Test of reliability of echocardiographic estimation of left ventricular dimensions and volumes

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This test is based on the incompressibility of myocardium, which dictates that left ventricular wall volume remains constant throughout the cardiac cycle.

The volumes occupied by the left ventricular cavity, by ventricular wall plus cavity, and hence by ventricular wall alone were estimated, both at end-systole and at end-diastole, from echocardiographic measurements of cavity transverse dimension and wall thickness. Wall volumes were determined by assuming an ellipsoid shape (the major axis being predicted from regression equations relating angiocardigraphic and echocardiographic cavity dimensions) and also by the cube method. A discrepancy between systolic and diastolic wall volume estimates indicates either that the measurements of ventricular dimensions were unreliable or that the assumptions of ventricular geometry involved in the volume calculations were incorrect.

Studies were made on 60 subjects. Using the ellipsoid formula, values for wall volume ranged from 66 to 719 ml; systolic and diastolic wall volumes correlated closely ($r=0.96$, mean difference= 6.8 ± 0.9 (SEM) %) supporting the reliability of the echocardiographic dimensions and estimates of cavity and wall volume. In the 12 patients with very large end-diastolic cavity transverse dimensions (6.5 to 8.6 cm) however, correlation was less good ($r=0.81$, mean difference= 14.3 ± 2.3 (SEM) %). Using the cube method, which does not allow for the changing relation between minor and major cavity axes with increasing cavity size, wall volumes were greater (76 to 986 ml) but correlation was similar ($r=0.94$, mean difference= 7.1 ± 0.9 (SEM) %).

Having established that it is possible to obtain close agreement between wall volumes determined at different points in the cardiac cycle, this test can be used to assess the reliability of echocardiographic left ventricular dimensions and volume estimates in individual subjects.

The noninvasive technique of echocardiography can be used to estimate several indices of left ventricular function including stroke volume, ejection fraction, ventricular mass, and wall stress. There are two main problems in the echocardiographic assessment of left ventricular function. The first problem is the difficulty which can be encountered in the recording and in the correct interpretation of left ventricular echocardiograms. The second problem lies in the fact that the estimation of left ventricular volumes is based on the measurement of a single cavity dimension and it, therefore, necessarily involves several assumptions as to the shape of the left ventricle. Though these assumptions are supported by angiocardigraphic

observations (Greene *et al.*, 1967; Sandler and Dodge, 1968; Gault, Ross, and Braunwald, 1968), the estimation of a three-dimensional shape from a single dimension is clearly open to criticism, particularly in patients with pronounced left ventricular cavity enlargement, where the cavity tends to be spherical rather than ellipsoid (Fortuin *et al.*, 1971; Gibson, 1973), and in patients with an irregular or atypical cavity shape, as may occur in hypertrophic cardiomyopathy and ischaemic heart disease (Gibson, 1973; Feigenbaum, 1975).

We tested the reliability of the information which can be derived from the left ventricular echocardiogram, on a within-patient basis, by comparing diastolic and systolic estimates of left ventricular wall volume. The left ventricular wall, being non-gaseous, is incompressible and thus left ventricular wall volume must remain constant

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throughout the cardiac cycle. Wall volume can be estimated from echocardiographic measurements of wall thickness and cavity transverse dimension. Measurement of these two ventricular dimensions, and hence estimates of wall volume, can be made at end-diastole, when wall thickness is at a minimum and cavity size is at a maximum, and also at end-systole, when wall thickness is at a maximum and cavity size is at a minimum. If the ventricular dimensions are reliable, and if the assumptions of ventricular geometry involved in echocardiographic estimation of left ventricular volumes are correct, then diastolic and systolic estimates of wall volume should agree. Lack of agreement indicates either that the ventricular dimensions or geometric assumptions are unreliable, or that the echocardiogram is technically unsatisfactory or has been misinterpreted.

Subjects and methods

Left ventricular echocardiograms obtained from 8 normal subjects and from 52 patients with disorders likely to cause left ventricular enlargement were studied. The echocardiograms were selected for their clarity; in all records it was possible unequivocally to identify left ventricular endocardium and epicardium.

