COMPARISON OF MEASUREMENTS OF LEFT VENTRICLE BY ECHOGRAPHY AND CINEANGIOGRAPHY

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A comparison of echocardiography with cineangiocardiology in estimating left ventricular dimensions and volumes was undertaken in 43 patients classified into four groups according to the pathophysiology of the left ventricle. There were high correlations between echographic and angiographic ventricular minor axis dimensions, however, when minor axis dimensions were more than 5.0 cm, there were underestimations of minor axis dimensions by echography.

From the mean value of long-to-short axis ratio of the left ventricle at end-diastole and end-systole, the following equations were derived for calculating left ventricular volumes from echo dimensions alone: $EDV = 0.837 Dd^3$, $ESV = 0.994 Ds^3$. That these equations allowed relatively accurate prediction of volumes over a wide range of ventricular sizes was confirmed by comparison with Pombo's formula and Fortuin's formula for calculating left ventricular volume by echo dimensions alone.

A comparison of echographic and cineangiographic ejection fraction (EF), relative changes in shortening of internal diameter (ΔS), and the mean velocity of circumferential fiber shortening (mean Vcf) was made in 33 patients with sinus rhythm. There were significant correlations between echographic and cineangiographic measurements. There was also good correlation between EF and mean Vcf by echocardiography, except one discordant patient with aortic insufficiency who showed decreased mean Vcf in the face of normal EF, all these results were confirmed by cineangiography. This discrepancy between EF and mean Vcf was ascribed to the prolonged ejection time which characterizes aortic insufficiency.

ECHOCARDIOGRAPHY has become an acceptable and useful noninvasive method of estimating left ventricular volume and function.¹⁻¹⁴ Close correlation, both in normal sub-

jects and in patients with heart disease, have been demonstrated between these echocardiographic estimations of left ventricular performance and their cineangiographic counterparts.^{11,13,14}

However, the use of a cube function of the echographic minor axis was an accurate predictor of volumes in smaller ventricular chambers, but overestimated volumes in large hearts.⁶ On the other hand, the use of Fortuin's equation (expressed in the first order) underestimated

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volumes in large left ventricles.

Accordingly, the present study was undertaken to further validate the relationship between left ventricular minor axis dimension as measured by echocardiography, and left ventricular axes and volumes as measured by cineangiography. For this purpose the relationship of long axis to short axis of the left ventricle by cineangiography is scrutinized, since this relationship is assumed to change according to the type of left ventricular overloading and the phase of the left ventricular movement.^{15,16} We have also characterized this relationship in mathematical terms so that accurate estimates of left ventricular volume are obtained from the echo measurements alone.

In addition we have examined mean Vcf as a valid index for evaluating left ventricular function in comparison with ejection fraction, and compared these measurements as obtained by both echocardiography and cineangiography.

SUBJECTS AND METHODS

Forty-three patients with different types of

heart disease were studied and were classified into four groups according to the pathophysiology of the left ventricle:

Group I consisted of eight patients with mitral stenosis, except one patient who had slight aortic insufficiency as well. Seven were in sinus rhythm and one was in atrial fibrillation. Their ages ranged from 20 to 59 (mean 37) and three were men.

Group II consisted of ten patients with mitral insufficiency (MI). All of them had pure mitral insufficiency, except one patient who had slight mitral stenosis as well. Six were in sinus rhythm and four were in atrial fibrillation. Their ages ranged from 21 to 56 (mean 39) and five were men.

Group III consisted of seven patients with aortic insufficiency (AI). Of these five had pure aortic insufficiency, while the other two had slight ventricular septal defect and patent ductus arteriosus as well. Their ages ranged from 29 to 62 (mean 43) and five were men.

Group IV consisted of eighteen patients with non-valvular heart disease (Non. V al. H.D.). Of

Fig.1. Representative example of ultrasound cardiogram. Time-distance dots indicate 1cm vertically and 0.2 second horizontally.

Abbreviations:

- Dd = left ventricular internal dimension in diastole corresponding to the R wave of the electrocardiogram
- Ds = left ventricular internal dimension in systole corresponding to the terminal portion of the T wave of the electrocardiogram
- S = ventricular septum
- END = left ventricular posterior wall endocardium
- EPI = left ventricular posterior wall epicardium
- PERI = left ventricular pericardium

these, eight had cardiomyopathy, four had ischemic heart disease (IHD), three had myxoma in the left atrium, two had ventricular septal defect, and one had constrictive pericarditis. Sixteen of the patients were in sinus rhythm and two were in atrial fibrillation. Their ages ranged from 21 to 66 (mean 39) and thirteen were men.

