
原 著

Transesophageal M-mode Echocardiography: Its Clinical Application for Evaluation of Left Ventricular Function Soon After Cardiac Surgery

TOMOHIKO MURAGUCHI

The 2nd Department of Surgery, Osaka City University School of Medicine
(Director: Prof. Dr. KATSUJI SAKAI)

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The 2nd Department of Surgery, Faculty of Medicine Kyoto University
(Director: Prof. Dr. YORINORI HIKASA)

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Introduction

With recent improvements in cardiovascular surgery more patients with advanced heart disease have become candidates for surgical treatment. In such patients, there is frequently a marked reduction in left ventricular function after open heart surgery due to the operative procedures, anesthetic techniques and cardiopulmonary bypass, including cardioplegic cardiac arrest and myocardial protection. A more accurate understanding of left ventricular function is essential to prevent postoperative low cardiac output syndrome, which is one of the serious complications of open heart surgery.

Systemic pressure, central venous pressure, left atrial pressure and cardiac output, which are the commonly used parameters of the patient's hemodynamic state, do not always provide a complete picture of left ventricular function. On the other hand, echocardiography is now being extensively used in the diagnosis of cardiac diseases and the assessment of cardiac function^{1,7,8,15,39,40,53}. Indeed, the results of echocardiography correlate well with those of angiocardiology^{3,9,12,28,38,41}, which is believed to be the most reliable method at the present time for the evaluation of left ventricular function.

However, as conventional echocardiography involves the anterior positioning of the transducer, thus interfering with the operative field, it is not usually performed during cardiac surgery. Moreover, its images soon after operation are of poor quality, because of the presence of the air in the anterior mediastinal space.

The author has introduced transesophageal echocardiography and assessed its clinical appli-

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Present address: The 2nd Department of Surgery, Osaka City University School of Medicine, 1-5, Asahi-machi, Abeno-ku, Osaka, Japan.

cation in the evaluation of left ventricular function soon after cardiac surgery.

I. CLINICAL APPLICATION OF TRANSESOPHAGEAL ECHOCARDIOGRAPHY.

Patients and Methods

Transesophageal transducer: A nonfocused transducer (5 MHz, 10 mm in diameter, Aerothec, U.S.A.) was used in this study after its edges had been made more blunt for easy swallowing. The transducer was attached to the tip of a selective bronchography catheter (Machida, FBC, No. 60073) to permit sufficient control of the transducer position and beam direction. With this catheter, the transducer can easily be introduced into the esophagus, angled at a point about 6 cm from the tip and rotated in any direction (Fig. 1).

Patients: Thirty patients, 13 males and 17 females, were examined by transesophageal echocardiography. Their ages ranged from 19 to 71 years ($\text{avg}=46.2\pm13.4$). Their diseases were; atrial septal defect (5), partial endocardial cushion defect (1), ventricular septal defect (1), mitral stenosis (6), mitral regurgitation (2), aortic regurgitation (3), ischemic heart disease (3), left atrial myxoma (1), dissecting aneurysm of the ascending aorta (2) and cerebrovascular disease (6).

Introduction of transducer: After the patients had fasted for 2-3 hours, scopolamine (0.01 mg/kg) was administered intramuscularly 30 minutes before the examination. The pharynx was anesthetized with 10 ml of 2% viscous xylocaine, and the transducer, which passed easily through the cricopharyngeal sphincter, was swallowed; this technique is similar to that for gastrofiberscopy. At a point about 35 cm from the mouthpiece used as a bite block, an aortic valve

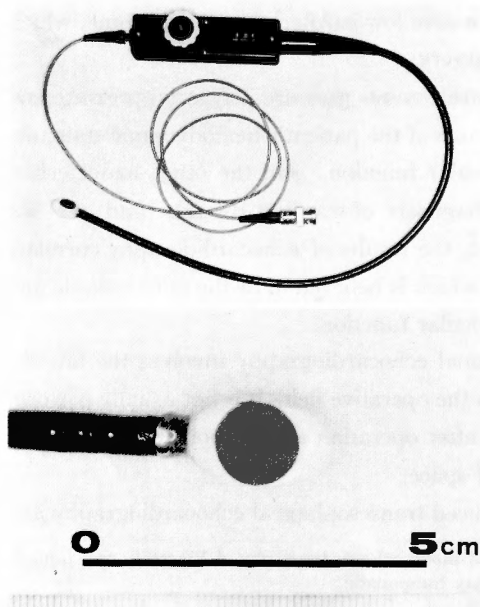


Fig. 1. Transducer developed for transesophageal echocardiography by author. The transducer position and beam direction can be altered by controlling the handle of the catheter.

echogram was easily obtained, and confirmed the position of the transducer. From this "key position", the transducer was advanced and/or rotated to obtain various echograms. Usually transesophageal echocardiography was performed in the supine position, but the right semilateral decubitus position was sometimes necessary to obtain the left ventricular echogram. At the same time all patients were examined by conventional anterior echocardiography (transducer: 3.5 MHz, 10 mm in diameter, Aerothec, U.S.A.).

The echocardiographic apparatus used was Aloka-SSD 110 S or Toshiba-01 A, and echograms were recorded on a strip-chart-recorder (Aloka-SSZ 91) or 35 mm film at a speed of 50 or 100 mm/sec combined with Lead II of the electrocardiogram.

Results

Transesophageal Echocardiography.

At a point about 35 cm from the mouthpiece, the aortic valve echogram was clearly recorded. Figure 2-A is the echogram of the aortic root, showing the left atrium, aortic valve and right ventricular outflow tract as a mirror image of the conventional anterior echocardiogram. Right and non-coronary aortic cusps are clearly identified. From this "key position", a slight clockwise rotation of the transducer makes it possible to obtain an atrial septal echogram (Fig. 2-B). An advance of about 1 cm with counter-clockwise rotation affords scanning of the anterior mitral leaflet (Fig. 2-C). Further advance with counter-clockwise rotation provides a left ventricular echogram. As shown in Fig. 2-D, the interventricular septum and posterior left ventricular wall can be seen. Figure 2-E is an echogram of the anterior and posterior left ventricular walls.

Comparison of Efficacy of Anterior and Transesophageal Echocardiography.

Transesophageal echocardiography was compared with anterior echocardiography in 30 patients (Fig. 3). With anterior echocardiography, an atrial septal echogram could be obtained in 5 patients (16.7%), an aortic valve echogram in 22 (73.3%), an anterior mitral leaflet echogram in 24 (80.0%) and a left ventricular echogram in 23 (76.7%). With transesophageal echocardiography, an atrial septal echogram could be obtained in 30 patients (100%), an aortic valve echogram in 30 (100%), an anterior mitral leaflet echogram in 30 (100%) and a left ventricular echogram in 26 (86.7%).

Comparison of Echocardiographic Measurements Obtained From Anterior and Transesophageal Echocardiography.

Various measurements were compared in 20 patients (Fig. 4). The correlation coefficients of the various measurements are as follows: aortic dimension ($r=0.836$), left atrial dimension ($r=0.984$), C-E amplitude of anterior mitral leaflet ($r=0.977$) and diastolic descent rate of anterior mitral leaflet ($r=0.978$). The end-diastolic left ventricular dimension measurement of patients without paradoxical movement of the interventricular septum was slightly greater on transesophageal than on anterior echocardiography, but the correlation was also good ($r=0.898$).

Transesophageal Echocardiograms in Various Heart Diseases.

