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Two-dimensional echocardiographic estimation of left atrial volume and volume load in patients with congenital heart disease

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Summary

To estimate the left atrial volume (LAV) and pulmonary blood flow in patients with congenital heart disease (CHD), we employed two-dimensional echocardiography (TDE). The LAV was measured in dimensions other than those obtained in conventional M-mode echocardiography (M-mode echo).

Mathematical and geometrical models for LAV calculation using the standard long-axis, short-axis and apical four-chamber planes were devised and found to be reliable in a preliminary study using porcine heart preparations, although length (10%), area (20%) and volume (38%) were significantly and consistently underestimated with echocardiography.

Those models were then applied and correlated with angiocardiograms (ACG) in 25 consecutive patients with suspected CHD. In terms of the estimation of the absolute LAV, accuracy seemed com-

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mensurate with the number of the dimensions measured. The correlation between data obtained by TDE and ACG varied with changing hemodynamics such as cardiac cycle, absolute LAV and presence or absence of volume load. The left atrium was found to become spherical and progressively underestimated with TDE at ventricular endsystole, in larger LAV and with increased volume load. Since this tendency became less pronounced in measuring additional dimensions, reliable estimation of the absolute LAV and volume load was possible when 2 or 3 dimensions were measured.

Among those calculation models depending on 2 or 3 dimensional measurements, there was only a small difference in terms of accuracy and predictability, although algorithm used varied from one model to another. This suggests that accurate cross-sectional area measurement is critically important for volume estimation rather than any particular algorithm involved.

Cross-sectional area measurement by TDE integrated into a three dimensional equivalent allowed a reliable estimate of the LAV or volume load in a variety of hemodynamic situations where M-mode echo was not reliable.

Key words

Two-dimensional echocardiography   Left atrium   Volume estimation   Volume load   Congenital heart disease

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Estimation of left atrial volume (LAV) and left atrial (LA) volume load with the left atrial dimension (LAD) determined by M-mode echo has been accepted as a convenient and sensitive method[1-5,9,19]. However, this method is not sufficiently quantitative for predictive estimation in the individual case[6,7]. Some authors attributed this to instability in beam angulation[3,8,9] and to variation in LA geometry[3,8-11]. Estimation of volume using one-dimensional measurement may cause considerable error and misleading diagnosis[10~14].

In this study we employed two-dimensional echocardiography (TDE) to study the LA in conventional cross-sections in order to eliminate those errors[10] and to make estimations reliable enough to predict individual volume load.

Before the clinical application, a pilot study was carried out to devise calculation models and to establish the methodology. In the clinical application of those models, emphasis was placed on the comparison of those models with the conventional one-dimensional (1D) method.

This study was concerned with the development of a TDE method for the LAV and volume load estimation in patients with congenital heart disease (CHD).

I. Pilot study

Methods and materials

TDE were recorded in the long-axis plane (L), in the short-axis plane (S) and in apical 4-chamber plane (F), respectively, on seven fixed porcine heart preparations with intraluminal pressure exerted in a waterbath. The echocardiograph used was a Toshiba Medical SSH-11A with a 78° scanning angle and the transducer had 32 elements with a frequency of 2.4 MHz. TDE figures were recorded with a 35 mm camera and the perimeter of the cross-section was marked with beaded pins inserted in the heart which was held in a plastic plate fixed to the transducer. Water was forced out through the aorta by means of plaster inserted into the pulmonary vein (PV) while monitoring the intracardiac pressure with another PV cannula. Casts were excised carefully after being kept in water for 24 hours. Roentogenograms of those casts were taken in the anatomical anteroposterior (AP) and lateral views. TDE cross-sections were made by cutting the casts according to the beaded pins placed at the time of TDE recording.

Area measurements were obtained by tracing the internal perimeter of the LA in the TDE