The ultrasound records were obtained using ALOKA SSD 3 type utilizing a 2.25 MHz transducer with a repetition rate of 1,000 impulses per second by the ultrasonic "B" mode display with simultaneous electrocardiogram. The patients were studied in the supine position. The transducer was applied to the third, fourth, or fifth intercostal space near the left sternal edge with the use of aquasonic gel to insure good acoustic coupling. The anterior leaflet of the mitral valve was identified and the transducer directed inferiorly and laterally in order to obtain and photograph simultaneous calibrated "time motion" echograms of the left ventricular posterior wall and septum.^{1,7}

Figure 1 illustrates a typical left ventricular echogram. The following echocardiographic measurements and calculations were obtained during a representative cardiac cycle from an echogram of very clearly demonstrated left ventricular septum and posterior wall.

1. End-diastolic diameter (Dd) was measured in

centimeters as an internal antero-posterior axis, or minor axis, of the left ventricle at the time of R wave peak of the electrocardiogram.

2. End-systolic diameter (Ds) was measured as the shortest internal diameter during the same cardiac cycle.

3. ΔS was calculated by using the following equation: $\Delta S = (Dd - Ds) / Dd$.

4. End-diastolic ventricular volume (EDV) was calculated in milli-liters by using the following three equations:

$$(1) \text{EDV} = \pi/3 Dd^3 \quad (\text{Pombo's formula})^2$$

$$(2) \text{EDV} = 59 Dd - 153 \quad (\text{Fortuin's formula})^6$$

$$(3) \text{EDV} = 0.837 Dd^3 \quad (\text{Our formula}).$$

5. End-systolic ventricular volume (ESV) was calculated in milli-liters by using the following three equations:

$$(4) \text{ESV} = \pi/3 Ds^3 \quad (\text{Pombo's formula})^2$$

$$(5) \text{ESV} = 47 Ds - 120 \quad (\text{Fortuin's formula})^6$$

$$(6) \text{ESV} = 0.994 Ds^3 \quad (\text{Our formula}).$$

6. Stroke volume (SV) was measured in milli-liters and calculated using the above three equations independently as follows:

$$\text{SV} = \text{EDV} - \text{ESV}.$$

7. Ejection fraction (EF) was measured by dividing SV by EDV.

8. Ejection time (ET) was measured in milli-seconds by the time from initial anterior movement of the posterior wall (Point C) to the peak

Fig.2. An echocardiogram which shows the method for calculating ejection time (ET). Time distance dots indicate 1cm vertically and 0.1 second horizontally.

Abbreviations:

S = ventricular septum

PWE = posterior wall echogram. For C and D see text.