Mitral stenosis with left atrial thrombus:

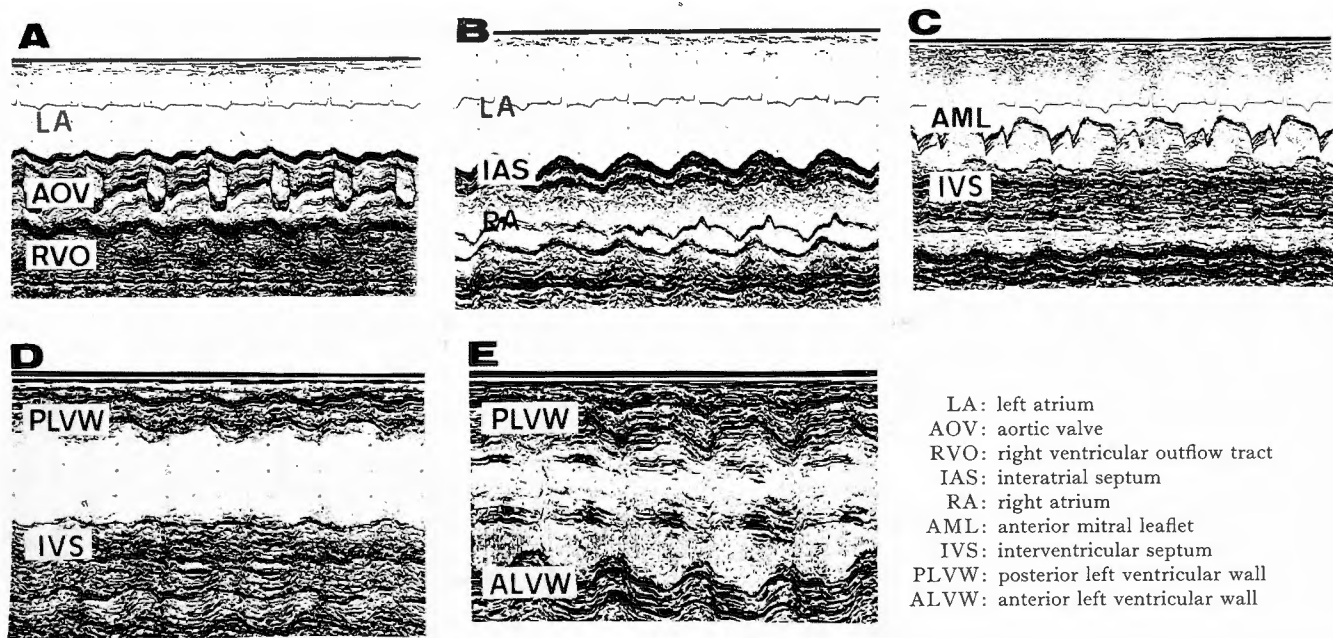


Fig. 2. Transesophageal M-mode echocardiograms obtained.
 A: aortic valve echogram, B: atrial septal echogram, C: echogram of anterior mitral leaflet, D: echogram of posterior left ventricular wall and interventricular septum, E: echogram of posterior and anterior left ventricular wall.

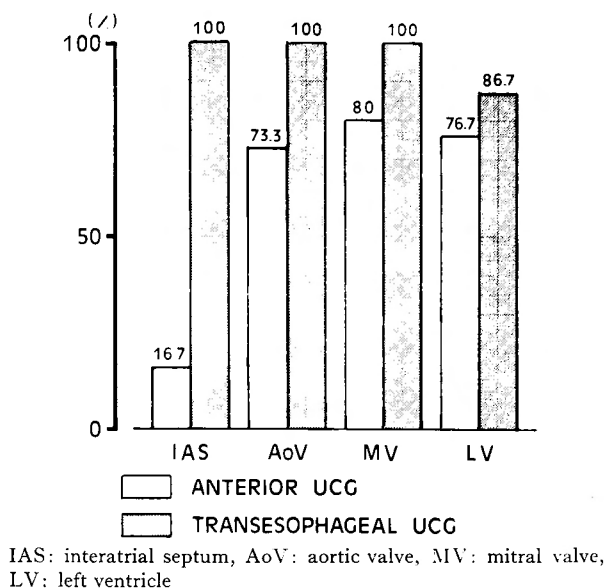


Fig. 3. Comparison of rates of detection between anterior and transesophageal echocardiography.

Figure 5 is the transesophageal echograms of a patient with mitral stenosis; these show an increased left atrial dimension and a reduced diastolic descent rate. A large band of multiple linear echoes is seen on the posterior left atrial wall. At surgery a large thrombus, which was lying on the posterior left atrial wall, was removed. The author had an opportunity to observe a mobile thrombus in the left atrium. This thrombus was floating in the left atrial cavity (Fig. 6).

Left atrial myxoma:

Figure 7 shows the preoperative echograms of a left atrial myxoma seen as cloudy echoes moving in the left atrium. The myxoma almost filled the mitral orifice during diastole. At operation, a myxoma, weighing 30 gm and attached by a stalk to the interatrial septum, was found and resected.

Mitral regurgitation due to ruptured chordae tendineae:

Increases in left atrial dimension, left ventricular end-diastolic dimension and diastolic descent rate of the anterior mitral leaflet indicate mitral regurgitation (Fig. 8). In early systole, ruptured chordae tendineae of the mitral leaflet prolapsed into the left atrium (arrow in middle panel).

Aortic regurgitation:

Figure 9 shows increased aortic dimension, diastolic separation of the aortic valve, fine fluttering of the interventricular septum and anterior mitral leaflet, and increased left ventricular end-diastolic dimension, indicating aortic regurgitation. In this case aortic stenosis is thought to co-exist with aortic regurgitation, because of the increase in echo intensity and restricted opening of the aortic valves.

