were performed with one of two commercially available two-dimensional phased array sector scanners (Varian Associates, Palo Alto, California). The unit's hand-held circular 2.25 MHz transducer measured 2.5 cm^2 and consisted of 32 elements excited as phased array. Images were presented in real-time format at 30 frames/s on the oscilloscope with superimposed horizontal and vertical 1 cm calibration marks and a simultaneously recorded electrocardiogram. The echocardiograms were recorded on a 0.5 inch (1.27 cm) video recorder. Measurements were subsequently made by using a commercially available light-pen computational system (Varian Associates) (7). This system allows the operator to trace endocardial outlines directly onto the recorded echocardiographic video images and from these outlines to calculate the volumes automatically according to the formulas discussed later.

Measurements

Previous reports have described several methods of determining left ventricular volume by echocardiographic techniques in which different echocardiographic views as well as different geometric assumptions and mathematical formulas are utilized. We used sev-

From the Cardiovascular Division of the Department of Medicine, CVRI University of California, San Francisco, California. This work was supported in part by Grant ROI-AM28121 from the National Heart, Lung, and Blood Institute, Bethesda, Maryland. Manuscript received August 3, 1982; revised manuscript received November 2, 1982, accepted November 5, 1982

Address for reprints: Nelson B. Schiller, MD, University of California, San Francisco, 521 Parnassus Avenue, Room C-340, San Francisco, California 94143.

0735-1097/83/030863-6$03 00

eral different models and formulas. All echocardiograms were made with the patient in the extreme left lateral recumbent position.

1) Area-length method, two chamber view. This view is obtained by placing the transducer on the apex and aiming the beam toward the left atrium so that the beam is parallel and posterior to the interventricular septum, thus excluding it from the picture. The beam is oriented to maximize the size of the left ventricle by rocking the transducer in an anterior and posterior direction. By our convention, in this view the apex of the left ventricle is at the top of the screen, the atrium at the bottom, the inferior wall to the viewer's left and the free wall to the viewer's right (8). When tracing the images, it is important to visualize the endocardium. The endocardium can be difficult to image, but with careful gain settings and attention to technique we were able to visualize this surface in 52 of 57 volunteers. In this view, the free wall is often the most difficult to visualize but can usually be brought into view by having the patient suspend respiration during the early phase of inspiration. The left ventricular chamber was traced along the innermost edge of the endocardial echo and minor irregularities of the ventricular surface were ignored. Papillary muscles were excluded from the tracings. The mitral valve was traced as a straight line across the anulus, regardless of where the leaflets were located. The long-axis length was measured from the furthest point of the apex to the midpoint of the straight line crossing the mitral valve anulus.

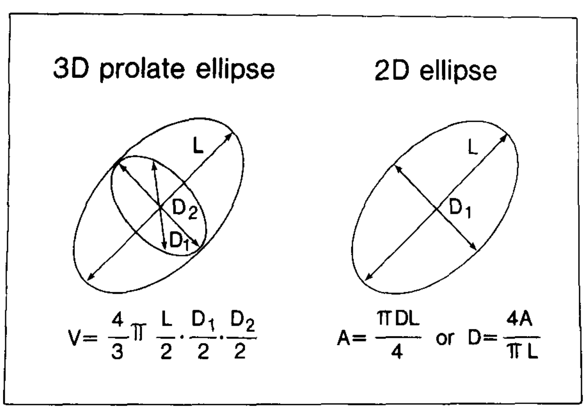
After recording these two measurements (that is, the perimeter outline and the long axis) with the light-pen computer system, the volume of the left ventricle was calculated using the method of Dodge et al. (9). This method assumes that the left ventricle is an ellipse (Fig. 1), the volume of which is given by the equation:

$$V = \frac{4}{3}\pi \cdot \frac{L}{2} \cdot \frac{D_1}{2} \cdot \frac{D_2}{2}$$

where L is the long axis and D_1 and D_2 are the minor axes taken from perpendicular projections. Note that in a perfect ellipse, D_1 and D_2 are equal and that D can be calculated from the formula:

$$D = \frac{4A}{\pi L}$$

Figure 1. Geometric forms and their respective formulas that constitute the Dodge method of volume (V) calculation. See text for further discussion. A = area; D = diameter; 2D and 3D = two- and three-dimensional, respectively, L = length.