TABLE I LEFT VENTRICULAR DIMENSIONS BY ULTRASOUND AND CINEANGIOGRAPHY

Gr.	Pt.	Echocardiography		Cineangiography					
		Dd	Ds	Dd	Ds	Ld	Ls	Ld/Dd	Ls/Ds
I	1	5.2	3.2	5.39	3.35	8.15	6.15	1.51	1.84
	2	4.4	2.6	4.78	2.02	7.69	6.23	1.61	3.08
	3	5.7	3.9	4.80	3.60	7.30	6.20	1.52	1.72
	4	5.3	3.2	5.22	3.03	7.31	4.42	1.40	1.46
	5	5.0	3.8	5.50	4.60	7.10	6.00	1.29	1.30
	6	5.3	3.6	5.50	4.20	9.70	7.70	1.76	1.83
	7	5.5	3.0	5.40	3.20	7.90	6.10	1.46	1.91
	8	5.5	2.7	5.92	4.06	9.51	7.64	1.61	1.88
mean								1.52	1.88
II	9	6.3	4.6	7.18	4.73	10.15	6.97	1.41	1.47
	10	6.2	3.4	6.00	3.94	12.00	5.77	2.00	1.46
	11	6.0	3.8	6.92	3.25	11.07	6.38	1.60	1.96
	12	6.8	4.4	7.20	4.05	9.08	6.60	1.26	1.63
	13	4.9	2.8	4.89	2.99	9.50	7.48	1.94	2.50
	14	5.9	3.8	6.24	4.56	10.12	8.27	1.62	1.81
	15	6.3	3.2	6.75	3.84	10.57	6.81	1.57	1.77
	16	6.2	4.6	6.60	4.40	11.05	7.80	1.67	1.77
	17	6.4	3.8	6.80	4.22	8.83	7.08	1.30	1.68
	18	6.6	4.6	7.59	5.55	9.38	7.38	1.24	1.33
mean								1.56	1.74
III	19	4.1	2.9	5.48	3.03	9.51	6.28	1.74	2.07
	20	7.3	5.0	8.85	5.26	10.08	8.38	1.14	1.59
	21	6.7	4.2	6.31	3.28	10.77	8.92	1.71	2.72
	22	4.8	2.8	5.52	3.29	7.72	5.03	1.40	1.53
	23	7.5	5.5	7.66	5.84	12.07	11.44	1.58	1.96
	24	7.0	4.4	7.84	4.69	12.34	7.29	1.57	1.55
	25	6.4	4.2	6.30	4.40	10.90	4.40	1.73	2.05
mean								1.55	1.92
IV	26	4.6	3.0	5.52	2.77	6.92	5.65	1.25	2.04
	27	5.6	4.3	6.55	4.87	9.69	7.69	1.48	1.58
	28	5.0	3.5	5.83	3.77	10.56	8.79	1.81	2.33
	29	4.8	2.8	5.81	3.45	10.46	8.31	1.80	2.41
	30	5.4	3.4	5.17	3.31	10.00	7.38	1.93	2.23
	31	6.7	5.2	6.32	4.88	10.68	9.35	1.69	1.92
	32	5.4	4.2	5.97	3.60	9.08	6.77	1.52	1.88
	33	6.1	4.1	4.91	3.75	8.46	6.31	1.72	1.68
	34	6.1	4.6	7.66	5.79	8.33	7.92	1.09	1.37
	35	5.3	2.9	5.00	2.60	9.20	5.80	1.84	2.23
	36	5.6	2.7	5.35	3.36	10.46	9.08	1.96	2.70
	37	4.9	2.7	4.67	2.55	12.75	7.88	2.73	3.09
	38	4.2	2.9	4.34	2.60	8.62	5.69	1.99	2.19

39	5.5	3.5	6.09	4.51	9.03	7.66	1.48	1.70
40	4.3	3.0	5.66	2.85	9.85	6.60	1.74	2.32
41	5.0	3.4	5.84	3.56	8.62	6.14	1.48	1.72
42	4.5	2.3	5.20	3.10	6.00	5.00	1.15	1.61
43	4.7	3.1	4.91	3.63	9.15	7.01	1.86	1.93
mean							1.68	1.91
total mean							1.58	1.91

Abbreviations: Dd = short axis diameter in diastole,
Ds = short axis diameter in systole,
Ld = long axis diameter in diastole,
Ls = long axis diameter in systole.
For groups I, II, III, IV see text.

of anterior wall motion (Point D)¹⁸ as shown in Fig. 2; or from the opening to the closing point of the aortic valve as shown in Fig. 3. ET was corrected by Katz's equation¹⁹ for the preceding R-R interval as follows:

$$ET_c = ET / \sqrt{R - R}$$

9. Mean Vcf was measured in thirty three patients with sinus rhythm in circumferences/sec from the following equation¹²:

$$\text{mean Vcf} = \Delta S / ET.$$

Diagnostic cardiac catheterization was performed in the postabsorptive state with patients in a supine position. After standard right heart catheterization was completed, left heart catheterization was performed in retrograde fashion

via the femoral artery (by Seldinger's method or by incision of the femoral artery) and cardiac output was measured by Fick principle. A quantitative assessment of the left ventricle was determined from single plane cineangiography in a right anterior oblique projection. Left ventricular cineangiograms were obtained using a film speed of 50 frames/sec as 30 to 45 cc of radiopaque contrast material was injected into the left ventricle or into the main pulmonary artery in two patients. Measurements and calculations were as follows:

1. The long axis was measured directly and the

Fig. 3. A representative ultrasound echography of aortic valve for measuring ejection time (ET). Time distance dots indicate 1cm vertically and 0.1 second horizontally.