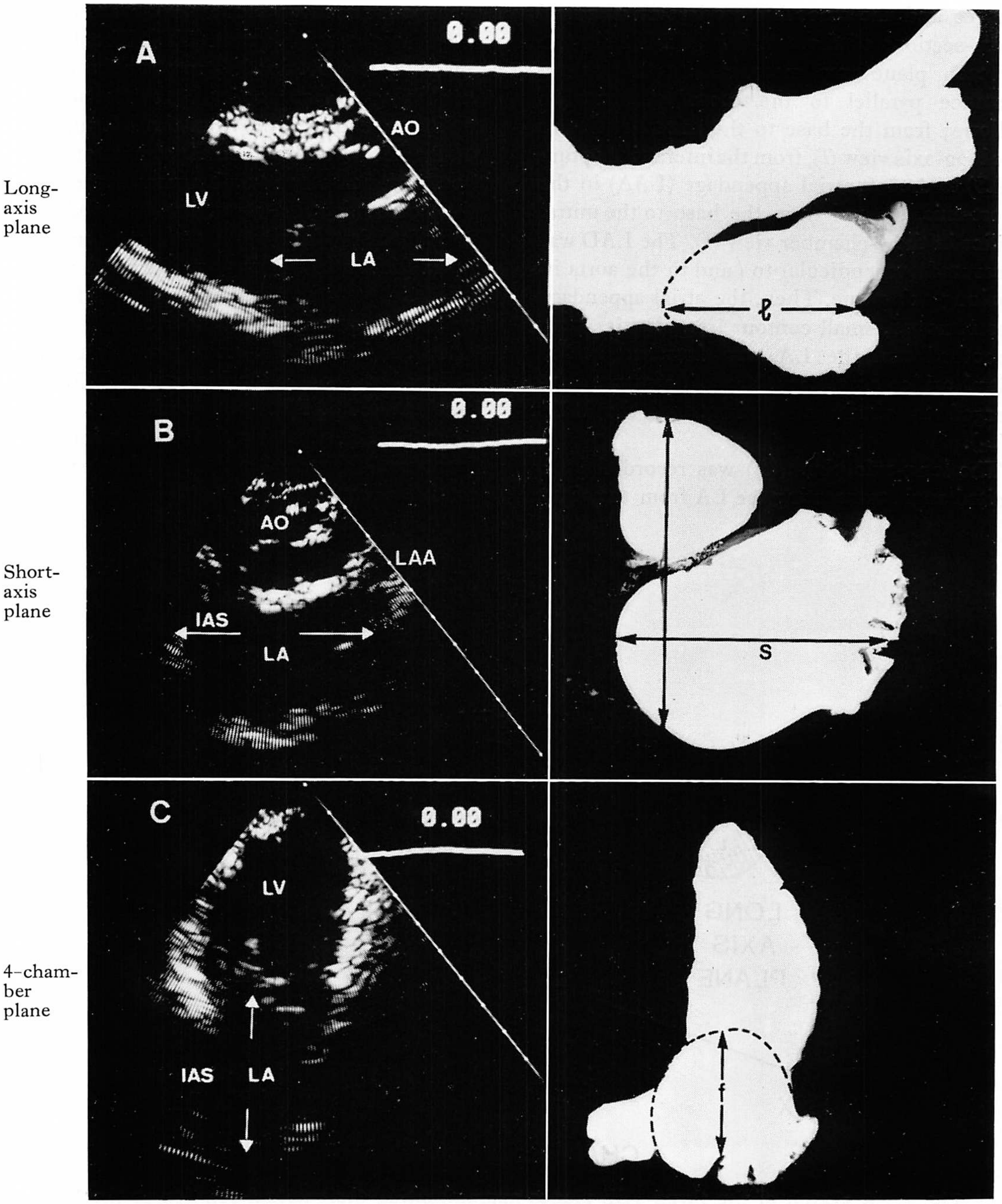


Fig. Echocardiograms of a submerged porcine heart preparation (left) **with three cross-sections of the cast** (right).

Arrows represent length measurements in each plane. Broken lines indicate the mitral valve and LA perimeter.

LA=left atrium; LV=left ventricle; Ao=aorta; IAS=interatrial septum.

images and the smoothed perimeter of actual cross-sections of the cast (**Fig. 1**). The length of each plane was measured in the longest distance parallel to the coordinate axes as follows; from the base to the mitral orifice in the long-axis view (*l*), from the interatrial septum (IAS) to the left atrial appendage (LAA) in the short-axis (s), and from the base to the mitral orifice in the 4-chamber view (f). The LAD was measured perpendicular to *l* and to the aorta in the long-axis plane. Then, the atrial appendage was removed, small contour irregularities were smoothed and the LA was detached at the mitral orifice area, then, the LA cast was submerged to obtain an estimate of the LAV (V_{wd}).

The long-axis plane (L) was recorded in a limited angle transecting the LA from the right ventricular outflow tract to the root of the aorta near the interatrial septum (IAS). The short-axis plane (S) was obtained by rotating the transducer 90 degrees, transecting both great arteries at their root and in a line from the LA appendage to the LA posterior wall. These are not the largest long- and short-axis LA measurements. The 4-chamber view, however, was recorded from a considerably wider angle and area around the apex. Although the plane was defined as orthogonal to the aforementioned planes from the apex *in vitro* study, it was not possible to reproduce consistently the exact plane *in vivo*.

Based on the relationships of the TDE cross-sections (L, S, F) to the *in vitro* LA preparations (**Fig. 2**), several volume calculation models (echo models) were devised to estimate the LAV as the following:

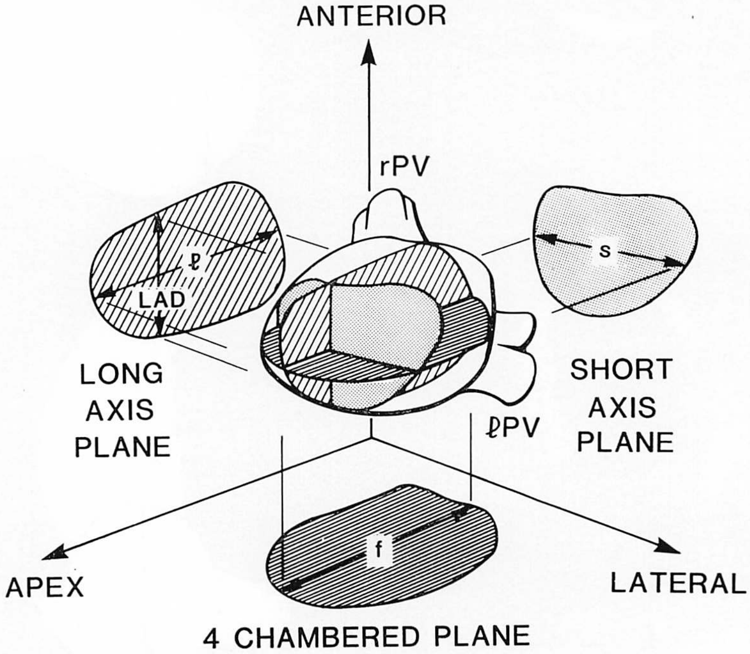


Fig. 2. A sketch of the three TDE planes approximating their actual relation to the left atrium.

Intersections of those planes form the anterior-posterior axis (TDE-AP), medial-lateral axis (TDE-ML) and base-apex axis (TDE-BA). Length was measured in each plane parallel to the axes in the TDE coordinate. These projections of cross-sections are derived from porcine heart preparations and serve as a basis for volume calculation models.