where A is the area of the planar image of the left ventricle and L is the long axis. Simple substitutions of these two formulas give the volume of the left ventricle as:

$$V = \frac{8}{3} \cdot \frac{A^2}{\pi L}$$

where A is calculated by the light-pen computational system by simple planimetry and L as a direct measurement of the long axis. It is apparent from this formula that any variation in A will have a major effect on the volume determination and that the longer L is, the smaller the volume will be. These measurements were performed at both end-diastole (start of the R wave) and end-systole (end of the T wave).

2) Area-length method, four chamber view. This view is obtained with the transducer in the same location as in the two chamber view except that it is rotated 90° counterclockwise so that the beam transects the septum and the right and left ventricles are seen side by side. By our convention, the right ventricle appears on the left and the left ventricle on the right of the viewer's screen. Measurements of the left ventricle from this view were made in the same manner as in the two chamber view during both systole and diastole. The calculations were the same as in the two chamber view.

3) Biplane method combining the two chamber and four chamber views. This method uses the same views described except that they are combined into the same formula for volume determination. Recall the previous formula for the volume of an ellipse. In the area-length methods we assumed that D_1 and D_2 were equal. In the biplane method the same formula is used except that D_1 and D_2 are not assumed to be equal. D_1 is calculated from the two chamber view and D_2 from the four chamber view. Each D value is substituted into the volume formula individually. The L used is the largest L and could come from either the two chamber or the four chamber view; usually the four chamber long axis was greater.

4) Biplane method combining the two chamber and the short-axis views. Previous studies have utilized biplane techniques that combine a two chamber apical view for calculation of D_1 with a parasternal short-axis view for calculation of D_2. The advantage was that this more closely approximated the two standard views obtained during angiographic biplane ventriculography. For purposes of comparison, we also measured our normal subjects by this technique. The two chamber view was the same as described previously. The parasternal short-axis view was most commonly obtained with the transducer in the third or fourth intercostal space along the left sternal border. The beam was oriented so that it passed through the left ventricle at right angles to the long axis of the heart. We tried to image the ventricle at the level where the tip of the papillary muscle is separated from the left ventricular wall, just apical to where mitral motion ceases. By convention we always oriented the beam so that the right ventricle was seen to the viewer's left and the left ventricle to the viewer's right on the screen. These two views were used to calculate volumes at end-systole and end-diastole. A relative advantage of this technique is the superior endocardial definition obtained in the short-axis view.

5) Modified Simpson's rule. Goerke and Carlsson (10) described a method of determining left ventricular volume by using a modified Simpson's rule formula. According to their method, volume is given by the formula:

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

This formula treats the ventricle as a stack of individual short cylinders. The ventricular volume is calculated as the sum of the volumes of each individual cylinder. The calculations can be easily made by a light-pen computer system that assumes orthogonal long-axis views of the ventricular chamber. The apical two chamber and four chamber views fulfill this requirement. It should be noted that a two chamber apical view and a short-axis view do not fulfill this assumption because they are not oriented along the long axis even though they are orthogonal. In this formula, h is equal to the number of individual cylinders and was equal to 20 in our particular computational system; a_i and b_i are equivalent to D_1 and D_2 of the ellipse formula and are calculated for each individual (i^{th}) slice of the ellipse. F is an enlargement factor. We used this formula to make volume measurements at both end-diastole and end-systole, as we did with the other methods.

All five methods just described were repeated three times and their results were averaged. The variation between each measurement was less than 10%. Ejection fraction was determined in the usual fashion as:

$$\frac{\text{Diastolic volume} - \text{Systolic volume}}{\text{Diastolic volume}} .$$

Statistical Analysis

Our data were analyzed using conventional statistical methods. The range, mean and standard deviation for each volume calculation were calculated. To determine normality, we computed the 90% upper confidence bounds for the 95th percentile (0.9UCB) as opposed to the usual "2 standard deviations." The value for "90% upper confidence bounds for the 95th percentile" may be either wider or narrower bounds than the usual "2 standard deviations" from the mean depending on the sample size. For our data, the "90% upper confidence bounds for the 95th percentile" sets limits that are slightly higher than 2 standard deviations and gives us more confidence that patients whose data fall outside this range truly have left ventricular volumes larger than the 95th percentile.