Abbreviations:

A.V.E = aortic valve echogram

TABLE II CORRELATION COEFFICIENT BETWEEN ECHOCARDIOGRAM USING THE THREE METHODS AND CINE-ANGIOCARDIOGRAM

		Pombo's Method	Fortuin's Method	Our Method
I	EDV	0.75	0.74	0.75
	ESV	0.62	0.60	0.61
	SV	0.81	0.89	0.85
	EF	0.72	0.78	0.72
II	EDV	0.80	0.83	0.80
	ESV	0.82	0.81	0.83
	SV	0.47	0.28	0.43
	EF	0.44	0.40	0.43
III	EDV	0.90	0.86	0.90
	ESV	0.96	0.90	0.96
	SV	0.74	0.67	0.76
	EF	0.54	0.65	0.62
IV	EDV	0.56	0.57	0.56
	ESV	0.80	0.79	0.80
	SV	-0.12	-0.09	-0.14
	EF	0.46	0.66	0.47
Tot	EDV	0.87	0.83	0.87
	ESV	0.87	0.84	0.87
	SV	0.72	0.55	0.72
	EF	0.48	0.58	0.51

minor axis was determined by the area length, according to the Dodge method²⁰ at end-systolic and end-diastolic phases respectively.

2. EDV and ESV were calculated with the use of a monoplane area length method^{21,22}

3. SV, EF, ΔS , and mean Vcf²³ were calculated as described for the echocardiographic determination. ET was calculated from the aortic pressure curve tracing²⁴ and was corrected by Katz's equation¹⁹ for the preceding R-R interval.

RESULTS

The echocardiographic and cineangiographic data for the 43 patients are presented in Table I. A comparison of Dd and Ds by the two techniques is also presented in Table I as well as Figs. 4 and 5. In both diastole and systole the correlation coefficients are highly significant except the Dd in group I. Measurements of Dd and Ds more than 5.0 cm by echography tend to be significantly underestimated in contrast to those obtained by cineangiography as shown in Figs. 4 and 5 ($p < 0.01$).

Correlation coefficients of EDV, ESV, SV, and EF by echocardiography calculated from the above three methods and those by cineangiography are shown in Table II. All correlations in the total group are highly significant ($p < 0.01$). A comparison between EDV, ESV, SV, and EF by echocardiography calculated by our formula and those by cineangiography is shown in Figs. 6

Fig. 4. Comparison of minor axis dimensions in end-diastole (Dd) determined by echocardiography and cineangiography. Solid line is the line of identity. For abbreviations see text.

Fig.5. Comparison of minor axis dimensions in end-systole (Ds) determined by echocardiography and cineangiography.

Fig.6. Comparison of end-diastolic volume (EDV) by ultrasound and cineangiography.

through 9.

The correlation of EDV by echocardiography using the above three methods with those calculated by cineangiography is shown in Fig. 10. It reveals that volumes calculated by Pombo's equation were relatively accurate in smaller volume chambers, but were overestimated with increasing chamber size. While, on the other hand, volumes calculated by Fortuin's

equation were underestimated with increasing chamber size, when Dd was more than 7.0 cm as shown in Fig. 10. However, the volumes obtained by our equation are closer to the line of identity and the standard error of the estimate is lower than the other two methods. For the calculation of EF, however, the correlation coefficient for Fortuin's method was highest ($r=0.58$, $p<0.01$) among the three methods.

Fig.7. Comparison of end-systolic volume (ESV) by ultrasound and cineangiography.

Fig.8. Comparison of stroke volume (SV) by ultrasound and cineangiography.

The measurement of EF as obtained by our method, ΔS , ETC and mean Vcf by echocardiography in thirty three patients was significantly correlated with those by cineangiography with $r=0.56$ ($p<0.01$), $r=0.44$ ($p<0.05$), $r=0.53$ ($p<0.01$), and $r=0.57$ ($p<0.01$) respectively. The correlation of mean Vcf by echocardiography and cineangiography is shown

in Fig. 11.

DISCUSSION

In light of the foregoing data the echocardiographic estimation of left ventricular volume by Pombo's formula² must be examined. Pombo's formula is based on the following three assumptions: (1) that the echo-measured minor axis is a

Fig.9. Comparison of ejection fraction (EF) by ultrasound and cineangiography.