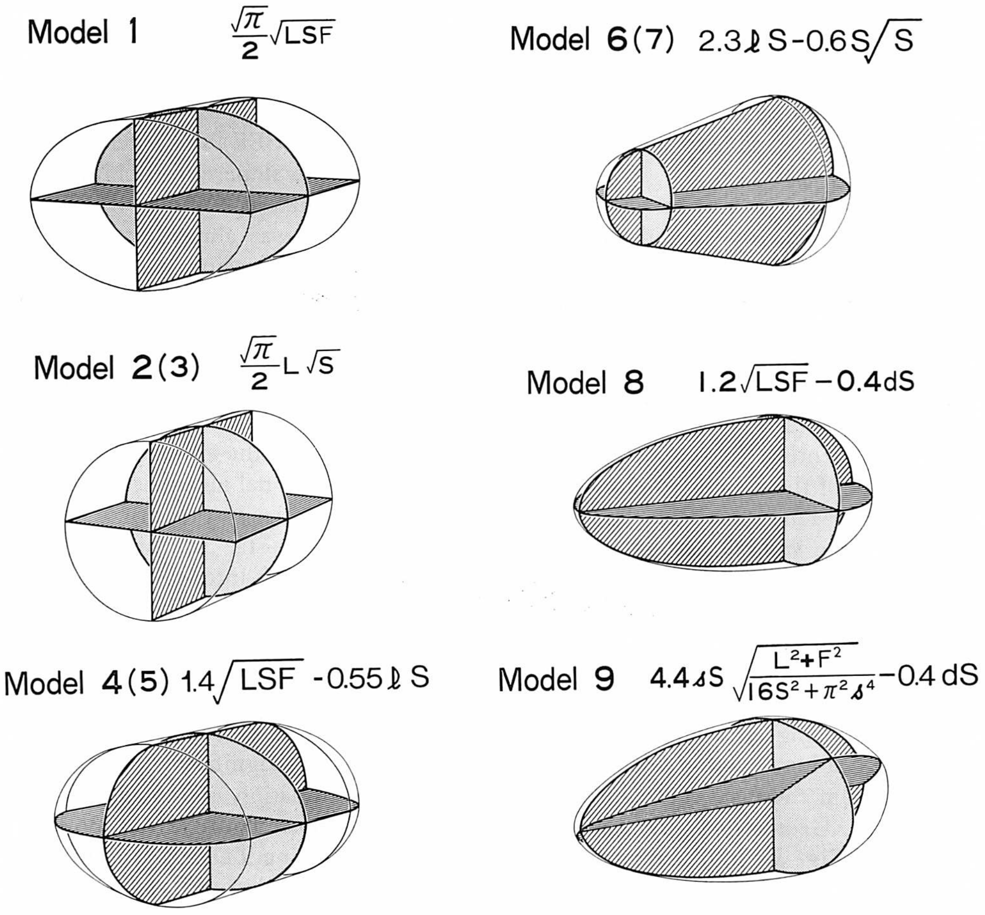


Fig. 3. Geometrical models illustrated with volume calculation formulas.

L, S, and F are area measurements and *l*, *s*, and *f* are length measurements from the long-axis, short-axis and 4-chamber planes, respectively. A " d " indicates the longer dimension between *l* and *f*.

In all figures the long-axis plane is marked by oblique hatching. The short-axis and 4-chamber planes are marked by dots and close spaced horizontal hatching, respectively.

Model 1: elliptic cylinder; 2(3): cylinder; 4(5): truncated ellipsoid; 6(7): hemispherically ended cone, the larger hemisphere having twice the diameter of the smaller hemisphere; 8: parabolic elliptic body with a right end equal to one-half of an ellipse; 9: identical to model 8 except the 4-chamber plane is not orthogonal to the long-axis plane.

Formulas for models 3, 5 and 7 are the same as for models 2, 4 and 6, respectively, with F used in place of L and *f* in place of *l*.

1. Depending on the length measurement (*l*, *s*, *f*, LAD), the volume can be calculated as:

   $$\frac{\pi}{6}\,(\text{length})^3$$

   under the assumption that length equals the diameter of a spherical LA (1D models).
2. Depending on the area measurement (L, S, F) the volume can be calculated as:

   $$\frac{8}{3\pi}\,\frac{(\text{area})^2}{\text{length}}$$

   under the assumption that the LA is a rotated ellipse around the axis of the measured length (2D models). This assumption is identical to that employed for calculation of the volume from monoplane ACG[15]. Those models, 1D and 2D, estimate the volume assuming that the unmeasured dimensions change proportionally.
3. Depending on the measurement of three or more dimensions, the volume can be calculated as an ellipsoid which has three different axes using area-length method and its modification. Volume calculations were made from these several mathematical models. Geometrical models are illustrated in **Fig. 3**. Both mathematical and geometrical models are included in this paper as 3D models.

Results

Echocardiographically measured length (*l*, *s*, *f*, LAD) and area (L, S, F) were compared to the corresponding actual cast measurements.

Linear regression equations and correlation coefficients were calculated and showed significant correlation, with low slope and elevated y-intercept but with consistent underestimation in every measurement. TDE measurements estimated only 90% of length (87%~93%) and only 80% of area (70%~81%) for each cross-section.

Volume estimation using echo models (1D, 2D, and 3D) based on actual cross-sectional measurements (V_{cs}) and on echo images (V_{echo}) were compared with the measured cast volume (V_{wd}) as a standard and then compared with each other. When V_{cs} were compared with V_{wd}, correlation seems to be better using additional dimensional measurements for volume estimation with error (SEE) and intercept becoming smaller and the slope approaching one in the correlation equation. Among the 3D models, however, there was almost no significant difference in terms of accuracy despite a significant variation in assumptions involved.

There was a tendency to underestimation even using actual cast measurements. Percent estimation (or estimated volume/standard volume ×100) of models employing ellipsoid reference figure was 88% on the average (74~97%) using actual cross-sectional measurements (V_{cs}). V_{echo} results were similar to those of V_{cs} when compared to V_{wd} as far as the aforementioned characteristics and inter-relations of methods and models. In general, however, correlation coefficients between V_{echo} and V_{wd} were a little lower than those between V_{cs} and V_{wd} and errors were larger although the difference was not statistically significant and the correlations were still highly significant.

Percent estimation of models employing an ellipsoid reference figure is 62% on the average (51%~71%) using TDE measurements (V_{echo}). Volumes calculated from biplane X-ray (Vx)[16,17] were found to be very accurate and percent estimation was 106% ($Vx=0.9\times V_{wd}+10$; $r=0.99$, SEE=2.1 m*l*).

II. Clinical study

Materials and data acquisition

Twenty-seven consecutive patients with suspected CHD who underwent both angiography (ACG) and TDE comprised this study. Age ranged from 0.5 to 39 years (average 7.4 years) and body weight from 6 to 69 kg (average 22 kg) (**Table 1**). Patients with complicating mitral valve disease (1) and atrial septal defect (1) were excluded from this study. ACG was

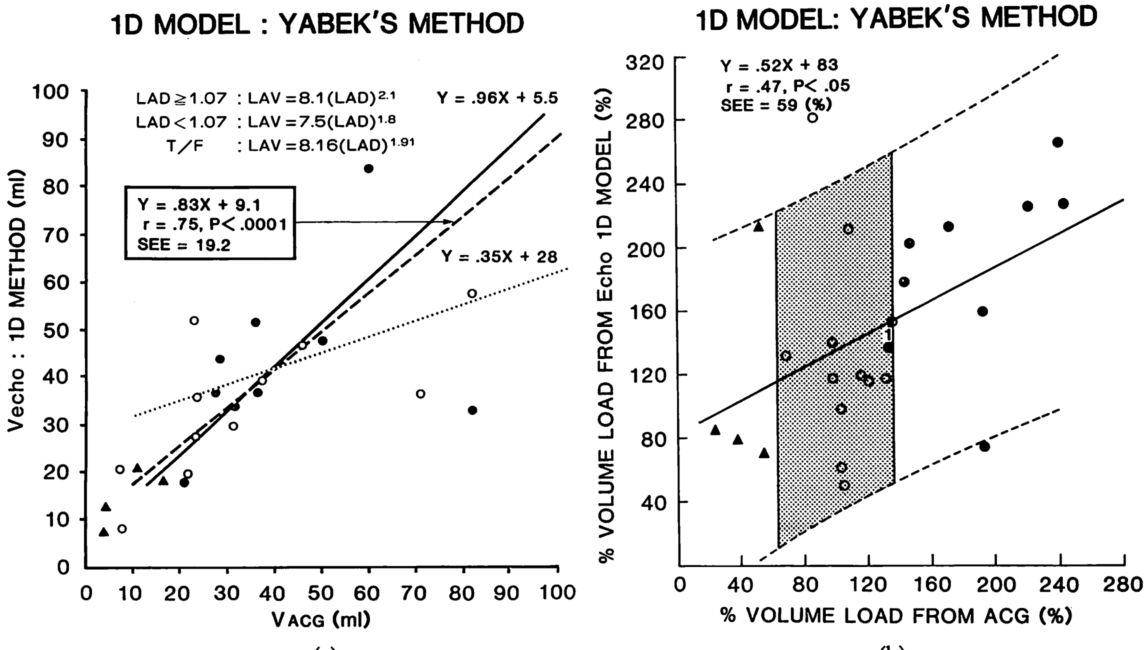
Table 1. Individual, angiocardiographic and echocardiographic data at ventricular end-systole (maximum LAV)