Results

Left ventricular volumes. Table 1 demonstrates normal left ventricular volumes as determined by each of the five techniques. The data are grouped according to sex. Men had a larger mean volume by all methods. The modified Simpson's rule method resulted in the following mean volumes: at end-diastole, men 111 and women 80 ml ($p < 0.001$); at end-systole, men 34 and women 29 ml ($p < 0.005$). The data were corrected for body surface area (m^2) and the means again computed. Table 2 shows average volumes by each technique for men and women grouped together and adjusted for body surface area. The linear regression line comparing left ventricular volume at end-diastole with body surface area for men and women is shown in Figure 2. This regression line indicates a weak correlation of left ventricular volume with body surface area in normal subjects. When the patients are separated according to sex and these volumes are normalized for body surface area (Table 3), men still have statistically larger left ventricular volumes. The modified Simpson's rule method resulted in an end-diastolic volume index of 58 ml for men and 50 ml for women ($p < 0.005$). At end-systole, no statistical difference between the sexes was demonstrated.

Ejection fraction. Tables 1 to 3 demonstrate that all these conventional methods provide very consistent values for ejection fraction. Mean ejection fractions ranged from 63 to 69% with a standard deviation of approximately 8%. There was no difference between men and women.

Table 1. Left Ventricular Volumes at End-Diastole and End-Systole as Determined by Various Methods

	End-Diastole			End-Systole			EF	
	Range	Mean ± SD	0.9UCB	Range	Mean ± SD	0.9UCB	Mean	0.9LCB
Men (n = 29)								
AL-2C view	73–201	130 ± 27	189	17–74	40 ± 14	73	69	53
AL-4C view	65–193	112 ± 27	171	13–86	35 ± 16	68	68	52
Biplane-2C+4C	69–194	124 ± 26	177	15–83	38 ± 13	66	69	53
Biplane-2C+SA	64–183	121 ± 27	180	18–76	38 ± 12	62	68	53
Modified Simpson's rule	62–170	111 ± 22	156	14–76	34 ± 12	58	69	52
Women (n = 23)								
AL-2C view	53–146	92 ± 19	132	11–53	31 ± 11	54	66	52
AL-4C view	59–136	89 ± 20	131	13–59	33 ± 12	58	63	50
Biplane-2C+4C	60–142	92 ± 17	128	16–56	32 ± 10	53	65	51
Biplane-2C+SA	71–118	89 ± 14	117	16–49	30 ± 8	47	66	52
Modified Simpson's rule	55–101	80 ± 12	105	13–60	29 ± 10	50	63	50

All data are in milliliters.
AL = area length; EF = ejection fraction, 4C = four chamber; SA = short axis, 2C = two chamber, 0.9LCB = 90% lower confidence bounds for the 95th percentile; 0.9UCB = 90% upper confidence bounds for the 95th percentile

Table 2. Left Ventricular Volumes Normalized for Body Surface Area in 52 Men and Women

	End-Diastole			End-Systole			EF	
	Range	Mean ± SD	0.9UCB	Range	Mean ± SD	0.9UCB	Mean	0.9LCB
AL-2C view	37–101	63 ± 13	86	7–36	20 ± 7	34	68	54
AL-4C view	37–94	57 ± 13	82	7–44	19 ± 8	35	67	51
Biplane-2C + 4C	41–94	61 ± 12	84	8–40	20 ± 7	34	67	53
Biplane-2C + SA	34–92	60 ± 12	83	10–37	19 ± 6	31	68	53
Modified Simpson's rule	36–82	55 ± 10	74	8–38	18 ± 6	30	67	52

All data are in ml/m² Abbreviations as in Table 1

We also evaluated the usefulness of a short cut method of calculating ejection fraction. This consisted of measuring the area of left ventricle as seen in the parasternal short-axis view at end-diastole and end-systole and calculating ejection fraction according to the formula:

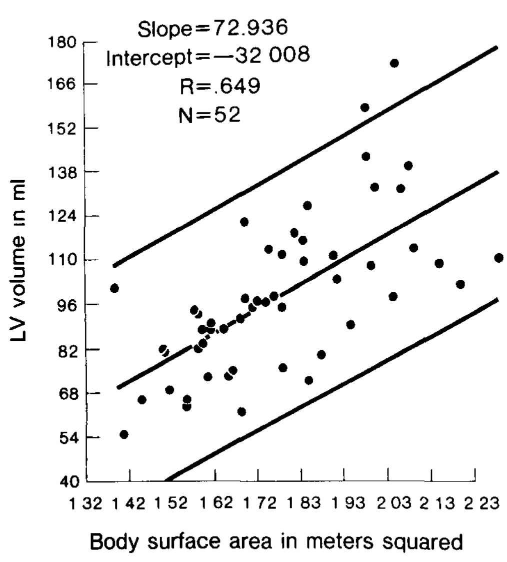
$$\frac{\text{End-diastolic area} - \text{End-systolic area}}{\text{End-diastolic area}}.$$

The linear regression line comparing the results of this method with the ejection fraction calculated by the Simpson's rule method demonstrated no correlation (Fig. 3).

Discussion

Our data demonstrate that in describing normal left ventricular volume, patients must be separated according to sex. Correction of end-diastolic left ventricular volume for body surface area does not completely account for this difference. This implies that additional undefined factors are also involved that contribute to larger left ventricular volume in men. Nevertheless, because the regression line between body surface area and heart size implies a relation between these two variables, it appears to be advantageous to also normalize volumes for body surface area.

Figure 2. Relation of left ventricular (LV) volume to body surface area in 52 normal men and women.



Comparison of methods. There was consistent variation in volumes among patients depending on which of the five methods was used. The area-length two chamber view method produced the largest volumes. Compared with the area-length four chamber view method, which used the same formula, volume difference may be explained by the fact that the two chamber view frequently appears to foreshorten the long axis of the left ventricle. In the ellipse formula the long axis length (L) is in the denominator. Therefore, any artifactual decrease of this length would lead to a falsely large volume. Because biplane methods combine the two chamber and four chamber views, it is not surprising that our biplane volumes were found to be between the volumes calculated by the area-length methods. The modified Simpson's rule method calculated the smallest volumes. For men, the mean end-diastolic and end-systolic volume index was 58 ml/m² and 18 ml/m², respectively.

The modified Simpson's rule method produced the smallest range of values and the smallest standard deviation. On repeated measurements of a single chamber (intraobserver variation), this method also provided the most reproducible volumes. This relative advantage did not prove statistically significant when compared with single plane methods ($p < 0.05$). It can be argued that even these ranges and standard deviations are rather large. However, we do not believe this to be a significant consideration. Many investigators (1–6), in addition to ourselves, have found very good reproducibility of the two-dimensional echocardiographic volume determination with both interobserver and intraobserver measurements. Therefore, even with a rather wide normal range, reproducibility for a single patient is good. This suggests that serial measurements on the same patient may be as valuable as the absolute volume. Furthermore, the inherent problems (discussed later) of two-dimensional echocardiography that cause a systematic underestimation of volume tend to cause a proportionally wider standard deviation of volume measurements in smaller ventricles compared with large ventricles (11,12). Because normal ventricles are generally smaller than abnormal ventricles, this problem was maximized in the study.

J AM COLL CARDIOL
1983,1(3) 863–8

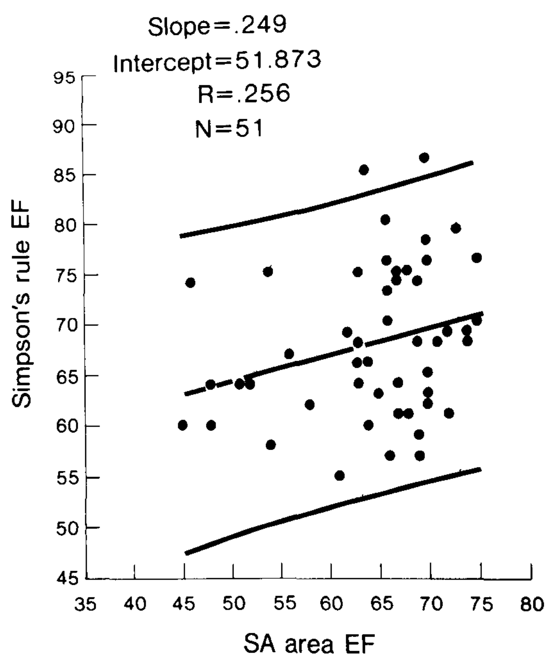
Table 3. Left Ventricular Volumes in Men Compared With Women and Normalized for Body Surface Area