Fig.10. Comparison of end-diastolic volume (EDV) by ultrasound using the three methods and cineangiography.

true minor axis; (2) that the left ventricular cavity is a prolate ellipse with equal minor axes; (3) that the long axis of the chamber equals twice the minor axis.

The first assumption is validated by the earlier authors^{2,6,7,10,11} and is confirmed by us. From our study echocardiography tended to underestimate Dd and Ds, when they were over 5.0 cm as compared with the data by cineangiocardio-

graphy. This may result from the difference of method in calculating left ventricular diameter. That is, it may result from the fact that cineangiography tends to measure left ventricular volume larger than the actual volume because it includes the papillary muscle in the calculation of the left ventricle^{20,25,26} as well as the effect of the contrast material²⁷⁻²⁹ (which increases the left ventricular volume).

The second assumption is validated by the previous authors,³⁰⁻³⁴ but is not validated in

Fig.11. Comparison of mean Vcf by ultrasound and cineangiography.

the presence of dyskinesia^{10,14,37} or abnormalities of cavity shape^{35,36,38} (such as in IHSS³⁹).

The last assumption applies well at end-diastole and end-systole in conditions in which the long-to-short axis ratio of the left ventricle is 2. However, this is not the case in large volume chambers since the ventricle becomes more spherical with a decrease in long-to-short axis ratio to less than 2.^{15,16,40-42} From our data (as shown in Table I) the left ventricles of patients with various heart diseases do not strictly conform to idealized geometrical shape, and show a variable relationship between the long and short axes. A common specific mean value was not found for each group (as classified according to the pathophysiology of the left ventricle).

Although the long-to-short axis ratio of the left ventricle was most reduced in markedly dilated hearts, it varied according to the type of heart disease. In group III (AI) this ratio was 1.58 in patient No.23 with Dd 7.66 cm. and 1.57 in patient No.24 with Dd 7.84 cm. In group II (MI) the ratio was 1.24 in patient No.18 with Dd 7.59 cm, and 1.26 in patient No.12 with Dd 7.20 cm. And in group IV the ratio was 1.09 in patient No.34 (IHD) with Dd 7.66 cm. Thus, the long-to-short axis ratio tends to change according to the pathophysiology of the left ventricle, in as much as long axis measurement changes according to the pathophysiology of the left ventricle.

(However, the long-to-short axis ratio does not change according to the pathophysiology in extremely enlarged ventricles as shown in patient No.20 with aortic insufficiency, where the long-to-short axis ratio was 1.14 with Dd 8.84 cm.)

Failure to account for the above change in chamber geometry with increasing heart volume would therefore theoretically result in a progressive overestimation of volume in larger-volume hearts. Such a problem yielded Fortuin's formula⁶ which is, however, expressed in the first order so that it underestimated the volume in enlarged hearts with Dd more than 7.0 cm. Accordingly, we tried to apply our formula by substituting the mean long-to-short axis ratio of the left ventricle (at end-systole and end-diastole obtained by cineangiography) into the following equation²⁰ to calculate the left ventricular volume by convention: $V = \pi/6 D^2 L$, where V is left ventricular volume, D is the minor diameter, and L is the longer of the major diameters.

Therefore, our investigations further validate the use of echocardiographic minor-axis dimensions as correlates of left ventricular volumes by substituting the proper value of the long-to-short axis ratio in the enlarged ventricle for L in the above formula in calculating left ventricular volume.

The correlations of ΔS , EF, and mean Vcf between echocardiographic and cineangiographic

determinations were also significant in that they confirm previous works by other investigators.^{11,13,14} Previous authors have reported that mean Vcf is a better index for evaluating left ventricular performance than EF due to the following two reasons: 1) mean Vcf is related to cardiac muscle function directly, and thus may provide information about ventricular performance which cannot be obtained from a consideration of EF alone,^{12,23,42} since EF is only an indicator of the pump performance of the heart. 2) Calculation of mean Vcf does not require any assumptions regarding left ventricular size or shape. However, the calculation of left ventricular volume and ejection fraction, by cubing the measured dimension, tends to exaggerate errors introduced by the assumption that there is a fixed ratio between the major and minor axes of the left ventricular chamber.¹⁴

In the calculation of mean Vcf, ΔS is an indicator of the extent of cardiac muscle shortening and mean Vcf adds to this the dimension of time of ejection, and in individual patients provides in itself different information than EF or ΔS . Therefore, the validity of mean Vcf as a better index than EF and ΔS must be examined.