	Subject			Angiography			Echocardiography									
							Length (cm)				Area (cm^2)			Volume (cm^3)		
	No	Age (yr/mo)	Diagnosis	V pn (cm^3)	V acg (cm^3)	%vol. load (%)	LAD	*l*	s	f	L	S	F	(1D) Yabek	(2D) $8/3\pi S^2/s$	(3D) $2/3sL$
Volume under load (n=4)	1	1/4	TF	16.4	3.9	24	0.9	2.6	2.8	2.1	2.8	2.5	2.2	7.2	1.8	5.3
	2	9	VSD+PS	28.9	10.9	38	1.7	4.4	3.2	3.5	5.5	3.7	3.7	20.3	3.7	11.7
	3	6	TF	8.2	4.3	53	1.2	2.0	2.4	2.1	1.6	2.1	2.4	12.3	1.6	2.6
	4	7	VSD+PS	30.2	16.6	55	1.6	3.9	4.0	3.4	4.3	5.9	4.9	17.7	7.4	11.5
Volume within normal range (n=12)	5	1	VSD+PS	11.1	7.7	69	1.0	3.1	3.6	3.7	2.6	3.6	5.6	8.1	3.0	6.3
	6	2/3	TF	8.2	7.1	87	1.6	3.2	3.1	3.5	3.7	3.7	4.9	20.5	3.8	7.6
	7	5	VSD+PS	23.7	23.5	99	2.4	4.3	4.9	4.3	7.2	6.9	8.2	35.7	8.3	23.6
	8	4	VSD	23.5	23.2	99	2.1	3.7	4.6	4.2	5.9	7.1	8.1	27.3	9.4	17.9
	9	9	NS	29.7	31.1	105	2.1	4.4	3.8	3.5	6.1	6.2	4.8	29.5	8.7	15.4
	10	15	NS	78.2	81.7	105	3.1	7.9	5.1	7.8	15.7	11.1	21.9	57.5	20.7	53.0
	11	15	NS	66.9	70.8	106	2.4	6.8	5.6	5.2	14.8	10.3	9.0	36.3	16.2	54.8
	12	5	VSD	20.9	22.8	109	2.4	4.4	3.5	4.2	5.4	4.6	5.6	51.8	5.1	12.5
	13	4	NS	18.7	21.7	116	1.7	3.7	4.2	4.3	6.1	6.4	7.2	19.5	8.3	17.1
	14	9	VSD	30.8	37.2	121	2.5	4.9	4.5	3.5	10.9	7.4	6.3	39.0	10.3	32.7
	15	7	VSD	34.6	45.7	132	2.3	5.6	5.0	5.7	10.2	8.2	11.7	46.6	11.5	33.7
	16	24	VSD	71.6	97.4	136	4.0	6.9	5.7	6.0	21.9	15.5	14.2	147.3	35.6	83.7
Volume over load (n=9)	17*	1	VSD	15.5	20.9	135	1.6	5.2	4.7	3.9	6.6	6.4	6.8	17.7	7.3	20.6
	18	4	VSD	24.8	35.7	144	2.4	5.0	4.7	5.1	8.3	6.7	8.5	51.4	8.1	25.8
	19	4	VSD	19.1	28.2	148	2.2	5.2	4.3	5.3	9.5	8.2	9.7	43.6	13.5	27.0
	20	3	VSD	16.0	27.4	172	2.1	3.8	4.1	3.0	5.2	5.5	4.2	36.6	6.2	14.0
	21	6	VSD	25.8	50.0	193	2.3	4.2	5.3	3.9	8.4	9.9	5.9	47.4	15.7	29.4
	22	39	PDA	42.1	82.0	195	2.3	5.3	6.3	4.7	11.4	11.3	10.1	32.8	17.2	47.8
	23	1/6	VSD	14.2	31.3	221	2.0	4.8	3.8	5.2	7.1	6.3	9.8	33.6	8.9	17.9
	24	5	VSD	24.9	59.6	240	3.0	4.7	4.9	4.7	10.0	9.4	11.4	83.7	15.4	32.5
	25	3	VSD	15.0	36.2	242	2.1	3.9	4.1	3.3	6.0	6.0	7.6	36.6	7.3	16.6
Mean		7/4		28.0	35.1	126	2.1	4.6	4.3	4.2	7.9	7.0	7.9	38.4	10.2	24.8
±SD		8/4		18.3	25.1	58	0.6	1.3	0.9	1.2	4.5	3.0	4.1	27.9	7.1	18.3

All cases (n=25) are divided into volume underload (n=4), within normal range (n=12) and volume overload (n=9) groups according to the observed and expected normal LAV ratio (V_{ACG}/V_{pn}) reported by Graham et al.[18) Normal range for infants differs from that of children. Infant number 17 is in the volume overload group.