The echocardiograms were recorded by the standard method (Feigenbaum, 1972) on light sensitive paper (Kodak Linagraph, 1895), at a paper speed of 50 mm/s, using a Smith Kline 20A

ultrasonoscope, 2.25 MHz 10 cm focussed transducer, and a Honeywell 1856 strip chart recorder. End-diastolic (Dd) and end-systolic (Ds) cavity transverse dimension, and end-diastolic (Wd) and end-systolic (Ws) left ventricular wall thicknesses were measured with the aid of the simultaneously recorded calibration scale (Fig. 1). Cavity transverse dimension was measured as the distance between left ventricular septal and posterior wall endocardium. Wall thickness was measured as the distance between posterior wall endocardium and epicardium. End-diastole was defined as the time of onset of the QRS complex of the simultaneously recorded electrocardiogram, and end-systole as the point of maximum anterior movement of the posterior wall.

Left ventricular wall volumes were calculated, at end-diastole and end-systole, by subtracting the estimated cavity volume from the estimated volume occupied by ventricular wall plus cavity. Two different formulae were used.

(1) Cube formula

This formula is based on the empirical observation that the cube of the cavity transverse dimension (D^3) approximates to the left ventricular cavity volume (Feigenbaum *et al.*, 1969). By assuming uniform wall thickness (W), the volumes occupied by ventricular wall plus cavity ($(2W + D)^3$) and hence by ventricular wall alone can be calculated, thus: wall volume = $(2W + D)^3 - D^3$ (Bennett and Evans, 1974).

FIG. 1 Left ventricular echocardiogram (Case 26). IVS, interventricular septum; PW, posterior wall; Ws and Wd, end-systolic and end-diastolic wall thickness respectively; Ds and Dd, end-systolic and end-diastolic cavity transverse dimension, respectively.

(2) Ellipsoid formula

The empirical observation on the relation of the cube of the cavity transverse dimension to cavity volume can be explained by assuming (a) that the left ventricle has the shape of an ellipsoid of revolution, a widely held assumption in angiocardio-graphic work (Dodge *et al.*, 1966; Greene *et al.*, 1967; Sandler and Dodge, 1968), and (b) that the cavity transverse dimension is equal to each minor axis and to the semi-major axis (Chapelle and Mensch, 1969; Popp and Harrison, 1970; Troy, Pombo, and Rackley, 1972). If these relations hold, the minor radii are each $D/2$ and the major axis is D , and the cavity volume becomes $4/3 \pi (D/2)^2 D = 1.047D^3 \approx D^3$.

However, with cavity dilatation, the cavity minor axis increases relative to the major axis, the ventricle becoming more spherical in shape (Fortuin *et al.*, 1971; Teichholz *et al.*, 1972; Gibson, 1973). In addition, the relation between major and minor axes varies during the cardiac cycle (Gault *et al.*, 1968). Gibson (1973), in a study of 50 patients with a variety of cardiac disorders, derived regres-

sion equations relating angiocardio-graphic measurements of cavity major axis (L) to echocardiographic measurements of cavity transverse dimension (D), at end-diastole and end-systole:

$$L_d = 5.90 + 0.98 D_d; L_s = 4.18 + 1.14 D_s.$$

These regression equations are similar to that derived from end-diastolic data by Ratshin, Rackley, and Russell (1974):

$$L_d/2 = 2.518 + 0.462 D_d.$$

By predicting the cavity major axis from Gibson's regression equations, left ventricular wall volume can be estimated, in the same way as angiocardio-graphic measurements are made (Rackley *et al.*, 1964), by using the formula for the volume of an ellipsoid. Thus: wall volume =

$$4/3 \pi (W + D/2)^2 (W + L/2) - 4/3 \pi (D/2)^3 L/2.$$

Correlation was sought between end-diastolic and end-systolic wall volume estimates, and the difference between these estimates was expressed as a percentage of the diastolic wall volume estimate. The subjects' clinical details, ventricular dimensions, and wall volume estimates are given in Table 1.