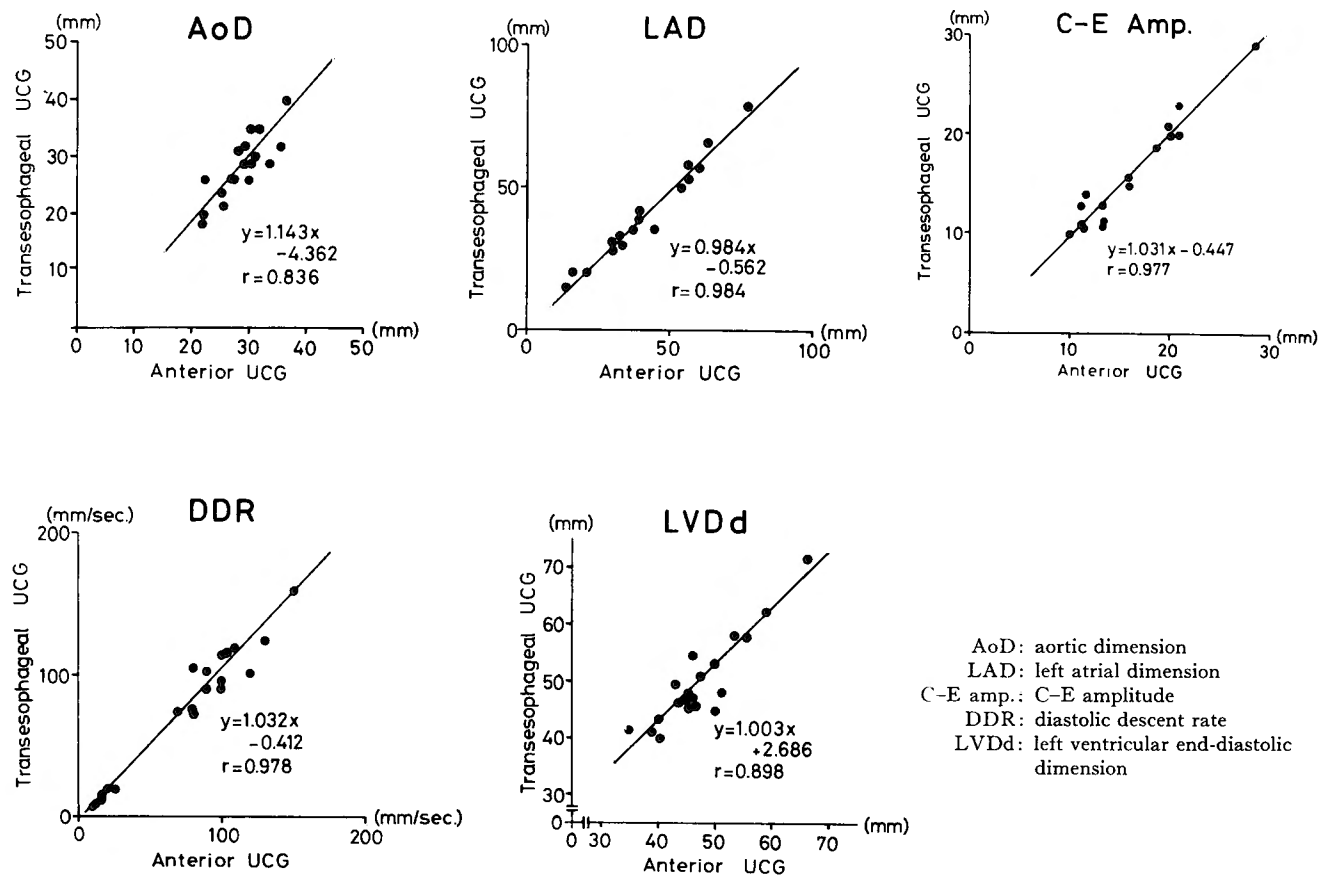


Fig. 4. Comparison of echocardiographic measurements between anterior and transesophageal echocardiography.

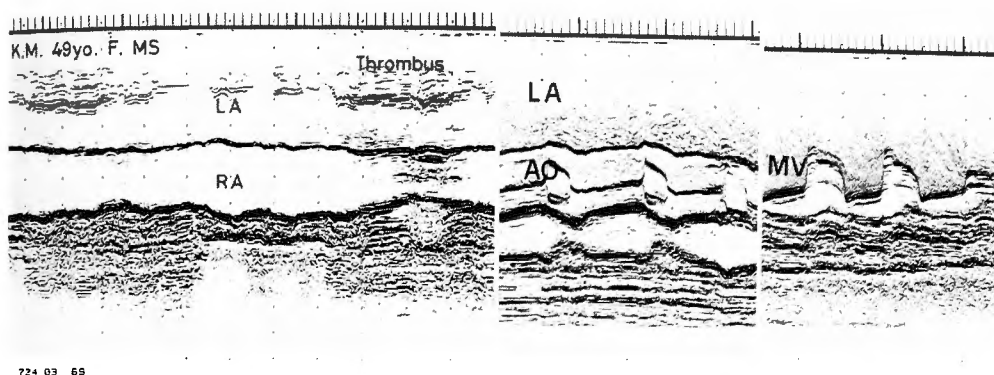


Fig. 5. Transesophageal echocardiograms of mitral stenosis with left atrial thrombus showing increased LAD and reduced DDR. A large band of linear echoes of the thrombus is seen (left panel).

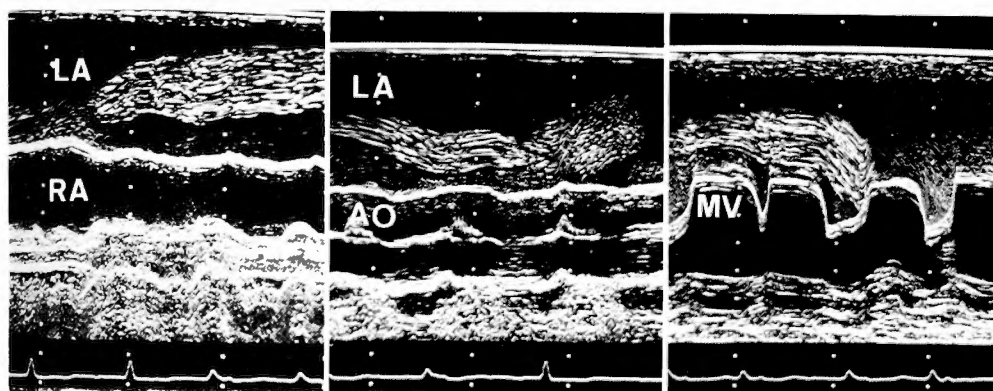


Fig. 6. Echocardiograms of mobile thrombus showing floating echoes in the left atrial cavity.

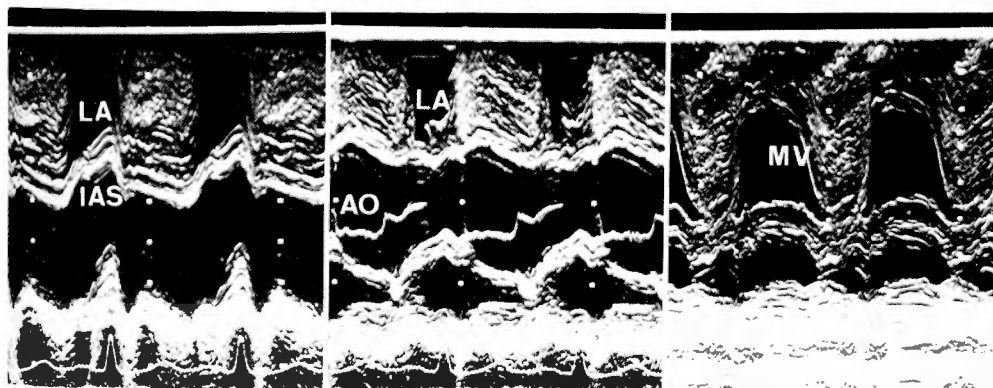


Fig. 7. M-mode echocardiogram of left atrial myxoma showing a large cloud of tumor echoes, highly mobile in left atrium.

Left ventricular pseudoaneurysm following mitral valve replacement:

Figure 10 is a cardiac scanning echogram of a patient who had had mitral valve replacement with Hancock's valve for mitral stenosis one year earlier. Counter-clockwise rotation of the trans-

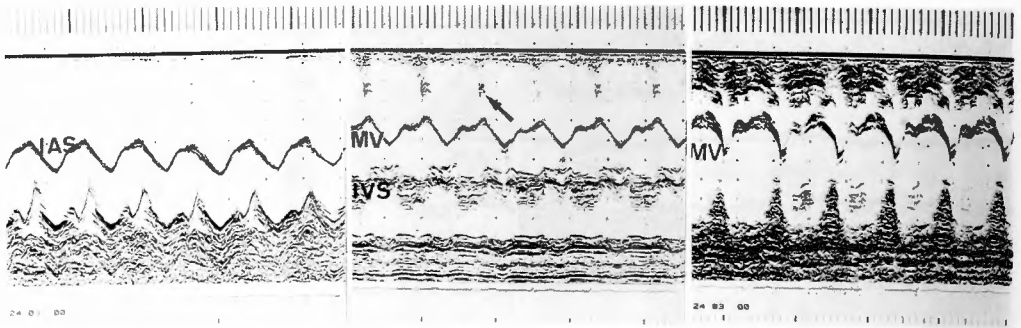


Fig. 8. Echocardiograms of mitral regurgitation showing ruptured chordae tendineae of mitral valve prolapsed into left atrium in early systole (arrow in middle panel). DDR and excursion of interatrial septum are increased because of mitral regurgitation and subsequent left ventricular rapid filling.