Calculation of mean Vcf is greatly influenced by ET, which is reported to be affected by three factors; i.e., heart rate^{24,44-46} stroke volume^{24,47-49} and mean aortic pressure or peripheral vascular resistance^{24,45,49,50}. In a situation where ET is diminished or prolonged relative to the extent of change of these three factors (such as in aortic insufficiency, aortic stenosis, mitral insufficiency, and heart failure⁵¹) mean Vcf changes in discordance with the value of EF and ΔS .

In the present study the echographic calculation of EF correlated well with mean Vcf ($r = 0.85$, $p < 0.01$). Nevertheless, the result was discordant in one patient (No.24 with AI) who had reduced mean Vcf (1.159 circ/sec) in the face of a normal EF (70%). These data are consistent with cineangiographic observations in which diminished mean Vcf (1.080 circ/sec) occurs in the face of other normal hemodynamic parameters ($V_{max} = 4.425$ circ/sec. $R-dp/dt = 0.05$ sec). This discrepancy of values between EF and mean Vcf is derived from the prolonged ET (QTc = 420 msec by echo and 462 msec by cine.) due to aortic insufficiency.^{24,43}

Therefore, the sensitivity of mean Vcf in assessing left ventricular function remains to be

clearly determined. Further studies in which data obtained by echocardiography as compared with other parameters of ventricular function obtained by invasive methodology are required to evaluate the validity of mean Vcf as a better index than EF for assessing left ventricular function.

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REFERENCES

1. POPP, R. L., WOLFE, S. B., HIRATA, T., & FEIGENBAUM, H.: Estimation of right and left ventricular size by ultrasound. *Amer. J. Cardiol.* 24: 523, 1969.
2. POMBO, J. F., TROY, B. L., & RUSSELL, R. O., Jr.: Left ventricular volumes and ejection fraction by echocardiography. *Circulation* 43: 480, 1971.
3. FEIGENBAUM, H., ZAKY, A., & NASSER, W. K.: Use of ultrasound to measure left ventricular stroke volume. *Circulation* 35: 1092, 1967.
4. FEIGENBAUM, H., WOLFE, S. B., POPP, R. L., et al.: Correlation of ultrasound with angiocardiology in measuring left ventricular diastolic volume. *Amer. J. Cardiol.* 23: 111, 1969.
5. TROY, B. L., POMBO, J., & RACKLEY, C. E.: Measurement of left ventricular wall thickness and mass by echocardiography. *Circulation* 45: 602, 1972.
6. FORTUIN, N. J., HOOD, W. P. Jr., SHERMAN, M. E., & CRAIGE, E.: Determination of left ventricular volumes by ultrasound. *Circulation* 44: 575, 1971.
7. MURRY, J. A., JOHNSTON, W., & REID, J. M.: Echocardiographic determination of left ventricular dimensions, volumes, and performance. *Amer. J. Cardiol.* 30: 252, 1972.
8. POPP, R. L. & HARRISON, D. C.: Ultrasonic cardiac echography for determining stroke volume and valvular regurgitation. *Circulation* 41: 493, 1970.
9. POMBO, J. F., RUSSELL, R. O. Jr, RACKLEY, C. E., & FOSTER, G. L.: Comparison of stroke volume and cardiac output determination by ultrasound and dye dilution in acute myocardial infarction. *Amer. J. Cardiol.* 27: 630, 1971.
10. GIBSON, D. G.: Estimation of left ventricular size by echocardiography. *Brit. H. J.* 35: 128, 1973.
11. BELENKIE, I., NUTTER, D. O., CLARK, D. W., McCRAW, D. B., & RAIZNER, A. E.: Assessment of left ventricular dimensions and function by echocardiography. *Amer. J. Cardiol.* 31: 755, 1973.
12. FORTUIN, N. J., HOOD, E. P. Jr, & CRAIGE, E.: Evaluation of left ventricular function by echocardiography. *Circulation* 46: 26, 1972.
13. COOPER, R. H., O'ROURKE, R. A., KARLINER, J. S., PETERSON, K. L., & LEOPOLD, G. R.: Comparison of ultrasound and cineangiographic measurements of the mean rate of circumferential fiber shortening in man. *Circulation* 46: 914, 1972.