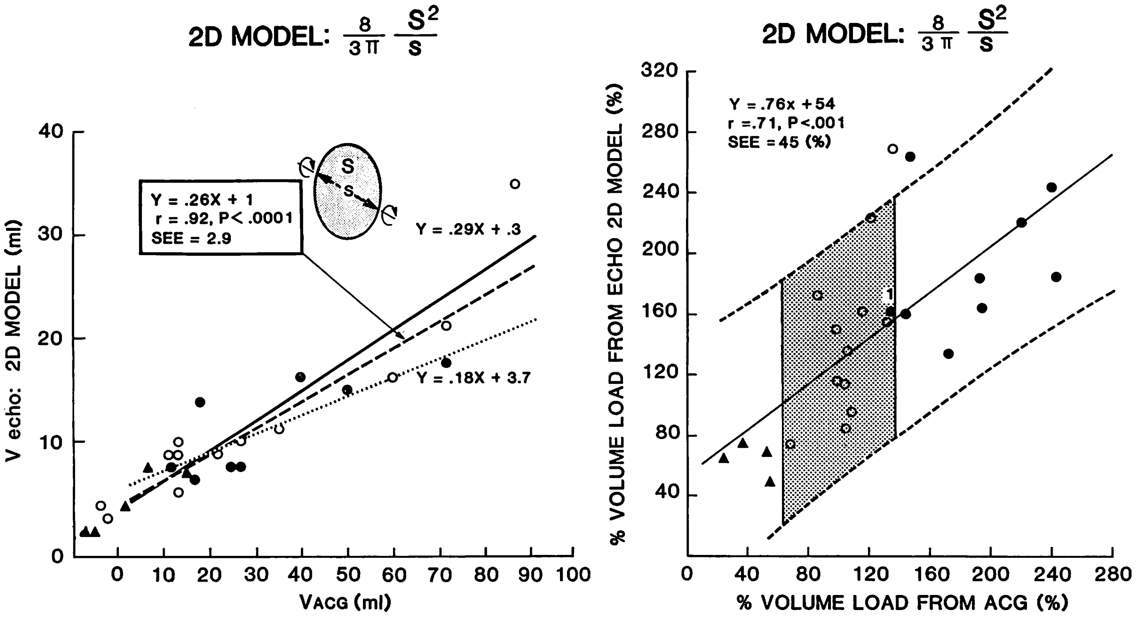
Diagnosis was derived from angiocardiographic or anatomical findings at operation. NS includes insignificant findings such as a functional murmur, minimal PS or insignificant VSD.

VSD=ventricular septal defect; PH=pulmonary hypertension; TF=tetralogy of Fallot; PDA=patent ductus arteriosus; PS=pulmonary stenosis.



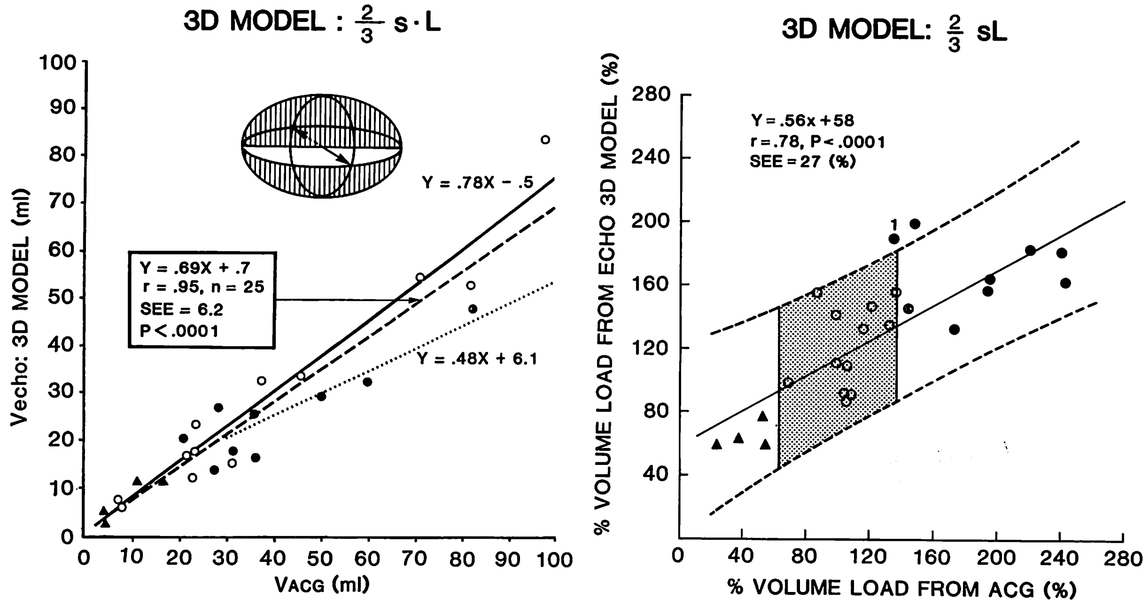
(a) (b)

Fig. 4



(a) (b)

Fig. 5



(a)

(b)

Fig. 6

Fig. 4a. Comparison of echocardiographically estimated LAV using the echo equations with V_{ACG} as a standard.

The solid line shows regression for the normal LA volume load group and the dotted line for the volume overload group. The dashed line represents regression for the entire groups.

Fig. 4b. Comparison of echocardiographically estimated LA volume load with ACG derived standard.

After the correction of V_{echo} for underestimation using regression equations for V_{ACG} and V_{echo}, both axes are divided by V_{pn} to show the distribution of the indexed LA volume load derived from TDE. These indices are compared to the same values derived from ACG.

Fig. 5a and 5b: same as Fig. 4a and 4b.

Fig. 6a and 6b: same as Fig. 4a and 4b.

Curved lines in Fig. 4~6 show 90% confidence limits and dotted area indicates the normal range reported by Graham et al. (Normal range for infants differs from that of children and the infant marked " 1 "on figures 4b, 5b and 6b is in the volume overload group).

3D models show an exellent correlation between echo and angio estimations of LAV. Figure on the left (Fig. 6a) shows that the LAV is progressively underestimated in the LA volume overload group as the LAV increases. Nevertheless, LA volume load estimation is satisfactory in differentiating the patients with the diminished LAV, those with the LAV in the normal range and the group with the increased LAV (Fig. 6b).

carried out at the end of the diagnostic catheterization with the patients in a supine position. Contrast material (1 m*l*/kg) was injected into the right heart (RV5, PA20) and the levo-phase was filmed at 60 frames per sec in the anteroposterior (AP) and in the left lateral (LL) views. TDE was recorded with an 8 mm cine camera in the L, S and F views with the patients in a supine position immediately after the ACG for the last 17 cases and within 24 hours of the ACG for the others. Patients were all in regular sinus rhythm and there was no remarkable hemodynamic change between examinations other than heart rate (HR). Both studies were carried out by one of the authors without knowledge of the other examinations, and the time between examinations was shortened to eliminate examiner bias and hemodynamic changes, respectively.