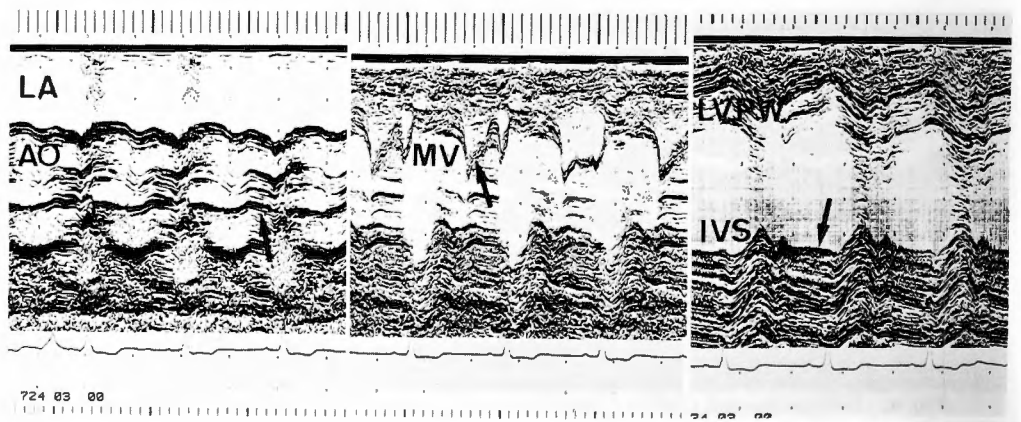


Fig. 9. Echocardiograms of aortic regurgitation showing increase in aortic dimension, diastolic separation of aortic valve (arrow in left panel), increase in left ventricular end-diastolic dimension, and fine fluttering of anterior mitral leaflet (arrow in middle panel) and interventricular septum (arrow in right panel).

ducer at the level of the mitral annulus allowed scanning of the abnormal cavity adjacent to the mitral annulus. Preoperative left ventriculography revealed a left ventricular pseudoaneurysm.

Dissecting aneurysm of the ascending aorta:

In Fig. 11, the ascending aorta is remarkably dilated from its origin, and an intimal flap is identified; mid-systolic closure can be seen in the aortic valve suggesting low cardiac output. The fluttering of the interventricular septum (arrow in right panel) is probably the result of aortic regurgitation.

Atrial septal defect:

Enlargement of the right ventricular outflow tract and paradoxical movement of the interventricular septum indicate right ventricular volume overload. The atrial septal echo is interrupted in the echogram obtained in the beam directed to the atrial septum (Fig. 12).

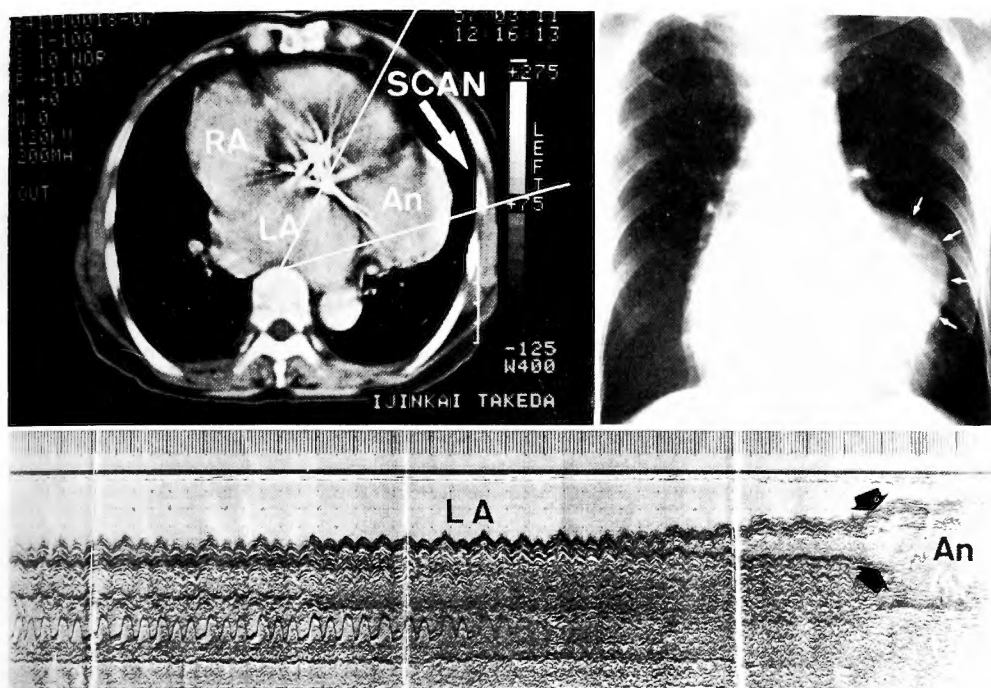


Fig. 10. Transesophageal M-mode scan of left ventricular pseudoaneurysm following mitral valve replacement showing abnormal cavity adjacent to the mitral annulus (An. in lower panel). Left upper panel is CT and right upper panel is chest x-ray film of the same patient.

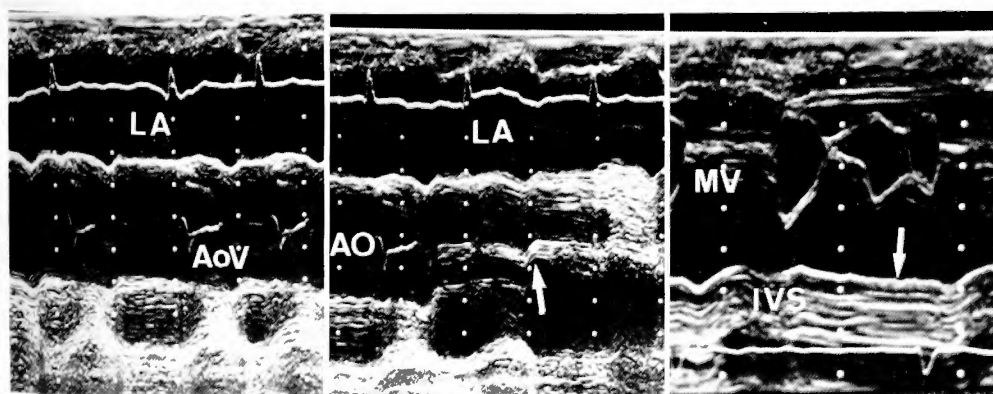


Fig. 11. M-mode echocardiogram of DeBakey's type I dissecting aneurysm showing aortic dilation and intimal flap (arrow in middle panel). Fine fluttering of interventricular septum is identified (arrow in right panel).

II. APPLICATION OF TRANSESOPHAGEAL ECHOCARDIOGRAPHY FOR EVALUATION OF LEFT VENTRICULAR FUNCTION SOON AFTER CARDIAC SURGERY.

Transesophageal echocardiography provides a continuous cardiac examination during and soon after operation. The purpose of this study is to assess the usefulness of transesophageal

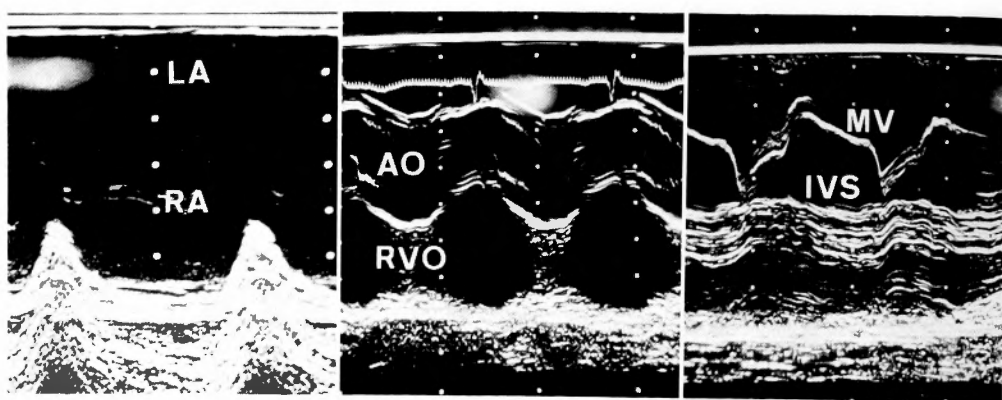


Fig. 12. Echocardiograms of atrial septal defect showing enlargement of right ventricular outflow tract and paradoxical movement of interventricular septum. Atrial septal echo is interrupted (left panel).

echocardiography in measuring changes of left ventricular function soon after cardiac surgery.

