Assessment of left ventricular function by single plane cineangiographic volume analysis

K. Chatterjee[1], M. Sacoor, G. C. Sutton, and G. A. H. Miller
From the Cardiac Department, Brompton Hospital, London S.W.3

Single plane cineangiography, either in the anteroposterior or in the right anterior oblique projection, can be used to determine left ventricular volumes. Volumes so obtained showed good agreement with those reported by others using biplane techniques. Ejection fraction and ejection rate derived from such volumes were normal in patients with mitral stenosis and with chronic compensated pressure and volume overloads, but were significantly reduced in patients with cardiomyopathy. Unlike ejection fraction and ejection rate, left ventricular end-diastolic pressure was not found to be a sensitive index for differentiating patients with and without left ventricular dysfunction.

Volumetric analysis of the left ventricle by serial biplane angiography is now an established method for quantitative assessment of left ventricular function (Dodge *et al.*, 1966; Dodge and Baxley, 1969; Arvidsson, 1961; Miller, Kirklin, and Swan, 1965; Kennedy *et al.*, 1968). This technique has the disadvantage that infrequent film exposures necessitate construction of a composite volume curve, and volume changes so measured represent an average of several cardiac cycles. Biplane cineangiography (Chapman *et al.*, 1958; Vogel, Horgan, and Strahl, 1970), on the other hand, permits analysis of beat-to-beat volume changes and assessment of reproducibility; moreover, the greater number of film exposures reduces the chance of inaccurate estimation of end-systolic and end-diastolic volumes. In clinical practice, single plane cineangiography is more commonly available for assessment of valve or myocardial function. Since others (Sandler *et al.*, 1965; Sandler and Dodge, 1968; Dodge *et al.*, 1966; Hermann and Bartle, 1968) have shown good correlation between volumes calculated by serial single plane and serial biplane angiography the possibility exists of utilizing single plane cineangiography during routine cardiac catheterization for left ventricular volume analysis. Indeed several workers (Carlisle *et al.*, 1964; Moore, 1965; Greene *et al.*, 1967; Hermann, Singh, and Dammann, 1969; Falsetti *et al.*, 1970) have employed cineangiography in the

right anterior oblique projection for this purpose. In the present study, the relation between left ventricular volumes calculated by single plane cineangiography in the anteroposterior and in the right anterior oblique projections has been investigated, as has the relation between known and angiographically calculated left ventricular volumes. Once the validity of single plane (anteroposterior) cineangiographic calculations of left ventricular volume had been established it became possible to investigate left ventricular function employing two indices, the ejection fraction and the ejection rate, derived from left ventricular volume measurement. This communication also reports the use of these indices to investigate left ventricular function in patients with no cardiac abnormality as compared with others with mitral stenosis, chronic pressure or volume load of the left ventricle, or left ventricular cardiomyopathy.

Patients

Forty-three patients were studied (18 female, 25 male, age range 4 to 68 years). On clinical, radiological, electrocardiographic, and haemodynamic findings they were divided into the following groups.

Group 1: Normal (7 patients) Three were investigated for atypical chest pain; two had suspected minor pulmonary embolism, one a mediastinal shadow, and one idiopathic dilatation of the pulmonary artery. Detailed investigation, including conventional cardiac catheterization, did not reveal any significant abnormality of the cardiovascular system in any patient.

Group 2: Mitral stenosis (4 patients) All

patients had isolated mitral stenosis; three were in sinus rhythm and one had atrial fibrillation, but with a slow ventricular rate. The mean mitral valve gradient, determined by recording simultaneous left ventricular diastolic pressure and pulmonary artery 'wedge' pressure, ranged from 5 to 20 mmHg at rest. All were receiving digitalis.

Group 3: Compensated pressure overload (6 patients) Five patients had aortic valve stenosis with peak systolic gradients ranging from 50 to 130 mmHg, while one had fixed membranous subaortic stenosis (gradient 65 mmHg). None had significant aortic regurgitation. All were in sinus rhythm and none was digitalized at the time of study. As no patient in this group had any clinical evidence of heart failure (raised jugular venous pressure, peripheral oedema, paroxysmal nocturnal dyspnoea, exertional dyspnoea or radiological pulmonary congestion or cardiac enlargement), they were regarded as having compensated pressure overload.