TABLE 1 Diagnoses, systolic and diastolic ventricular dimensions, and wall volumes

Case No.	Diagnosis	Age (y)	s/d	W (cm)	D (cm)	L (cm)	Wall volume (ml)	
							Cube	Ellipsoid
1	Normal	29	s	1.55	3.30	7.95	226	192
			d	0.90	5.35	11.15	212	180
2	Normal	38	s	1.35	2.80	7.50	144	131
			d	0.85	4.45	10.25	145	130
3	Normal	25	s	1.50	3.10	7.70	197	170
			d	0.95	4.85	10.65	194	168
4	Normal	27	s	1.55	2.45	6.95	156	140
			d	1.10	3.70	9.55	155	146
5	Normal	25	s	1.55	3.10	7.70	213	186
			d	0.95	4.80	10.60	190	166
6	Normal	20	s	1.45	2.70	7.25	156	139
			d	0.95	3.90	9.70	136	127
7	Normal	18	s	1.35	3.30	7.95	180	155
			d	0.95	4.65	10.45	181	159
8	Normal	18	s	1.50	3.15	7.75	201	173
			d	0.95	5.00	10.80	204	175
9	Coarct	30	s	1.95	2.75	7.30	273	230
			d	1.25	4.60	10.40	261	231
10	Coarct	31	s	2.00	3.05	7.65	322	266
			d	1.05	6.00	11.80	315	255
11	Coarct	20	s	2.40	3.05	7.65	455	377
			d	1.55	5.35	11.15	450	366
12	Coarct	17	s	2.20	3.00	7.60	378	308
			d	1.30	5.20	11.00	334	278
13	Coarct	20	s	2.05	3.15	7.75	350	286
			d	1.40	5.15	10.95	366	303
14	Coarct	17	s	2.30	3.00	7.60	412	333
			d	1.45	5.00	10.80	368	306
15	Coarct	20	s	2.40	3.05	7.65	455	377
			d	1.55	5.35	11.15	450	366

Continued

TABLE 1 *continued*

Case No.	Diagnosis	Age (y)	s/d	W(cm)	D(cm)	L(cm)	Wall volume (ml)	
							Cube	Ellipsoid
16	Hypert	53	s	2.50	2.70	7.30	437	416
			d	1.70	4.90	10.70	454	374
17	Hypert	40	s	2.60	3.00	7.60	524	415
			d	1.90	5.00	10.80	557	451
18	Hypert	30	s	2.05	3.00	7.60	331	273
			d	1.45	4.75	10.55	341	288
19	AS	43	s	1.90	1.85	6.30	174	157
			d	1.20	3.65	9.50	173	162
20	AS	33	s	2.10	2.00	6.50	230	202
			d	1.30	3.70	9.50	199	183
21	AS	30	s	1.70	2.70	7.25	207	187
			d	1.10	4.10	9.90	181	152
22	AS	19	s	1.70	3.15	7.75	250	210
			d	1.10	5.00	10.80	248	212
23	AS	44	s	2.00	2.90	7.50	304	254
			d	1.50	4.10	9.90	289	253
24	AS	52	s	2.00	2.20	6.70	228	198
			d	1.30	4.00	9.80	223	201
25	AS	58	s	2.30	2.35	6.85	323	270
			d	1.60	4.25	10.05	337	290
26	AS	18	s	2.05	2.15	6.65	234	205
			d	1.35	4.05	9.85	241	215
27	AS	19	s	1.75	1.85	6.30	147	134
			d	1.20	3.35	9.15	153	147
28	AS	43	s	1.90	1.85	6.30	174	157
			d	1.20	3.65	9.50	173	162
29	AS, LVF	58	s	1.90	7.20	12.40	958	690
			d	1.35	8.30	14.05	759	554
30	AS, AR	45	s	2.20	2.60	7.10	325	270
			d	1.40	4.65	10.45	313	269
31	AS, AR	47	s	2.60	3.10	7.70	542	427
			d	1.70	5.60	11.40	553	440
32	AS, AR	50	s	3.00	3.00	7.60	710	541
			d	2.30	4.80	10.60	720	575
33	AS, AR	52	s	1.55	4.50	9.30	348	276
			d	1.25	5.70	11.50	366	297
34	AS, AR	30	s	2.80	3.60	8.30	736	560
			d	1.80	5.90	11.70	652	510
35	AS, AR	36	s	2.15	2.65	7.20	317	264
			d	1.50	5.00	10.80	387	321
36	AS, AR	19	s	1.80	3.50	8.15	315	258
			d	1.30	5.00	10.80	314	264
37	AS, AR, MS	57	s	2.15	2.45	6.95	293	247
			d	1.50	4.25	10.05	304	264
38	AS, AR, MS	46	s	1.80	2.05	6.50	172	151
			d	1.05	4.05	9.85	166	152
39	CAF	26	s	1.85	3.65	8.35	348	270
			d	1.15	5.65	11.45	322	264
40	AR	27	s	1.90	3.45	8.10	340	277
			d	1.10	6.10	11.90	345	277
41	AR	19	s	2.05	4.95	9.80	620	470
			d	1.35	7.65	13.40	661	492
42	AR	46	s	2.25	4.90	9.75	713	537
			d	1.40	7.50	13.25	671	501
43	AR	37	s	1.60	3.60	8.30	268	222
			d	1.00	5.60	11.40	263	216
44	AR	6	s	1.00	2.50	7.05	76	66
			d	0.65	3.50	9.35	68	69
45	AR	32	s	2.15	3.70	8.40	461	365
			d	1.05	6.80	12.60	391	305
46	AR	56	s	1.85	5.90	10.90	679	506
			d	1.55	7.35	13.10	744	556