Patients and Methods

Patients: Twenty patients, 9 males and 11 females, who underwent cardiac operation in the Second Department of Surgery of Kyoto University Hospital or the Department of Cardiovascular Surgery of Takeda Hospital, in Kyoto, were studied. The ages ranged from 21 to 59 years ($\text{avg} = 43.7 \pm 12.0$). Their diseases were: atrial septal defect (5), partial endocardial cushion defect (1), ventricular septal defect (1), mitral stenosis (6), mitral regurgitation (1), aortic regurgitation (2), ischemic heart disease (2) and constrictive pericarditis (2).

Patch closure of atrial septal defect was performed in 6 patients, patch closure of ventricular septal defect in 1, mitral valve replacement in 7, aortic valve replacement in 2, aortocoronary bypass in 2 and pericardectomy in 2.

These patients were divided into 5 groups: Group I, 6 patients with atrial septal defect including 1 with partial endocardial cushion defect; Group II, 6 patients with mitral stenosis; Group III, 4 patients with left ventricular volume overload; Group IV, 2 patients with ischemic heart disease; Group V, 2 patients with constrictive pericarditis.

Anesthesia: As a premedication, morphine sulfate (0.1 mg/kg) and scopolamine (0.01 mg/kg) were administered intramuscularly 1 hour before the operation. Induction of anesthesia was performed with diazepam (0.2 mg/kg) and morphine sulfate (1–2 mg/kg, drip-infused for about 15 minutes) during oxygen inhalation. Intubation was facilitated with the additional intravenous administration of 1 mg/kg of succinylcholine and xylocaine spraying of the larynx. To maintain anesthesia, pure oxygen or 50% nitrous oxide in oxygen with a non-depolarizing muscle relaxant was used.

Cardiopulmonary bypass: A William-Harbey H 1500 bubble oxygenator or Travenol membrane oxygenator with hemodilution technique (20–25% of minimal hematocrit value) was used for cardiopulmonary bypass. Two caval drainage tubes were inserted into the superior and

inferior vena cava from the right atrium; an arterial cannula was inserted into the left femoral artery. The bypass pump was driven at a flow rate of 2.4 L/min/BSA (M^2). In cases of atrial septal defect, artificial fibrillation with normothermia was employed, but in the others, moderate hypothermia (about 30°C of rectal temperature) and cardioplegic cardiac arrest with Young's solution and MIK solution³⁶⁾ were used for myocardial protection, with topical cooling with ice slush. MIK solution was infused into the aortic root every thirty minutes (10 ml/kg).

Hemodynamic measurements: After patients were anesthetized, a 21 G plastic needle was inserted into the left radial artery, and an 8F Swan-Ganz Catheter (Edward Laboratories) was inserted into the pulmonary artery from the right internal jugular vein by the puncture method. Systemic arterial pressure and pulmonary capillary wedge pressure were recorded using a fluid-filled transducer (Gould Stetham, Model P23 ID) on a polygraph (Sanei, Model 141-6) with electrocardiogram. Cardiac output was measured by the thermo-dilution method with a Cardiac Output Computer (Edward Laboratories, Model 9520A). Cardiac index (CI) and stroke volume (SV) were calculated by the formulas.

$$\text{Cardiac Index (CI)} = \text{Cardiac Output (CO)} / \text{BSA (M}^2\text{)}$$

BSA: Body Surface Area

$$\text{Stroke Volume (SV)} = \text{Cardiac Output (CO)} / \text{Heart Rate (HR)}$$

One month after the operation, hemodynamic measurements were performed with cardiac catheterization.

Echocardiograms: After induction of anesthesia and intubation, the pharyngeal region was anesthetized locally with 10 ml of 2% viscous xylocaine, and the transesophageal transducer was introduced into the esophagus orally. Echocardiograms were recorded before, during and immediately after operation, and 3, 6, 12 and 24 hours after operation. Echocardiograms were also obtained during cardiac catheterization one month after operation by the procedure described previously.

The echocardiographic apparatus used was Aloka-SSD 110 S, and echocardiograms were recorded on an Aloka-SSZ 91 Strip-Chart-Recorder with electrocardiogram at a paper speed of 50 or 100 mm/sec.

Echocardiographic measurements: Figure 13 demonstrates the echocardiographic measurements made in this study. Pre-ejection phase (PEP) and left ventricular ejection time (LVET) were measured as the duration from the beginning of QRS of the electrocardiogram to aortic valve opening and from aortic valve opening to closure, respectively. Left ventricular end-diastolic dimension (EDD) was measured at the peak of the R wave of the electrocardiogram, and left ventricular end-systolic dimension (ESD) was measured as the shortest dimension during systole.

Stroke volume (SV), ejection fraction (EF), mean velocity of circumferential fiber shortening ($mVcf$), systolic time intervals (STI) and peak systolic pressure/left ventricular end-systolic dimension ratio (PSP/ESD) as indices of systolic function, and "normalized compliance" (Compl.) as an index of diastolic characteristics, were calculated by the formulas:

$$SV = EDD^3 - ESD^3$$

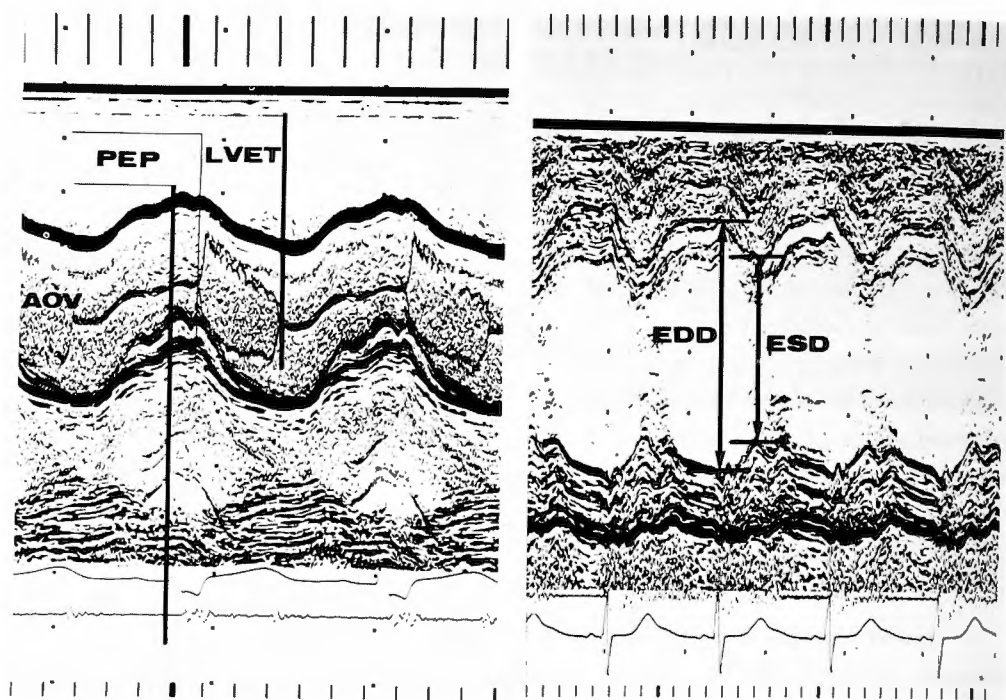


Fig. 13. Echocardiographic measurements in this study; PEP: pre-ejection phase, LVET: left ventricular ejection time, EDD: left ventricular end-diastolic dimension, ESD: left ventricular end-systolic dimension.

$$EF = SV / EDD^3$$

$$mVcf = (EDD - ESD) / EDD \cdot LVET$$

$$STI = PEP / LVET$$

$$Comp. = (EDD^3 - ESD^3) / mPCWP \cdot ESD^3$$

mPCWP: mean Pulmonary Capillary Wedge pressure.