Group 4: Compensated volume overload (9 patients) Six patients had severe aortic regurgitation as judged by aortic cineangiography. In none was there any significant aortic valve gradient. Three patients had mitral regurgitation; in two regurgitation was severe and in one it was moderate, as judged by left ventricular cineangiography. Mitral regurgitation was due to ruptured chordae in two patients and to rheumatic heart disease in one patient. All patients in this group were in sinus rhythm and only one patient was receiving digitalis. No patient was in clinical heart failure at the time of study; these patients were therefore regarded as having compensated volume overload.

Group 5: Cardiomyopathy (7 patients) All patients had both clinical and radiological cardiomegaly, all were in heart failure and were digitalized at the time of study. None had any significant valve lesion and all were thought to have primary myocardial disease of unknown aetiology, though coronary artery disease was not excluded as selective coronary arteriography was not undertaken.

Group 6: Homograft replacement of mitral valve (10 patients) All had cineangiography performed in both anteroposterior and right anterior oblique projections. In the present study, data obtained from these patients were only used to compare left ventricular volumes calculated in the two projections. The results of volumetric analysis of left ventricular function in these patients have been reported elsewhere (Sutton, Chatterjee, and Miller, 1971).

Method
Cineangiography was performed at a film speed of 35 frames/sec. Contrast medium,[1] 1 to 1·5 ml/kg body weight, was injected either into the

[1] Sodium, calcium and magnesium metrizoate (Triosil '75'). Glaxo Laboratories Ltd., Greenford, Middlesex.

main pulmonary artery or, in a few patients, into the aortic root or the left ventricle. In all patients left ventricular or systemic arterial pressure and a standard lead electrocardiogram were recorded simultaneously to exclude significant haemodynamic alterations as a result of angiography. Correction for image magnification and distortion from non-parallel x-rays was performed according to the method of Greene *et al.* (1967) by filming a metal grid of 1 cm squares placed at the midchest level of the patient. The outline of the left ventricle was traced from each cine frame and the planimetered area and longest measurable length were determined (Dodge *et al.*, 1960, 1966; Greene *et al.*, 1967). After correcting all measurements for image magnification left ventricular volumes were calculated by the area-length method of Dodge *et al.* (1966), using an ellipsoidal reference figure.

The correlation between the actual volume and the calculated volume in the anteroposterior projection was determined from observations made in five barium-filled postmortem hearts. Each heart was suspended in a position approximately corresponding to that of a living heart in the anteroposterior projection. A known increment of barium sulphate paste was injected and a short run of cine exposures made at each increment of volume. The calculated volumes by this method in the anteroposterior projection underestimate the actual volume (Fig. 1). Hence, calculated volumes in all patients were corrected for this underestimation according to the regression equation $V = 1.477 \ V^1 - 4.40$ (where $V =$ actual volume and $V^1 =$ calculated volume in ml). All estimated volumes were also corrected for body surface area and were expressed in ml/m².

FIG. 1 *Comparison between measured volumes by single plane cineangiography in anteroposterior projection (V^1) and actual volume (V) of barium sulphate injected in postmortem hearts. Measured volume underestimates the actual volume.*

$$r = 0.955$$
$$V = -4.40 + 1.477 V'$$
$$S_{yx} = 9.0$$
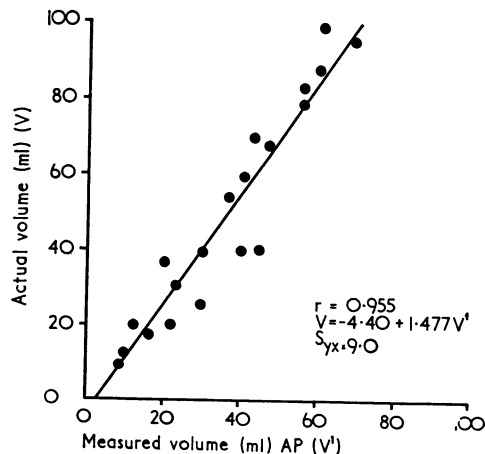
All volume calculations were performed by computer, and for each patient a volume curve covering several cardiac cycles was obtained from which the end-diastolic volume and the end-systolic volume were read directly (Fig. 2). The total left ventricular stroke volume was obtained by subtracting the end-systolic from the end-diastolic volume and the ratio of left ventricular stroke work to end-diastolic volume gave the ejection fraction. By drawing a tangent on the ejection portion of the volume curve the rate of ejection in ml/sec was calculated. As the rate of ejection is dependent, not only on the contractile state, but also on the size of the heart, it was corrected for this factor by dividing it by the end-diastolic volume (normalized ejection rate) and was expressed in vol/sec (Hood, Rackley, and Rolett, 1968a). Left ventricular end-diastolic pressure was measured immediately after the 'a' wave when this was clearly visible, and where no 'a' wave existed, at 0·05 sec after onset of the QRS (Braunwald, Fishman, and Cournand, 1956).