Average measurements of several consecutive ACG cycles were used according to the method of Dodge[16)] and Sauter[17)] to the calculate the LAV without the LAA (V_{ACG}). Magnification was corrected by using a metal marker of known size filmed at the end of the ACG. The predicted normal LAV (V_{pn}) at ventricular end-systole were calculated using the equation reported by Graham et al.[18)] According to the ratio of the two, or $V_{ACG}/V_{pn} \times 100$ (percent volume load from the ACG), patients were divided into three groups: volume overload ($n=9$), normal range ($n=12$) and volume underload ($n=4$) (**Table 1**).

Measurements on the TDE were carried out at maximum, or at the time of a R wave of the simultaneous ECG and at minimum, or a d-point of M-mode echo marked on the ECG. The internal cardiac perimeter was determined at a constant timing mark on the ECG and traced onto the paper from TDE images on 8 mm cine films. Each TDE image was identical to that observed in the pilot study and the same area and length measurements were recorded (**Fig. 1**). In some instances, it was necessary to review multiple frames to measure accurately internal cardiac perimeter. Measurements were averaged for more than five consecutive cycles to decrease respiratory influence and technical error. Magnification was corrected according to the calibration on the TDE.

The heart rate (HR) differed significantly ($p<0.001$) on each examination as follows: On the ACG 123 ± 25/min, and on the TDE 94 ± 21/min.

To analyze the influence of HR, patients were divided into two groups of greater HR difference (HR difference$\geqq 28$/min, $n=12$) and smaller HR difference (HR difference<28/min, $n=13$). In each group ACG and TDE data were correlated and compared with each other. There was no significant difference in the two groups in terms of correlation coefficient and the extent of estimation. All patients were therefore treated as the same irrespective of HR difference.

Methods

1. Echo models (1D, 2D, 3D) devised in the pilot study were correlated with the ACG as a standard and then compared with each other.
2. Effects of cardiac cycle, the absolute LAV and the absence or presence of volume load on those echo-angio correlations were studied and compared among the echo models.
3. Hemodynamic changes in LA geometry were studied by comparing the contours of three orthogonal TDE figures[19)] and of biplane ACG images using the following parameters;
    a. Ratio of major axis to minor axis (axis ratio) in which minor axis is defined as area measurement divided by major axis (length measurement) assuming the image an ellipse. This ratio is calculated as:

$$\frac{\pi}{4}\,\frac{(\text{length})^2}{\text{area}}$$

    b. Ratio of area measurements of two orthogonal planes (area ratio) which gives the spatial relationship of the axes perpendicular to the common measured orthogonal axis.
4. These cross-sectional areas were also measured in ten normal children by two different examiners to assess intra- and inter-examiner reproducibility.

Results

1. Echo-angio correlation in LA volumetry

The echo derived LAV was correlated with ACG derived LAV at end-systole (n=25, $V_{ACG}=35\pm25$ m*l*, mean±SD). Findings were similar to those obtained in the pilot study. In general, echo models using more dimensional information had higher correlation coefficients, smaller estimate errors and better correlations with V_{ACG} (**Figs. 4A, 5A, 6A**).

Although length (*l*, s, f, LAD) or area (L, S, F) measurements themselves also correlated fairly well with V_{ACG} on the whole, volume estimation using an individual echo measurement was unsatisfactory because of significant overlap. Cubing the measurement, as in 1D models, failed to improve the correlation because this procedure cubes the errors as well.

Among 3D models, there is only a small difference in terms of accuracy although the algorithms used varied from one model to another and bore little resemblance to actual LA contour. Area in the 4-chamber view (F) correlated poorly with V_{ACG}; 3D models using this measurement (models 3, 5, 7) showed a poorer correlation with V_{ACG} than the same models using area obtained in the long-axis view (L) (models 2, 4, 6).

As shown in the pilot study, a 4-chamber plane may not be orthogonal to the long-axis plane in this clinical study. This prompted us to devise Model 9 which calculates volume without assuming the two planes as orthogonal. However, this model failed to improve the correlation indicating that the problem may not be the relation to the other planes but the plane itself. Area-length method a had better correlation than any other complicated models using more variables or measurements. This may not be due to model fitness but to the fact that it was the same method employed to calculate the standard V_{ACG}.

2. Effect of various hemodynamics on echo-angio correlation

a. Effect of cardiac cycle

At ventricular end-diastole (minimum LAV), echo-derived LAV (V echo) were correlated with V_{ACG} and compared to that found at ventricular end-systole (maximum LAV) (end-diastole: n=25, $V_{ACG}=10\pm7.8$ m*l*). There was no consistent or significant difference between the echoangiographic correlation coefficients at the two phases of the cardiac cycle in any of the echo models. However, the extent of estimation of volume by echo models, namely percent estimation, was found to be decreased at end-systole and differed significantly on the average from that of the end-diastole in almost all echo models. Since this might be due to the absolute volume change accompanying the cardiac cycle, 12 points of similar V_{ACG} (range from 13 m*l* to 25 m*l*, 6 end-systole and 6 diastole) were chosen to compare the effect of cardiac cycle on percent estimation.

There was no consistent or significant effect of cardiac cycle on percent estimation in this volume range. Since the same was true when the range was widened to 20 points (volume range from 11 m*l* to 35 m*l*, 10 end-diastole, 10 end-systole), the effect of cardiac cycle on percent estimation observed here was thought to be mainly due to the absolute volume changes of the cardiac cycle.

Unlike the case with volumetry of the ventricle, the measurement of the minimum LAV has less clinical use. Therefore subsequent analysis was performed only at end-systole (maximum LAV).

b. Effect of absolute LAV

Patients were divided into two groups according to V_{ACG}; smaller LAV ($V_{ACG}\leqq28$ m*l*, n=12, $V_{ACG}=16\pm8.2$ m*l*) and larger LAV ($V_{ACG}>28$ m*l*, n=13, $V_{ACG}=53\pm22$ m*l*). Correlation of V echo to V_{ACG} was compared between those groups. Although there was no consistent or significant difference in correlation coefficients between the groups, percent estimation decreased consistently in the larger volume group in every echo model. Among the echo models, this tendency was prominent in Yabek's[8] method as well as with the area or length measurement alone in which the difference became significant.

At volumes less than 10 m*l* (V_{ACG}), every echo model showed a tendency to increase the percent estimation as well as the deviation. This may result from a proportional increase in measurement error as the volumes become smaller. However, other factors might be involved such as change in LA contour and change in spatial relation of TDE planes to the LA with the cardiac cycle. V_{ACG}, used as a standard in this study may also be affected by a change in absolute volume.

c. Effect of volume load

In terms of correlation coefficient, there was no consistent or significant difference among the groups of volume load in most of the echo models. However, when percent estimation was plotted as a function of percent volume load from ACG, all echo models showed a progressive underestimation of volume with increasing volume load, although on the average the difference in percent estimation was not statistically significant except with the method of Yabek[8] and with area or length measurement alone.