	Men					Women				
	Diastole		Systole		EF	Diastole		Systole		EF
	Mean	0.9UCB	Mean	0.9UCB	Mean	Mean	0.9UCB	Mean	0.9UCB	Mean
AL-2C view	68	94	21	35	69	37	81	19	33	67
AL-4C view	58	84	18	34	69	56	82	20	36	64
Biplane-2C + 4C	64	88	20	32	69	58	80	20	34	66
Biplane-2C + SA	63	87	20	32	68	56	74	19	31	66
Modified Simpson's rule	58	80	18	30	69	50	66	18	32	64

All numbers are in ml/m^2. Abbreviations as in Table 1

Comparison with angiocardiographic measurements. We did not perform left ventricular angiography on our patients because the purpose of this study was not to validate angiography or two-dimensional echocardiography as the standard for volume determination, but rather to assess the normal range of left ventricular volume as determined by two-dimensional echocardiography. Nevertheless, published angiographically determined normal left ventricular volumes vary between 70 and 78 ml/m^2 at end-diastole and 20 and 30 ml/m^2 at end-systole (13, 14) and, compared with these data, our data represent a 25% systematic underestimation of left ventricular volume by Simpson's rule and a 15% underestimation using the area-length analysis of the two chamber view. This consistent volume underestimation by two-dimensional echocardiography has been found by others (2,3). Decreased volume calculation may be an obligatory result of some of the limitations of echocardiography.

Figure 3. Relation of ejection fraction (EF) as calculated by the Simpson's rule method to the ejection fraction calculated using the change in area of the left ventricular chamber as seen from the parasternal short-axis (SA) view.



Limitations of echocardiographic method. Several limitations must be considered when using two-dimensional echocardiography to measure ventricular volumes. First, the left ventricle is imaged at the innermost surface of the most prominent trabeculae because they are the first to reflect ultrasound. Two-dimensional echocardiography, therefore, may exclude the volume of blood within the intertrabecular areas. None of the standard echocardiographic views used in volume calculation image the aortic outflow tract, which contributes to left ventricular volume. The technician must be very careful to maximize the two-dimensional sector scan images or falsely low volumes could result. High gain settings on the sector scan machine may widen the endocardium, thus decreasing the ventricular volume. We recommend that the gain settings be as low as possible. Implicit in all of these limitations is the assumption that the endocardium can be distinctly recognized. In our study, 5 (9%) of 57 normal subjects were excluded because the endocardium was not adequately visualized. It is probable that this percent would become higher when applied to a clinical population. All patients should have their blood pressure recorded before each echocardiographic study because fluctuations in blood pressure can directly change left ventricular volume.

It is to be expected that instrumentation may affect volume measurements. In our study, we chose a 2.25 MHz transducer because this carrier frequency can penetrate and image distant cardiac structures. This feature is particularly important for volume measurements because in the apical long-axis view, structures lie more than 10 cm from the surface imaging window. Higher frequency transducers can be expected to better resolve endocardial borders in the near field but not the critically important cardiac base.

Recently, Jacobs et al. (15) presented evidence that in fields of greater than 6 cm depth, lateral (but not axial) resolution deficiencies of imaging equipment may contribute to underestimation of ventricular volumes. Because this is a systematic error of the echographic technique, it is important to use echocardiographic data and not angiographic normal data for clincial application.