Results

The correlation between the actual volumes and calculated volumes in the anteroposterior projection from observations in barium-filled hearts is shown in Fig. 1. Though there was excellent correlation ($r = 0.955$), the calculated volume underestimated the actual volume. Hence, the calculated volumes have been corrected for this underestimation as described above.

Comparison between calculated volumes in the anteroposterior and right anterior oblique projections (Group 6, Fig. 3) indicated that volumes calculated in the same patient in the latter projection were considerably larger than those in the former projection.[1] Despite this difference in estimated volumes in the two projections, the ejection fraction in the same patient remained practically unchanged (Fig. 4) suggesting that, for calculation of ejection fraction by single plane cineangiography, either projection could be employed.

Left ventricular volume data obtained by single plane cineangiography in the antero-posterior projection in 33 patients (Groups 1 to 5) are summarized in Table 1. The end-diastolic volume in normal controls (Group 1, mean 70 ± 17, range 54 to 108 ml/m²) was not significantly different from patients with mitral stenosis (Group 2, mean 69 ± 18, range 51 to 88 ml/m²) or with compensated pressure

[1] When changes in corresponding planimetered areas and measured major axes in the two projections were compared, the percentage increase in area was relatively more than the percentage increase in the major axis when the patient was rotated from the antero-posterior to the right anterior oblique projection, accounting for the larger calculated volume in the latter projection.

EDV = end-diastolic volume

ESV = end-systolic volume

LVSV (stroke volume) = EDV − ESV

EF (ejection fraction) = $\dfrac{EDV - ESV}{EDV}$

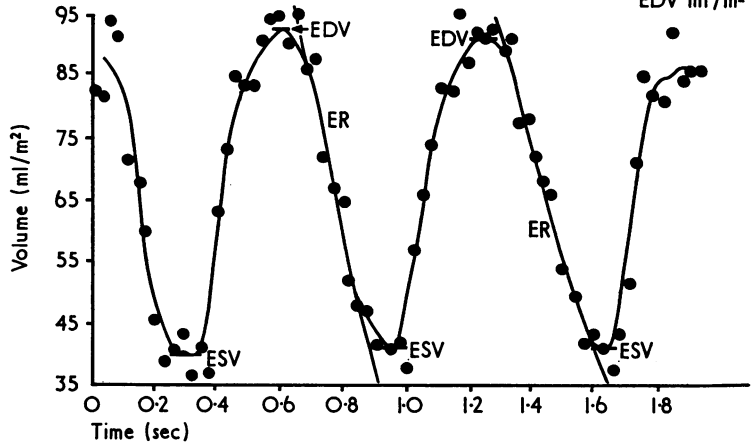ER (normalised ejection rate) = $\dfrac{de/dt \ ml/sec}{EDV \ ml/m^2}$

FIG. 2 *A typical non-composite volume curve as obtained by computer analysis showing beat-to-beat reproducibility.*

overload (Group 3, mean 74 ± 18, range 53 to 93 ml/m²). It was significantly greater in patients with cardiomyopathy (Group 5, mean 167 ± 28, range 133 to 206 ml/m²) and, as would be expected, in those with compensated volume overload (Group 4, mean 172 ± 58, range 130 to 308 ml/m²) (Fig. 5). The angiographically determined left ventri-