Since the average LAV is identical in the normal range group (39±28 m*l*) and the volume overload group (41±18 m*l*), the degree of volume load itself might be responsible for this tendency to underestimation. In order to estimate the volume load by TDE, V_{echo} were corrected for underestimation using correlation equation with V_{ACG} and then divided by individual V_{pn} to obtain a closer estimation of percent volume load as measured on ACG. Percent volume load from echo = corrected $V_{echo}/V_{pn} \times 100$.

The echo estimation of percent volume load was compared with that of ACG as the standard for every echo model (**Figs. 4B, 5B, 6B**). With 2D and 3D models the estimation of volume load corresponded well to that of ACG. With 1D models and Yabek's method, on the other hand, individual predictive evaluation was unreliable because of considerable overlap and wide deviation, although group averages were significantly different.

3. LA geometric change with changes in hemodynamics.

At end-systole the LA averaged 4.6±1.3 cm in base-apex (BA) axis, represented by dimension *l*; 4.3±0.9 cm in medial-la teral (ML) axis which was dimension *s* and 2.1±0.6 cm in the anteroposterior (AP) axis or LAD.

With a change in the cardiac cycle, the dimension ratio consistently became smaller at end-systole in all of the planes studied. (ACG–AP: $p<0.005$, TDE–L: $p<0.001$, TDE–S: $p<0.02$). However, the ratio remained greater than one through both phases of the cardiac cycle indicating that all images became more circular at end-systole while keeping the original oblate contour, and that the LA tended to became more spherical at ventricular end-systole. The same tendency was found in studying the area-ratio; at ventricular end-systole the AP axis increased more than the RL axis in ACG ($p=0.07$) and the BA axis extended significantly more than the ML axis in TDE ($p=0.04$).

With a change in absolute volume, namely between groups of the larger LAV and the smaller LAV, ACG–AP ($p=0.06$) and TDE–S ($p=0.07$) planes showed a tendency to become circular with the increased LAV. In TDE, the BA axis ($p=0.03$) and the AP axis ($p=0.15$) increased more than the ML axis in the larger LAV group. With increasing volume load, there was a slight tendency for the images to become more circular in ACG–AP ($p=0.15$) and ACG–LL ($p=0.13$) planes. The ACG–AP axis showed a tendency to become larger and to approach the length of the other axes. In contrast, TDE measurements did not change significantly with volume load.

Discussion

Volume underestimation

LV volumetry has been extensively studied by TDE[10,23~29] but LA volumetry based on TDE has not been comprehensively reported[21]. In order to establish the methodology and to ascertain the validity of TDE in LA volumetry, a pilot study was carried out using porcine heart preparations. In this study, volume estimation based on actual cross-section or on TDE images correlated well with standard measurements. However, in contrast to studies of the LV[10,24,26,27], standard volumes were consistently and significantly underestimated by TDE, and this was thought to be mainly due to the following two factors:

1. The area used for volume calculation did not necessarily include the largest cross-section as assumed in the calculation models. As seen in the pilot study, planes measured by TDE were often less than the maximal cross-section; deviated medially as in the long-axis plane, apically as in short-axis plane and anteriorly as in the apical 4-chamber plane (**Fig. 1**). The average estimation of volume using the ellipsoid reference model based on actual cast cross-sections was 88%, this underestimation possibly related to assumptions inherent in the calculation models themselves. In addition, since the projected image of the ACG is always equal to or bigger than the largest cross-section, the calculated volume using cross-sections may further underestimate volume compared to values obtained with the ACG as a standard.

2. Echocardiographic visualization of a cardiac chamber differs from that obtained from the submerged cast of the chamber. In the cast study, problems inherent to TDE, such as emergence of side lobes as a result of poor lateral resulution30), mixing resonance echoes and the presence of trabeculations all act in favor of overestimation. On the other hand, these same factors cause underestimation of chamber size in the porcine heart study as in clinical applications30). TDE measurements underestimated equivalent length by 10% and area by 20% on the average. This underestimation *in vitro* is consistent with the finding reported by others28,29).

In contrast to the exact delineation of the chamber size in the experimental studies using casts31,32), in most clinical situations chamber measurements are underestimated by TDE8~10,23,25,33). In this regard, this pilot study using porcine heart preparations might simulate clinical applications better than the cast study. In the clinical study, echo models using the ellipsoid reference figure underestimated ACG volume by 47% on the average. This underestimation was thought to be explained mainly by the two aforementioned factors found in the pilot study.

Cross-sectional characteristics

For LA volumetry by TDE, the long-axis, short-axis and 4-chamber planes were chosen for the following reasons; first, all of them are fundamental in clinical practice and are presumed to be more reproducible than other special cross-sections. Secondly, the LA is easily detectable and imaged in one frame in each of the above planes. Thirdly, these three planes are supposed to be orthogonal19), this assumption providing the basis for calculation models and geometric analysis. In the clinical study, two-dimensional LA images in ACG and TDE became more circular in ventricular end-systole with larger absolute volume and in the presence of volume load, suggesting that LA geometry becomes more spherical with increased volume load. This is consistent with the finding that the LA becomes flattened with decreased volume load (pancake effect)13,14).

In addition, among the three assumed coordinate axes (**Fig. 2**) which are the intersection of the three TDE planes employed here, the anteroposterior axis, or LAD, paralleled most specifically the volume change of the LA as reported by others2,3,8). This finding is in accord with the result that the 4-chamber plane, which does not contain this axis, showed the poorest correlation with LAV. Several other shortcomings of the 4-chamber plane include poorer interexaminer reproducibility23), poorer image quality related to the distance from the transducer12), and perimeter drop-out caused by pulmonary veins. The other two cross-sectional planes, namely the long- and short-axis views, can be imaged by rotating the transducer without detaching it from the patient and therefore are more reliable in their perpendicularity and reproducibility.

Attempts were made to minimize reported wide variation in TDE measurements by selecting specific TDE planes familiar to the examiner. In our clinical study inter- and intra-examiner percent error in area measurement was within 10% for every plane. There was no significant difference in percent error for all planes, although 4-chamber view measurements showed slightly more variation. Twelve of 25 patients in this study were reevaluated by TDE one to six months after the intial study. Any change in percent volume load from TDE (3D model) of those patients was found to be consistent with the clinical course including surgical correction.