Reliability of ejection fraction measurements. We found excellent correlation of ejection fraction and volume measurements, regardless of the technique used. This was found for all sizes of ventricles and was independent of sex. Previous reports (11,12) have shown the high reliability of ejection fraction as determined by two-dimensional echocardiography. Presumably this is because any chamber size error made by any of the techniques would affect the end-diastolic and end-systolic measurements proportionally and thus not alter ejection fraction. Ejection fraction calculated from simple area measurement at end-diastole and end-systole does not correlate with ejection fraction calculated from conventional methods of volume determination. This is an important observation because single plane area changes have been suggested as a useful method of rapid ejection fraction calculation applicable to "continuous digital print-out" systems of ejection fraction monitoring in the operating room setting or coronary care unit.

Conclusions. The purpose of this study was to determine normal population volume variables of the left ventricle as determined by different algorithms currently in clinical use. We found that men have larger left ventricular volumes than women even after correction for body surface area. Furthermore, there is significant variation in these normal variables depending on the algorithm used. We found that the modified Simpson's rule method of volume determination produces the smallest volumes and the data are the most reproducible by inter- and intraobserver variation. The area-length method using either the two chamber or the four chamber view, although based on a simplified algorithm, is useful because it is simple and rapid. In addition, single plane analysis is especially useful when technical difficulties prevent adequate orthogonal long-axis views required by the Simpson's rule algorithm. On the basis of our data, we see little clinical use for the biplane area-length method because it offers little additional accuracy over the single plane area-length method and is as time-consuming to calculate as the biplane Simpson's rule method. Ejection fraction was independent of the algorithm employed.

References

1. Eaton LW, Maughan WL, Shoukas AA, Weiss JL. Accurate volume determination in the isolated ejecting canine left ventricle by two-dimensional echocardiography. Circulation 1979;60:320–6.
2. Starling MR, Crawford MH, Sorenson SG, Levi B, Richards KL, O'Rourke RA. Comparative accuracy of apical biplane cross-sectional echocardiography and gated equilibrium radionuclide angiography for estimating left ventricular size and performance. Circulation 1981;63:1075–84.
3. Schiller NB, Acquatella H, Ports T, et al. Left ventricular volume from paired biplane two-dimensional echocardiography. Circulation 1979;60:547–55.
4. Helak J, Reichek N. Quantitation of human left ventricular mass and volume by two-dimensional echocardiography: in vitro anatomic validation. Circulation 1981;63:1398–407.
5. Schiller NB, Ports TA, Silverman NH. Quantitative analysis of the adult left heart by two-dimensional echocardiography. Semin Ultrasound 1981;2:178–83.
6. Helak JW, Plappert T, Muhammad A, Reickek N Two-dimensional echocardiographic imaging of the left ventricle: comparison of mechanical and phased array systems in vitro. Am J Cardiol 1981;48:728–35
7. Daigle R, Paineter W, Anderson W, Schiller NB. A light pen system for cross-sectional echocardiography. Ultrasound Med 1977;4:477–8.
8. Silverman NH, Schiller NB. Apex echocardiography. Circulation 1978;57:503–11.
9. Dodge HT, Sandler H, Ballow DW, Lord JD Jr. The use of biplane angiocardiography for the measurement of left ventricular volume in man Am Heart J 1960;60:762–76.
10. Goerke RJ, Carlsson E Calculation of right and left cardiac ventricular volumes: method using standard computer equipment and biplane angiograms Invest Radiol 1967;2:360–7.
11. Carr KW, Eagler RL, Forsythe JR, Johnson AD, Gosink B. Measurement of left ventricular ejection fraction by mechanical cross-sectional echocardiography. Circulation 1979;59.1196–205.
12. Folland ED, Parisi AF, Moynihan BS, Jones DR, Feldman CL, Tow DE. Assessment of left ventricular ejection fraction and volumes by real-time, two-dimensional echocardiography. Circulation 1979,60: 760–6.
13. Wynne J, Green LH, Mann T, Levin D, Grossman W. Estimation of left ventricular volumes in man from biplane cineangiograms filmed in oblique projections Am J Cardiol 1978,41:726–32
14. Kennedy JW, Baxley WA, Figley M, Dodge H, Blackman J. Quantitative angiocardiography. I. The normal left ventricle in man. Circulation 1966;34:272–8.
15. Jacobs L, Hall J, Gubernick I, Meister S, Barrett M Axial versus lateral resolution: inherent errors in two-dimensional echocardiography imaging (abstr). Am J Cardiol 1982;49:1020.