Results

In 20 patients, transesophageal echocardiograms were obtained before, during and immediately after operation, and 3, 6, 12, 24 hours, and one month postoperatively. Echocardiographic measurements were obtained from the left ventricular and aortic valve echograms, and various indices of left ventricular function were calculated at each of the above times, and the significance of these indices was evaluated. Postoperative changes in various indices of left ventricular function are summarized in Table 1.

Echocardiographic Evaluation of Systolic Function.

Changes in systolic indices:

In Group I, all systolic indices were maintained well with a slight decrease in EF, mVcf and PSP/ESD 6 to 12 hours after operation. SV gradually increased after closure of the atrial septal defect with minimal postoperative impairment of left ventricular function (Fig. 14).

Table 1. Changes in the indices of left ventricular function soon after cardiac surgery.

Case	Index	Before Operation	After Operation					
			0	3	6	12	24 (hr.)	1 (mo.)
Atrial Septal Defect (including partial endocardial cushion defect) (Group I)	SV (ml)	69.7±11.1	67.6±16.9	72.1±5.9	72.6±12.8	78.6±9.8	81.6±5.8	86.9±8.4
	EF	0.70±0.10	0.69±0.07	0.70±0.11	0.66±0.14	0.56±0.12	0.69±0.07	0.68±0.06
	mVcf (circ./sec.)	1.32±0.54	1.40±0.28	1.43±0.38	1.36±0.45	1.36±0.39	1.41±0.24	1.40±0.27
	STI	0.33±0.04	0.29±0.07	0.29±0.04	0.30±0.04	0.28±0.06	0.25±0.03	0.25±0.03
	PSP/ESD (mmHg/mm)	5.05±2.61	3.88±0.76	3.83±1.35	3.71±1.34	3.72±0.98	4.35±1.57	5.92±1.93
	Compl. (/mmHg)	0.44±0.21	0.26±0.19	0.34±0.22	0.33±0.25	0.33±0.28	0.36±0.25	0.42±0.28
Mitral Stenosis (Group II)	SV (ml)	45.2±19.2	54.9±28.3	58.9±33.1	54.2±27.3	59.2±35.4	65.5±30.0	55.9±13.5
	EF	0.56±0.12	0.60±0.15	0.58±0.14	0.54±0.13	0.56±0.15	0.65±0.07	0.55±0.03
	mVcf (circ./sec.)	1.03±0.27	1.30±0.46	1.10±0.34	1.10±0.35	1.03±0.40	1.12±0.31	0.97±0.07
	STI	0.46±0.02	0.34±0.12	0.38±0.10	0.44±0.10	0.39±0.16	0.33±0.11	0.39±0.04
	PSP/ESD (mmHg/mm)	3.10±1.24	3.35±0.99	3.25±0.87	3.20±0.91	2.91±0.59	3.27±0.50	2.81±0.65
	Compl. (/mmHg)	0.08±0.04	0.12±0.05	0.13±0.09	0.14±0.10	0.15±0.11	0.21±0.13	0.27±0.05
Left Ventricular Volume Overload (Group III)	SV (ml)	179.3±74.9	77.2±22.6	72.2±25.2	68.1±12.2	68.8±16.9	75.8±26.6	69.1±11.1
	EF	0.66±0.07	0.61±0.09	0.55±0.06	0.60±0.08	0.61±0.07	0.63±0.04	0.60±0.07
	mVcf (circ./sec.)	1.07±0.22	1.18±0.26	1.12±0.16	1.25±0.06	1.24±0.07	1.27±0.10	1.15±0.14
	STI	0.31±0.13	0.48±0.07	0.46±0.07	0.42±0.15	0.38±0.17	0.42±0.10	0.42±0.09
	PSP/ESD (mmHg/mm)	2.40±0.45	3.48±0.96	3.18±0.27	3.36±0.63	3.40±0.28	3.78±0.35	3.52±0.72
	Compl. (/mmHg)	0.16±0.06	0.13±0.09	0.09±0.05	0.12±0.03	0.14±0.04	0.15±0.03	0.34±0.09
Ischemic Heart Disease (Group IV)	SV (ml)	80.6	80.9	63.9	64.5	77.8	74.1	62.5
	EF	0.62	0.73	0.57	0.62	0.70	0.71	0.66
	mVcf (circ./sec.)	1.27	1.36	1.04	1.15	1.28	1.42	1.30
	STI	0.28	0.24	0.35	0.26	0.28	0.33	0.32
	PSP/ESD (mmHg/mm)	3.52	3.71	3.28	3.63	3.78	3.65	4.00
	Compl. (/mmHg)	0.34	0.14	0.07	0.09	0.19	0.17	0.43
Constrictive Pericarditis (Group V)	SV (ml)	55.8	95.3	96.2	105.3	109.5	102.4	93.5
	EF	0.65	0.78	0.79	0.73	0.74	0.68	0.62
	mVcf (circ./sec.)	1.29	1.72	1.75	1.32	1.53	1.48	1.30
	STI	0.40	0.24	0.25	0.25	0.24	0.27	0.26
	PSP/ESD (mmHg/mm)	4.75	4.87	4.80	4.32	4.81	4.23	4.79
	Compl. (/mmHg)	0.13	0.64	0.63	0.60	0.54	0.49	0.55

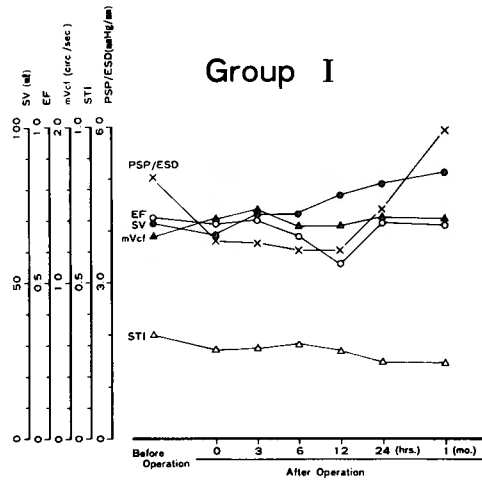


Fig. 14. Changes of systolic indices in Group I.

In Group II, the indices improved immediately after operation, but then gradually became worse. After 6 to 12 hours, EF, mVcf and PSP/ESD decreased, but STI increased. Although there was an increase in SV one month after operation, other indices did not show significant improvement (Fig. 15).

In Group III, SV was greatly reduced after operation; EF decreased, while mVcf and PSP/ESD increased (Fig. 16).

In Group IV, all indices were maintained relatively well with EF over 0.57, mVcf over 1.04, STI under 0.35 and PSP/ESD over 3.28 during the first 24 hours after operation, despite the obvious reduction 3 to 6 hours postoperatively. There were slight increases of these indices one month postoperatively (Fig. 17).