Effect of hemodynamics on LA volumetry by TDE

All echo models had a tendency to underestimate LA volume at ventricular end-systole, with larger absolute volume and in the presence of volume overload. Among the echo models, this tendency was more obvious in 1D models than in 2D or 3D models and became significant with length or area measurements alone and with Yabek's method8). With methods where the second or third dimension was not measured, volume was underestimated progressively with increasing volume.

The spatial relation of TDE cross-sections to the LA is important because increasing underestimation is most conspicuous in the cardiac cycle with a change in volume, geometry and position in respect to the TDE transducer. Since TDE cross-sections are not necessarily constant in their relationship to the heart during the cardiac cycle, we focused on the ventricular endsystolic phase to measure the maximum LAV in order to differentiate volume loads. Nevertheless, there are other possible factors affecting LA volumetry with TDE such as LA geometrical change, heart rate change and intra- and inter-examiner reproducibility.

Consistent with the finding of greater underestimation in hemodynamic groups with the increasingly spherical LA, the change in geometry of the LA may be partly responsible for this underestimation. Indeed, the larger the volume, the more difficult to transect the LA at its equator or in its largest cross-section with TDE12,34). The same finding was reported in measuring the LV with M-mode echo9). In addition, with the same extent of deviation from the equator, underestimation is more likely in the spherical LA with volume load than in a flattened LA without volume load.

Geometric configuration was reported to be not critical when volumetry was carried out with angiographic projection images35). The LV geometry and its spatial relation to the X-ray beam are assumed constant by Sauter et al15) as in studies of the RV by Arcilla et al35). Unfortunately, none of these assumptions is true in volumetry using TDE. In this clinical study, changing LA geometry resulted in a fluctuating percent estimation in length or area measurement alone and 1D models and necessitated different correlation equations with changes in hemodynamics36). The use of one correlation equation for these models regardless of the individual hemodynamics increases error and invalidates the estimation. This means that these measurements are inadequate by themselves for volume estimation12).

Yabek et al8) attempted to deal with the problem by initially using LAD to the aortic diameter ratio (LAD/AO) and allotting a correlation equation for each group. We nevertheless continued to note a tendency to change in percent estimation and large error as was the case in 1D models (**Fig. 4**). In LA volumetry depending on area measurement (2D or 3D models), a geometric change might also affect LA measurement in contrast to lesser effects on measurement derived from ACG. Nevertheless, volume and volume load estimation were found to be reliable in models depending on area measurement (**Figs. 5, & 6**). Strictly speaking, however, the roentogenographic projection method for volume estimation is not free from the influence of hemodynamics, especially of absolute volume22). In LV volumetry, Graham et al18) used different correlation equations above and below 15 m*l*, and in LA volumetry, Arcilla et al37) reported that the ACG method used by Sauter17) as the standard might underestimate volumes under 20 m*l*. Standards derived from ACG might actually underestimate at smaller LAV and might explain the tendency to acute increase in percent estimation at smaller LAV found with TDE. This remains conjectual until a reliable volume estimation method becomes available.

Effect of heart rate

There was a significant difference in HR at the time of ACG as compared to TDE although every effort was made to minimize the hemodynamic change between studies. In volume studies on the LA, HR was suggested as one of the decisive factors after body size[18,37]. However, we found no difference in echo-angio correlation irrespective of HR difference. Contrast injection might increase volume[38] and counteract the effect of tachycardia. Conversely, tachycardia might be a response to the mechanical effect of contrast injection or acute volume load.

In any case, changing HR did not seem to generate a significant difference in calculated LAV because the constant for HR in the equation was very small[37]. This might be due to the fact that the cyclic volume change of the LA is responsible for only 38% of the total stroke volume[39] as two-thirds of stroke volume passes through a LA acting merely as a conduit. This might explain the minimal effect of HR on LA volumetry in contrast to the situation in LV volumetry[9,27,49].

Comparison among echo models

M-mode echo is more reliable than TDE as far as accuracy in axial linear measurement. However, greater assumptions and errors occur when M-mode echo is used for volume estimations[10,12,20,36]. On the other hand, as shown in this pilot study, TDE measurement presents more problems than M-mode echo[30]. Nevertheless, actual measurement of the second or third dimension succeeded in greatly minimizing assumptions and errors as compared to 1D models[3,10,14,23,36]. Cross-sectional area measurements are necessary for satisfactory clinical accuracy regardless of the particular model or assumptions used[22,37]. However, area measurement should be transformed into a 3D equivalent with substitution in appropriate equations when estimating volume[8].

LAD measurement was a sensitive way to estimate LA volume or volume load because its axis paralleled hemodynamic changes better than the other axes[3,8]. However, 1D measurement alone showed only a qualitative difference on the average in groups and was thought to be unreliable when any hemodynamic or geometric change occurred[3,11,14]. Cross-sectional area measurement by TDE integrated into a 3D equivalent allowed a reliable estimate of LA volume or volume load in a variety of hemodynamics in a clinical setting.

超音波心断層法による先天性心疾患の左房容積計測

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超音波心断層法（TDE）を用いて，Mモード法では得られない角度から，左房容積および左房容量負荷を推定する方法を考案，検討した．

1. 基礎実験：ブタ摘出心を水没して断層心エコー図（TDE）の長軸，短軸および4腔断層図記録を行った後，鋳型をとって左房容積を求めた．このTDEの1次元（軸長）および2次元（面積）のデータを鋳型の実測値と比較する一方，これらから左房容積を求める各種の計算式を考案した．TDE計測値は実測値と良く相関したが，常に一定の有意な過小評価（軸長10%，面積20%，容積38%）を示した．

2. 臨床応用：TDEによる左房容積推定を先天性心疾患連続25症例に行い，心血管造影法（ACG）によるものと比較した．

その結果，左房容積推定において，TDEとACGとの相関関係は，①心周期，②容積の大小，および③容量負荷の有無により影響され，容量負荷を有する大きな左房であるほど，左房は心室拡

張期に球型に近づき，そのため TDE では容積を過小評価することがわかった．しかし，計測する次元が多い程，この影響が薄れて推定が正確になる傾向があり，2次元(面積)以上の計測に基づくモデルでは，かなり正確な左房容積および容量負荷の推定が可能であった．

結論：3次元モデルの間では，用いたアルゴリズムにかなりの差があるにもかかわらず，推定の正確さや信頼性の上で差がみられないことから，左房容積推定において，正確な断面積計測が特定のアルゴリズムよりもはるかに重要であると考えられた．TDE を用いた断面積計測に基づく左房容積推定法は，M モード法によるものと異なり，循環動態による影響が少なく，臨床上有意義と考えられた．

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