Continued

TABLE 1 *continued*

Case No.	Diagnosis	Age (y)	s/d	W(cm)	D(cm)	L(cm)	Wall volume (ml)	
							Cube	Ellipsoid
47	AR, MR	19	s	1.90	4.70	9.55	510	395
			d	1.30	6.60	12.35	491	381
48	AR, VSD	23	s	2.35	5.90	10.90	986	719
			d	1.45	8.55	14.30	876	633
49	AR, VSD	17	s	2.00	4.20	9.00	477	375
			d	1.10	6.50	12.50	384	306
50	AR, MS	43	s	1.75	4.55	9.35	428	335
			d	1.25	6.40	12.15	443	347
51	AVR	50	s	1.90	4.30	9.10	452	355
			d	1.10	6.80	12.60	415	323
52	AVR	32	s	2.00	2.35	6.85	243	209
			d	1.30	4.30	10.10	249	219
53	MR	23	s	2.00	5.00	9.90	604	460
			d	1.05	7.80	13.55	496	372
54	MR	52	s	2.00	5.25	10.15	647	487
			d	1.55	8.10	13.85	874	638
55	MR	51	s	1.95	3.45	8.10	356	289
			d	1.20	5.70	11.50	346	282
56	MR	30	s	1.95	3.00	7.60	302	251
			d	1.10	5.65	11.45	303	249
57	MR, MS	51	s	1.55	3.70	8.40	264	218
			d	1.00	5.55	11.35	259	215
58	PDA	10	s	1.05	3.00	7.60	106	96
			d	0.60	4.70	10.50	102	92
59	PDA	16	s	1.45	4.25	9.05	289	234
			d	0.95	5.70	11.50	254	210
60	COCM	42	s	1.55	6.15	11.20	559	569
			d	1.00	7.50	13.25	435	522

s=end-systolic data; d=end-diastolic data; W=wall thickness; D=cavity transverse dimension; L=estimated major axis; Coarct=aortic coarctation; hypert=essential hypertension; AS=aortic stenosis; AR=aortic regurgitation; MS=mitral stenosis; MR=mitral regurgitation; CAF=coronary artery fistula; VSD=ventricular septal defect; AVR=leaking aortic prosthesis; PDA=persistent ductus arteriosus; COCM=congestive cardiomyopathy.

Results

Overall, there was close correlation between diastolic and systolic wall volume estimates using both the cube formula and the ellipsoid formula (Table 2). In some of the patients however, mainly those with pronounced cavity enlargement, agreement was poor. An example is shown in Fig. 2.

In subjects with normal or moderately enlarged cavities, wall volumes determined using the cube formula were slightly greater than those determined using the ellipsoid formula. In patients with very large cavities, where the predicted major axis was substantially less than twice the minor axis, wall volumes calculated using the cube formula were much greater than those determined from the ellipsoid formula.