FIG. 3 *Comparison between calculated endsystolic and diastolic volumes in 10 patients (Group 6) by single plane cineangiography in anteroposterior (AP) and right anterior oblique (RAO) projections. Volumes in right anteroposterior overestimate volumes in anteroposterior projection.*
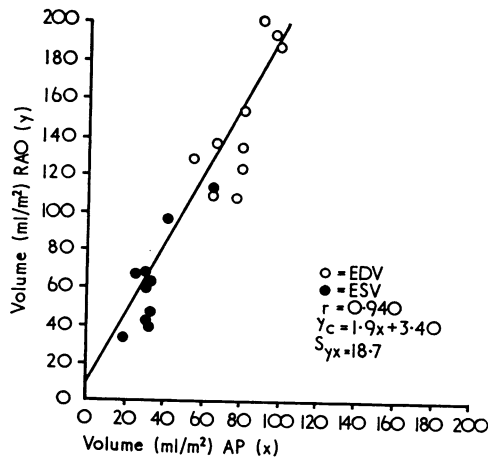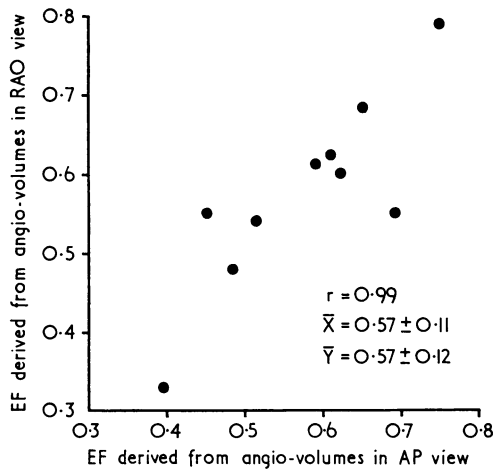
FIG. 4   *Ejection fraction in 10 patients (Group 6) derived from calculated volumes in anteroposterior and right anterior oblique projections. The ejection fraction remains unchanged with change of projection.*

FIG. 5   *End-diastolic volumes in patients in Groups 1 to 5. Mean value for each group is shown by horizontal line. End-diastolic volume is raised only in patients with compensated volume overload (Group 4) and cardiomyopathy (Group 5).*

cular stroke volume in normals (Group 1, mean 49 ± 10 ml/m²) was not significantly different from that in patients with mitral stenosis (Group 2, mean 51 ± 11 ml/m²) or with compensated pressure overload (Group 3, mean 58 ± 17). In patients with compensated volume overload (Group 4) the left ventricular stroke volume was, as expected, higher (mean 106 ± 35 ml/m²) and was slightly reduced in patients with cardiomyopathy (Group 5, mean 37 ± 8 ml/m²) (Fig. 6).

The ejection fraction in normal subjects was 0.70 ± 0.03. In patients with mitral stenosis it was 0.75 ± 0.03 and in patients with compensated pressure overload 0.75 ± 0.06. A few patients with mitral stenosis or aortic stenosis had 'supernormal' ejection fractions (Fig. 7) due to smaller end-systolic volumes but normal end-diastolic volumes. The patients with compensated volume overload had a slightly lower ejection fraction (mean 0.61 ± 0.06), but the difference was not significant
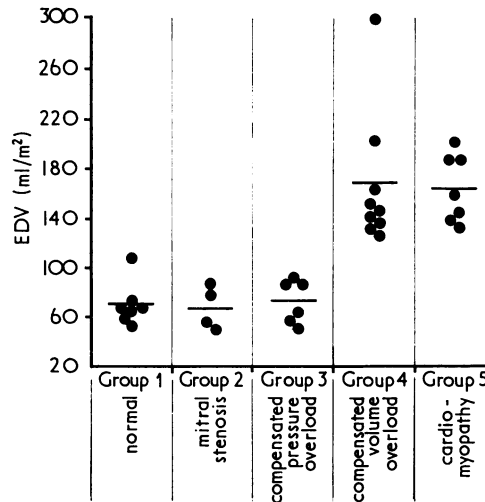
as compared with normal subjects. In contrast, patients with cardiomyopathy had a very low ejection fraction (mean 0.22 ± 0.05) and the difference as compared with normals was highly significant ($P < 0.001$).

The normalized ejection rate (Fig. 8) in normal controls (Group 1) was 3.24 ± 0.86 vol/sec (range 2.08 to 4.59 vol/sec), and it was similar in all other groups except those with cardiomyopathy who had a significantly ($P < 0.001$) lower value (1.09 ± 0.47, range 0.66 to 1.31 vol/sec). There was a good correlation ($r = 0.814$) between ejection fraction and normalized ejection rate and both were significantly low only in patients with cardiomyopathy.