14. LUDBROOK, P., KARLINER, J. S., PETERSON, K., LEOPOLD, G., & O'ROURKE, R. A.: Comparison of ultrasound and cineangiographic measurements of left ventricular performance in patients with and without wall motion abnormalities. *Brit. H. J.* 35: 1026, 1973.
15. FRIMER, M., PORTER, C. M., RACKLEY, C. E., & DODGE, H. T.: Left ventricular chamber geometry and function in heart disease (abstract). *Circulation* 40: Suppl. III: 85, 1969.
16. TEICHHOLZ, L. E., KREULEN, T. H., HERMAN, M. V., & GORLIN, R.: Problems in echocardiographic volume determinations: echo-angiographic correlations (abstract). *Circulation* 46: Suppl. II: 75, 1972.
17. FEIGENBAUM, H., STONE, J. M., LEE, D. A., NASSER, W. K., & CHANG, S.: Identification of ultrasound echoes from the left ventricle by use of intracardiac injections of Indocyanine Green. *Circulation* 41: 615, 1970.
18. INOUE, K., SMULYAM, H., MOOKHERJEE, S., & EICH, R.: Ultrasonic measurements of left ventricular wall motion in acute myocardial infarction. *Circulation* 43: 778, 1971.
19. KATZ, L. N. & FEIL, H. S.: Clinical observations on the dynamics of ventricular systole; I. Auricular fibrillation. *Arch. Int. Med.* 32: 672, 1923.
20. DODGE, H. T., SANDLER, H., BALLEW, D. W., & LORD, J. D.: The use of biplane angiocardiology for the measurement of left ventricular volume in man. *Amer. Heart J.* 60: 762, 1960.
21. HERMAN, H. J. & BARTLE, S. H.: Left ventricular volumes by angiocardiology: Comparison of methods and simplification of techniques. *Cardiovas. Res.* 2: 404, 1968.
22. KENNEDY, J. W., TRENHOLME, S. E., & KASSER, I. S.: Left ventricular volume and mass from single plane cineangiograms. A comparison of anteroposterior and right anterior oblique methods. *Amer. Heart J.* 80: 343, 1970.
23. KARLINER, J. S., GAULT, J. H., ECKBERG, D., MULLINS, C. B., & ROSS, J., Jr.: Mean velocity of fiber shortening. *Circulation* 44: 323, 1971.
24. WEISSLER, A. M., PEELER, R. G., & ROEHL, W. H., Jr.: Relationships between left ventricular ejection time, stroke volume, and heart rate in normal individuals and patients with cardiovascular disease. *Amer. Heart J.* 62: 367, 1961.
25. DODGE, H. T., SANDLER, H., BAXLEY, W. A., & HAWLEY, R. R.: Usefulness and limitations of radiographic methods for determining left ventricular volume. *Amer. J. Cardiol.* 18: 10, 1966.
26. KASSER, I. S. & KENNEDY, J. W.: Measurement of left ventricular volumes in man by single plane cineangiocardiology. *Invest. Radiol.* 4: 83, 1969.
27. ROWE, G. G. et al.: The physiologic effect of contrast media used for angiocardiology. *Circulation* 13: 896, 1956.
28. BROWN, R., RAHIMTOOLA, S. H., DAVIS, G. D., & SWAN, H. J. G.: The effect of angiographic contrast medium on circulatory dynamics in man. *Circulation* 31: 234, 1965.
29. MILLER, G. A. H. & SWAN, H. J. G.: Effect of chronic pressure and volume overload on left heart volumes in subjects with congenital heart disease. *Circulation* 30: 205, 1964.
30. SANDLER, H. & DODGE, H. T.: Use of single plane angiocardiology for the calculation of left ventricular volume in man. *Amer. Heart J.* 75: 325, 1968.
31. RUSHMER, R. F., CRYSTAL, D. K., & WAGNER, C.: Functional anatomy of ventricular contraction. *Circ. Res.* 1: 162, 1953.
32. ROSS, J., Jr., SONNENBLICK, E. H., COVELL, J. W., KAISER, G. A., & SPIRO, D.: Architecture of the heart in systole and diastole: Technique of rapid fixation and analysis of left ventricular geometry. *Circ. Res.* 21: 409, 1967.