Discussion

In most cases there was close agreement between estimates of left ventricular wall volume at end-systole, when wall thickness is at a maximum and cavity size is at a minimum, and at end-diastole, when wall thickness is at a minimum and cavity

size is at a maximum. This supports the reliability of the wall thickness and cavity dimension measurements, and of the assumptions involved in the volume determinations. The agreement does not *establish* the reliability of the measurements, but it is certainly consistent with it, and lack of agreement is certainly inconsistent with reliability. In some cases, mainly those with very large ventricular cavities, agreement was poor indicating in these cases, either that the measurements of ventricular dimensions were unreliable or that the assumptions of ventricular geometry involved in the volume calculations could not be applied.

Though agreement was not improved by use of the method based on the ellipsoid formula, we feel that this method is likely to yield more realistic estimates of wall volume since it does take into account the changing relation between major and minor axes which occurs during the cardiac cycle and with increasing cavity size, whereas the cube method is based on a fixed relation between the two axes.

The test is based on the constancy of ventricular wall volume throughout the cardiac cycle. It might

TABLE 2 Comparison of systolic and diastolic wall volume estimates

	C/E	n	r	P<	Mean difference (%)
All subjects	C	60	0.94	0.001	7.1 ± 0.9 (SEM)
	E		0.96	0.001	6.8 ± 0.9 (SEM)
Subjects with	C	12	0.82	0.001	15.9 ± 2.6 (SEM)
Dd ≥ 6.5 cm	E		0.81	0.001	14.3 ± 2.3 (SEM)
Subjects with	C	48	0.99	0.001	4.8 ± 0.7 (SEM)
Dd < 6.5 cm	E		0.98	0.001	4.9 ± 0.7 (SEM)

C and E=wall volumes estimated by cube and ellipsoid formulae respectively; Dd=end-diastolic cavity transverse dimension; n=number of subjects; r=correlation coefficient; P=significance level; SEM=standard error of mean.

be argued that a change in wall volume could occur as a result of expulsion of blood from the myocardium during systole. Assuming a myocardial blood flow of 66 ml/min per 100 g (Brachfeld, Bozer, and Gorlin, 1959), i.e. approximately 1 ml/s per 100 g, and using a mean transit time for the coronary circulation of 7 seconds (Gorlin, 1960), the coronary blood volume is calculated to be 7.0 ml/100 g. If the myocardium were completely emptied of blood during systole, it would only account for a 7 per cent change in wall volume. It is extremely unlikely that the myocardium is

completely emptied of blood in systole. An assessment of the volume of blood likely to be expelled from the myocardium in systole can be obtained by a consideration of the total coronary flow. Using the above estimate for myocardial blood flow and assuming a heart rate of 60/minute, only approximately 1 ml blood/min per 100 g of myocardium can be expelled. Even if all this flow occurred between end-diastole and end-systole, it could only constitute 1 ml blood volume to 100 g myocardial tissue or approximately 1 per cent. In view of the range of heart rates possible and the uncertain apportioning of blood between the left and right ventricular myocardium, it seems best to assume simply that any myocardial volume change related to expulsion of blood will account for between 1 and 7 per cent and will probably be much closer to the former than the latter.

Comparison of systolic and diastolic wall volume estimates has been used in angiocardiographic studies to assess the reliability of wall thickness and cavity volume measurements (Hugenholtz, Kaplan, and Hull, 1969; Lewis and Sandler, 1971). A difference of up to 25 per cent is usually regarded as acceptable (Lewis and Sandler, 1971; Sandler and Alderman, 1974). Agreement between wall volume estimates in this echocardiographic study was closer probably because of the tendency to

FIG. 2 Patient with severe left ventricular failure (Case 29). Distinct difference between systolic and diastolic estimates of wall volume using both cube (26%) and ellipsoid (25%) formulae.

overestimate end-systolic wall thickness, and hence wall volume, by angiocardiology (Hugenholtz *et al.*, 1969).

In conclusion, close agreement can be obtained between echocardiographic systolic and diastolic wall volume estimates. Having established this, comparison of wall volume estimates can be used to assess the reliability of measurements of ventricular dimensions and volumes in individual subjects. It is suggested that differences in excess of 10 per cent between systolic and diastolic left ventricular wall volume estimates point to lack of reliability of measurements of left ventricular volumes.

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