In Group V, SV was significantly increased by pericardectomy. Systolic indices improved

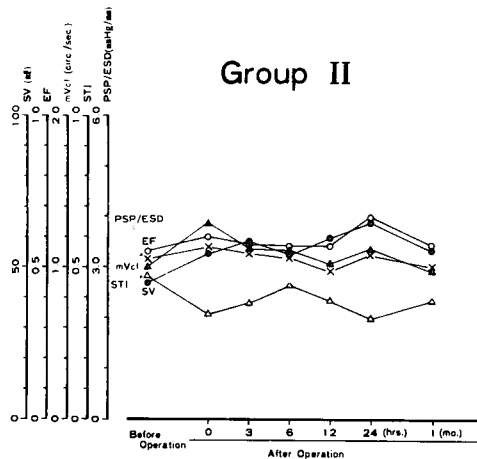


Fig. 15. Changes of systolic indices in Group II.

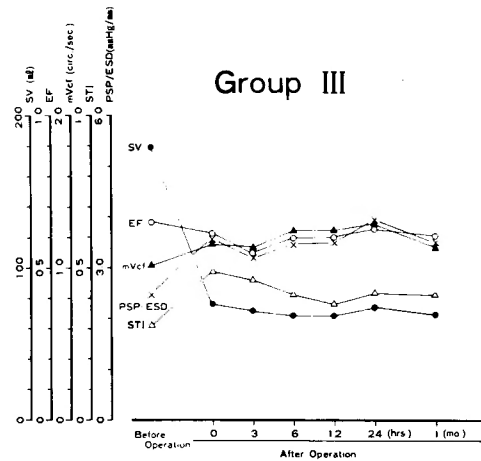


Fig. 16. Changes of systolic indices in Group III.

immediately after operation and remained satisfactorily during the postoperative course (Fig. 18).

Comparison of SV between transesophageal echocardiography and thermo-dilution:

The SV value obtained by transesophageal echocardiography was slightly greater than that obtained by thermo-dilution; a high correlation ($r=0.849$) was noted between these two values (Fig. 19).

Relationship between EF and CI:

A close relationship was seen between EF and CI ($r=0.763$). All patients with EF under 0.5 and many with EF under 0.6 were treated for low cardiac output syndrome (LOS) (Fig. 20).

Relationship between mVcf and CI:

As shown in Fig. 21, a close relationship was also seen between mVcf and CI ($r=0.789$); in

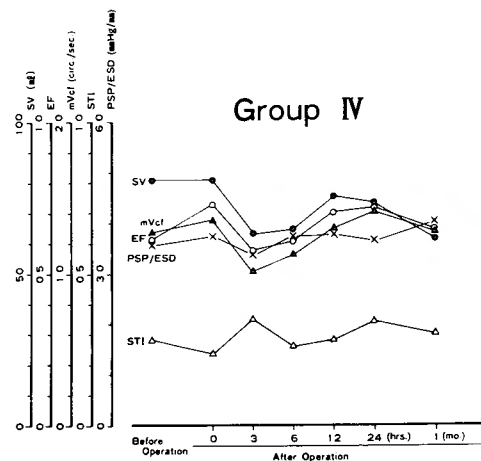


Fig. 17. Changes of systolic indices in Group IV.

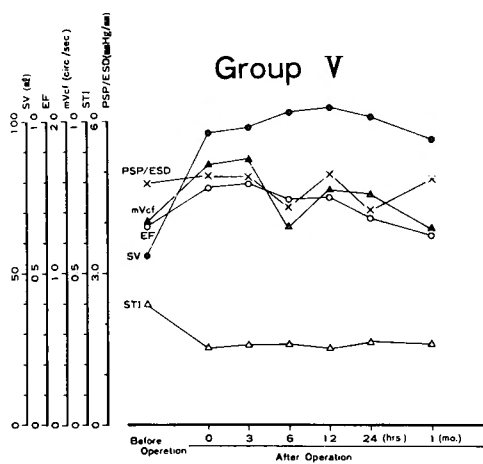


Fig. 18. Changes of systolic indices in Group V.

most patients with LOS, mVcf was under 1.0.

Relationship between STI and CI:

The relationship between STI and CI is illustrated in Fig. 22. STI correlated inversely with CI ($r=-0.625$); all patients with STI over 0.6 and many patients with STI over 0.45 had LOS.

Relationship between EF and PSP/ESD:

As shown in Fig. 23, there was a positive linear relationship between EF and PSP/ESD ($r=0.756$); most LOS patients had a PSP/ESD ratio below 3.0.

Echocardiographic Evaluation of Diastolic Characteristics.

Changes in “normalized compliance” (Fig. 24):

“Normalized compliance” of Group I was reduced from a preoperative value of 0.44 ± 0.21 to 0.26 ± 0.19 postoperatively.

In Group II, this value improved slightly after operation, but remained under 0.21 ± 0.13

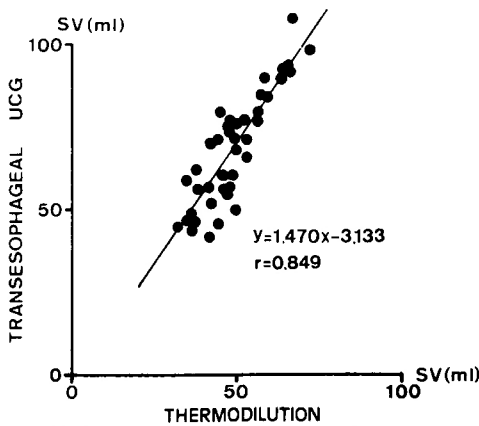


Fig. 19. Comparison of SV between thermo-dilution and transesophageal echocardiography.

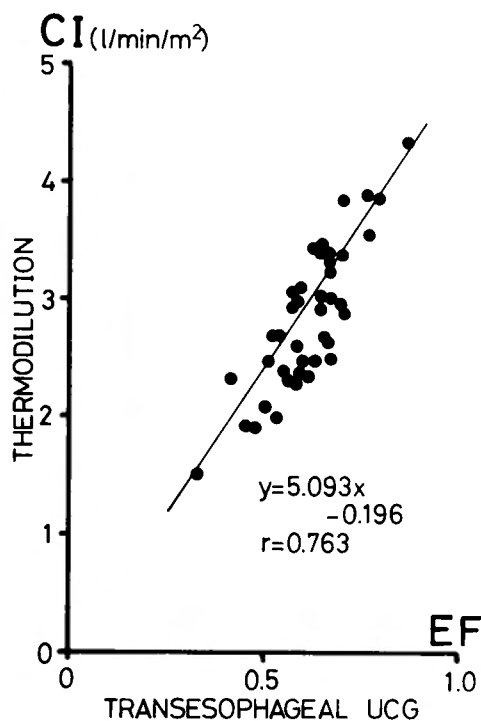


Fig. 20. Relationship between EF and CI.

for 24 hours. One month after operation "normalized compliance" increased.

In Group III, "normalized compliance" was 0.16 ± 0.06 preoperatively and did not increase noticeably until 24 hours after operation. However, one month after operation it increased

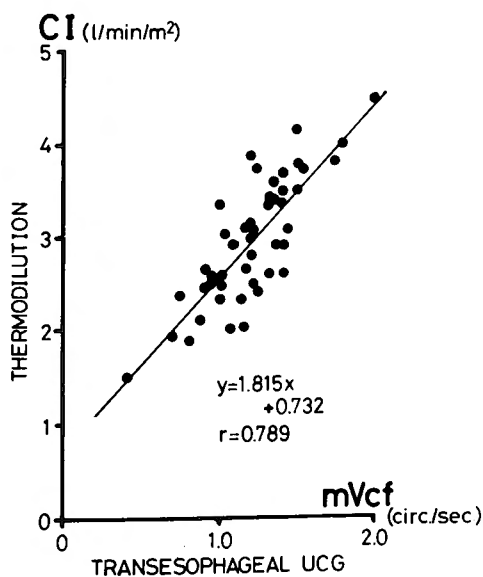


Fig. 21. Relationship between mVcf and CI.