The left ventricular end-diastolic pressure measured in 32 of the 33 patients was not found to be a sensitive index in differentiating

TABLE I   *Left ventricular volume data in 33 patients*

Groups	No. of patients	End-diastolic volume (ml/m²)	Left ventricular stroke volume (ml/m²)	Ejection fraction	Normalized ejection rate (vol/sec)
1 Normal	7	70 ± 17	49 ± 10	0.70 ± 0.03	3.24 ± 0.86
2 Mitral stenosis	4	69 ± 18	51 ± 11	$0.75 \pm 0.03^\star$	3.08 ± 0.56
3 Compensated pressure overload	6	74 ± 18	58 ± 17	0.75 ± 0.06	2.80 ± 0.54
4 Compensated volume overload	9	$172 \pm 58^{\star\star}$	$106 \pm 35^{\star\star}$	0.61 ± 0.06	2.79 ± 0.53
5 Cardiomyopathy	7	$167 \pm 28^{\star\star}$	$37 \pm 8^\star$	$0.22 \pm 0.05^{\star\star}$	$1.04 \pm 0.47^{\star\star}$

Significance as compared with normals: $^\star = P < 0.05$. $^{\star\star} = P < 0.001$.
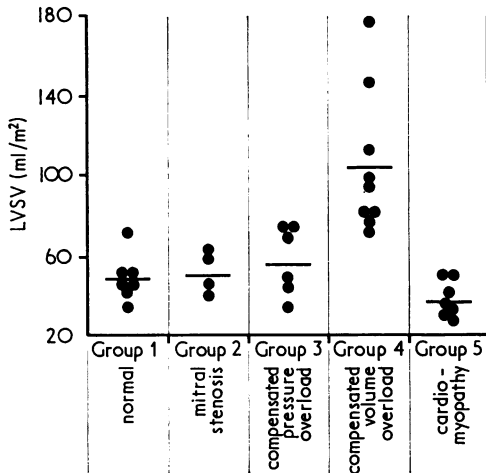
FIG. 6 *Left ventricular stroke volume in ml/m² in Groups 1 to 5. Mean values are shown by horizontal lines. Left ventricular stroke volume is significantly increased only in Group 4.*

FIG. 8 *Normalized ejection rate in vol/sec in Groups 1 to 5. Mean values are shown by horizontal lines. Ejection rate is significantly reduced in patients with cardiomyopathy (Group 5).*

between patients with and without left ventricular dysfunction; thus there was no correlation between left ventricular end-diastolic pressure and ejection fraction on the one hand ($r = 0.459$), or the end-diastolic volume ($r = 0.317$).

Discussion

The data obtained in this study in different groups of patients are very similar to those

FIG. 7 *Analysis of ejection fraction in Groups 1 to 5. Mean values are shown by horizontal lines. The ejection fraction is significantly reduced in patients with cardiomyopathy (Group 5).*
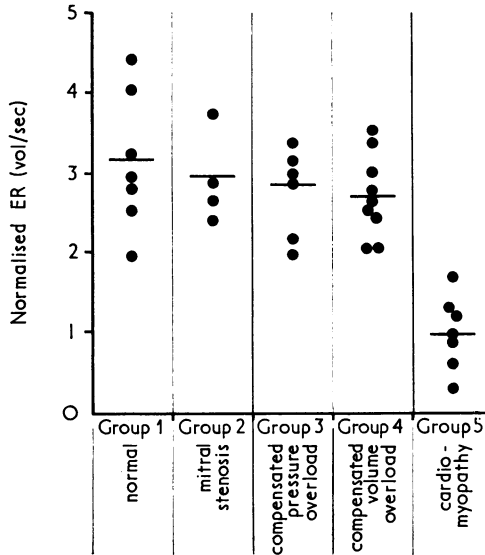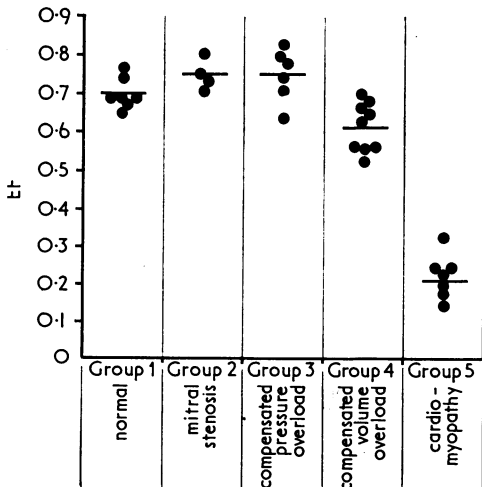