33. LINC, P. R. & BOVE, A. A.: Geometry of the left ventricle as studied by a high-speed cineradiographic technique. *Fed. Proc.* 28: 1330, 1969.
34. TSAKIRIS, A. G., DONALD, D. E., STURM, R. E., & WOOD, E. H.: Volume, ejection fraction, and internal dimensions of left ventricle determined by biplane videometry. *Fed. Proc.* 28: 1358, 1969.
35. HELLER, S. J. & CARLETON, R. A.: Abnormal left ventricular contraction in patients with mitral stenosis. *Circulation* 42: 1099, 1970.
36. DIAMOND, M. A., DILLON, J. C., HAINE, C. L., CHANG, S., & FEIGENBAUM, H.: Echocardiographic features of atrial septal defect. *Circulation* 43: 129, 1971.
37. GENTZLER, R. D., II, GAULT, J. H., HUNTER, A. S., LIEDTKE, A. J., & LEAMAN, D. M.: Asymmetric left ventricular contraction in patients with previous myocardial infarction. *Circulation* 48: 352, 1973.
38. GIBSON, D. G. & BROWN, D.: Measurement of instantaneous left ventricular dimension and filling rate in man, using echocardiography. *Brit. Heart J.* 35: 114, 1973.
39. BRAUNWALD, E., LAMBREW, C. T., ROCKOFF, C. D., ROSS, J., Jr., & MORROW, A. G.: Idiopathic hypertrophic subaortic stenosis: I. A description of the disease based upon an analysis of 64 patients. *Circulation* 30: (suppl. IV): IV-3, 1964.
40. MILLER, G. A. H., KIRKLIN, J. W., & SWAN, H. J. C.: Myocardial function and left ventricular volumes in acquired valvular insufficiency. *Circulation* 31: 374, 1965.
41. DODGE, H. T. & BAXLEY, W. A.: Hemodynamic aspects of heart failure. *Amer. J. Cardiol.* 22: 24, 1968.
42. GAULT, J. H., ROSS, J., Jr., & BRAUNWALD, E.: Contractile state of the left ventricle in man: Instantaneous state of the left ventricle in man: Instantaneous tension-velocity-length relations in patients with and without disease of the left ventricular myocardium. *Circ. Res.* 22: 451, 1968.
43. MOSKOWITZ, R. L. & WECHSLER, B. M.: Left ventricular ejection time in aortic and mitral valve disease. *Amer. J. Cardiol.* 15: 809, 1965.
44. GARRARD, C. L., Jr., WEISSLER, A. M., & DODGE, H. T.: The relationship of alterations in systolic time intervals to ejection fraction in patients with cardiac disease. *Circulation* 42: 455, 1970.
45. BRAUNWALD, E., SARNOFF, S. J., & STAINSBY, W. N.: Determinants of duration and mean rate of ventricular ejection. *Circ. Res.* 6: 319, 1958.

46. WILLEMS, J. & KESTELOOT, H.: The left ventricular ejection time. Its relation to heart rate, mechanical systole and some anthropometric data. *Acta. Cardiol.* 22: 401, 1967.
47. WEISSLER, A. M., HARRIS, W. S., & SCHOENFELD, C. D.: Bedside techniques for the evaluation of ventricular function in man.
48. REMINGTON, J. W., HAMILTON, W. F., & AHLQUIST, R. P.: Interrelation between the length of systole, stroke volume and left ventricular work in the dog. *Amer. J. Physiol.* 154: 6, 1948.
49. WALLACE, A. G., MITCHELL, J. H., SKINNER, N. S., & SARNOFF, S. J.: Duration of the phases of left ventricular systole. *Circ. Res.* 12: 611, 1963.
50. WIGGERS, C. J.: Studies on the consecutive phases of the cardiac cycle: II. The laws governing the relative duration of ventricular systole and diastole. *Amer. J. Physiol.* 56: 439, 1921.
51. WEISSLER, A. M., HARRIS, W. S., & SCHOENFELD, C. D.: Systolic time intervals in heart failure in man. *Circulation* 37: 149, 1968.