previously reported (Miller and Swan, 1964; Miller *et al.*, 1965; Sanmarco and Bartle, 1964; Kennedy *et al.*, 1966, 1968; Hood *et al.*, 1968b; Hermann *et al.*, 1969). Thus, while the end-diastolic volume was increased in response to a chronic volume overload, the ejection fraction remained normal, suggesting that in these patients myocardial function was unimpaired. In contrast, the increase in end-diastolic volume in patients with cardiomyopathy was not associated with a corresponding increase in left ventricular stroke volume resulting in a low ejection fraction. This low ejection fraction characterizes impaired myocardial function (Dodge *et al.*, 1966; Dodge and Baxley, 1968; Jones *et al.*, 1964; Miller and Swan, 1964; Miller *et al.*, 1965; Bunnell, Grant, and Greene, 1965; Grant, Greene, and Bunnell, 1965; Bartle, Sanmarco, and Dammann, 1965; Hood *et al.*, 1968b).

The rate of ejection, when corrected for heart size, was also found to be a useful index of left ventricular function, confirming the findings of Hood *et al.* (1968a). Only patients with cardiomyopathy had a significantly low normalized ejection rate; all other patients (mitral stenosis, compensated pressure overload, and compensated volume overload) had values within the normal range. There was a good correlation between ejection fraction and normalized ejection rate, and both were

TABLE 2 *Comparison of calculated volumes in normal subjects by single plane cineangiography in AP projection with those derived by other angiographic methods*

Authors	Angiographic method*	End-diastolic volume (ml/m^2)	End-systolic volume (ml/m^2)	Left ventricular stroke volume (ml/m^2)	Ejection fraction
Arvidsson (1961)	Biplane serial	85	28		0·67
Miller and Swan (1964)	Biplane serial	85±11·65	28±8·75	56±8·9	0·67±0·08
Sanmarco and Bartle (1964)	Biplane serial	80±10			
Moore (1965)	Single plane cine; RAO			55±7	0·78±0·04
Kennedy et al. (1966)	Biplane serial	70±20		45±13	0·67±0·08
Arvidsson (1966)	Biplane serial	72	20		0·72
Hood et al. (1968b)	Biplane serial	79·3±4·4	27·8±2·5		0·665±0·30
Hermann et al. (1969)	Single plane cine; RAO	70±16			0·60±0·08
Falsetti et al. (1970)	Single plane cine; RAO				0·71±0·17
Present study (1970)	Single plane cine; AP	70±17	21±7	49±10	0·70±0·03

* RAO = right anterior oblique; AP = anteroposterior.

equally sensitive in differentiating patients with and without left ventricular dysfunction.

In contrast, left ventricular end-diastolic pressure was not found to be a useful index of left ventricular function. In some patients with cardiomyopathy end-diastolic pressure was normal, while in some without clinical heart failure it was raised. Nor was there any correlation between end-diastolic pressure and the ejection fraction or normalized ejection rate. These findings support the view that left ventricular end-diastolic pressure is not a reliable index of left ventricular function (Braunwald and Ross, 1963).

Though volumes calculated by single plane cineangiography in the anteroposterior projection somewhat underestimate the actual volume, an excellent correlation was found between the two. The calculated volumes corrected for this underestimation were in close agreement with those reported by other workers who have used biplane angiography (Arvidsson, 1961, 1966; Miller and Swan, 1964; Sanmarco and Bartle, 1964; Kennedy et al., 1966; Hood et al., 1968b) or single plane cineangiography in the RAO projection (Moore, 1965; Hermann et al., 1969; Falsetti et al., 1970) (Table 2). There was also an excellent correlation between volumes calculated by single plane cineangiography in the right anterior oblique and in the anteroposterior projections in the same patients, though the values were consistently larger in the right anterior oblique projection. This overestimation in the right anterior oblique projection was also found in postmortem heart studies (Greene et al., 1967). Despite these variations in calculated volumes with

change of projection the ejection fraction in the same patient remained practically unchanged. Indeed ejection fraction derived from calculated volumes by single plane cineangiography in the anteroposterior projection in this study is very similar to that reported by Falsetti et al. (1970) who employed cineangiography in the right anteroposterior projection (Table 2). These findings suggest that for routine clinical practice estimation of the ejection fraction, unlike end-diastolic pressure, can provide useful information about left ventricular function in patients with various cardiac disorders in the chronic state. It can be easily derived from volume analysis by single plane cineangiography during routine cardiac catheterization, and either the anteroposterior or the right anterior oblique projection, whichever is appropriate, can be employed.

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