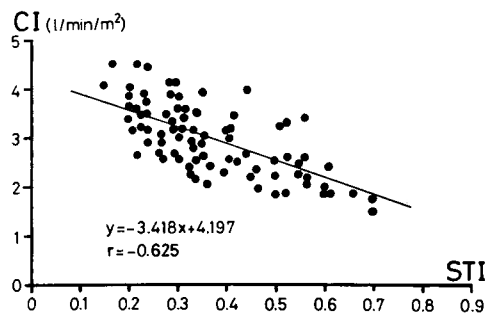


Fig. 22. Relationship between STI and CI.

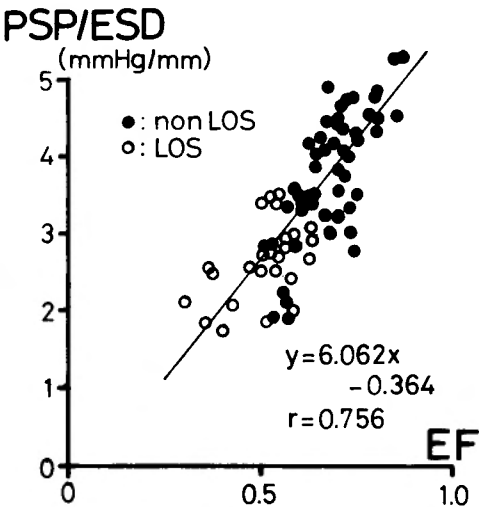


Fig. 23. Relationship between EF and PSP/ESD.

significantly.

In Group IV, it decreased immediately after operation, but then increased gradually. After

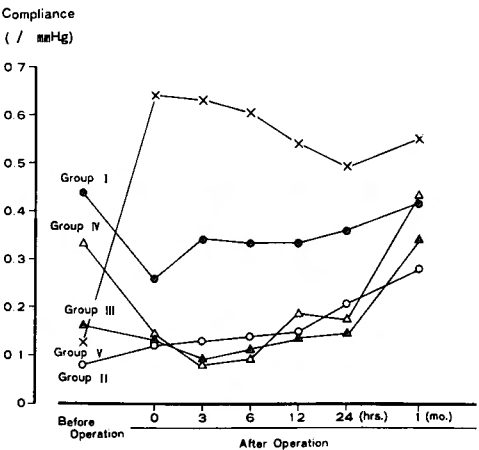


Fig. 24. Changes in "normalized compliance"

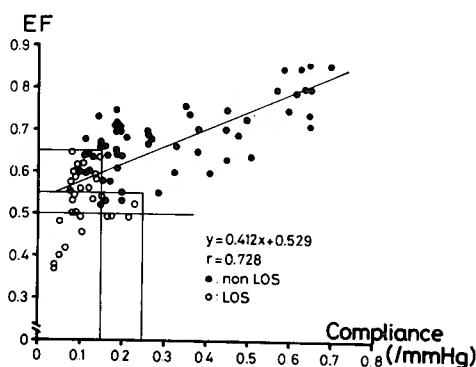


Fig. 25. Relationship between "normalized compliance" and EF.

one month, a definite increase was observed.

"Normalized compliance" of Group V was 0.13 preoperatively and significantly improved by the removal of constrictive pericardium.

Relationship between "normalized compliance" and EF:

Between these two indices there was a positive linear relationship ($r=0.728$) after operation. Patients with EF under 0.5 had LOS without exception. Nevertheless, those with EF under 0.55 and "normalized compliance" under 0.25, and those with EF under 0.65 and "normalized compliance" under 0.15 frequently had LOS (Fig. 25).

Discussion

Transesophageal Echocardiography.

Since it was first clinically introduced by EDLER and HERZ in 1954⁴⁶, echocardiography has become a useful tool in the qualitative and quantitative diagnosis of cardiac diseases⁸). Indeed, it provides much interesting information without any risk. The usefulness of M-mode echocardiography during open heart surgery was first reported by JOHNSON et al. in 1972²⁵). SPOTNIZ et al. in 1976⁴⁸) and STOM et al. in 1978⁵⁰) also employed this method to evaluate left ventricular function during open heart surgery. Other intraoperative observations have been reported as well^{18, 49, 52}). The disadvantage of their method is that surgeons must interrupt their activity to manipulate the sterilized transducer on the heart surface. There are some other limitations of use. Image quality of the anteriorly applied echocardiography usually depends on cardiac position, cardiac size, lung volume and distance from chest wall to heart in closed chests. Therefore, the image quality is frequently poor in early postoperative patients, who are on controlled ventilation with drainage tubes in their anterior mediastinal space.

Transesophageal echocardiography, first introduced by FRAZIN et al. in 1976¹³), may solve these problems.

The transducer was designed for easy swallowing by making the edges more blunt and attached to the tip of a selective bronchography catheter for adequate control. The transducer can be swallowed easily and safely with mild gagging as it passes through the cricopharyngeal

sphincter. In intubated patients, anterior retraction of the intratracheal tube with Macintosh's laryngoscope permits smooth introduction of the transducer into the esophagus.

Figures 26 and 27 show the transducer position, echo beam direction and corresponding echograms: 1) atrial septal echogram, 2) aortic valve echogram, 3) anterior mitral leaflet echogram, 4) interventricular septal and posterior left ventricular free wall echogram, 5) anterior and posterior left ventricular free wall echogram.

Thus, it is possible to obtain a clear echogram which is a mirror image of the anterior parasternal echocardiogram. Furthermore, the acoustic window of transesophageal echocardiography is so wide that scanning of the atrial septum and anterior left ventricular free wall is also possible^{31,32,43}. Cardiac scanning by withdrawing the transducer with a counter-clockwise to clockwise rotation presents a continuity of the anterior aortic wall to the interventricular septum, and of the posterior aortic wall to the anterior mitral leaflet. This method can also be used for the diagnosis of cono-truncal lesion (Fig. 28).

In 30 patients undergoing trasesophageal echocardiography, an atrial septal echogram could be obtained in 100%, an aortic valve echogram in 100%, an anterior mitral leaflet echogram in 100% and a left ventricular echogram consisting of anterior and posterior free walls in 86.7%. These rates of detection are obviously higher than those by conventional anterior echocardiography. MATSUZAKI et al³¹ also reported a superior rate of detection by this method in 12 patients with chronic obstructive lung disease. In this study, every transesophageal echogram is clear with finer detail, and the image quality is maintained well even during and after cardiac

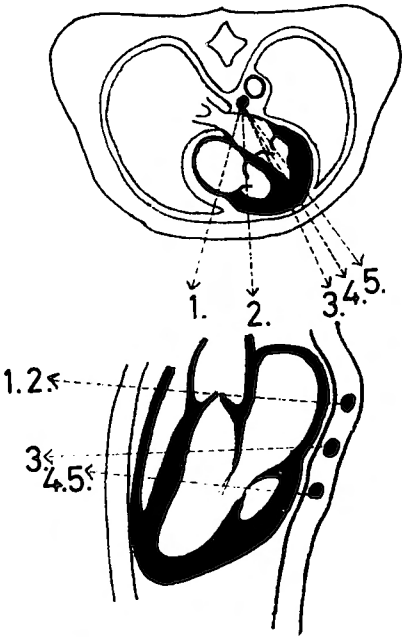


Fig. 26. Diagram of the heart showing the cardiac structures traversed by ultrasonic beam as the transducer scans interatrial septum (position 1) to anterior and posterior left ventricular wall (position 5).

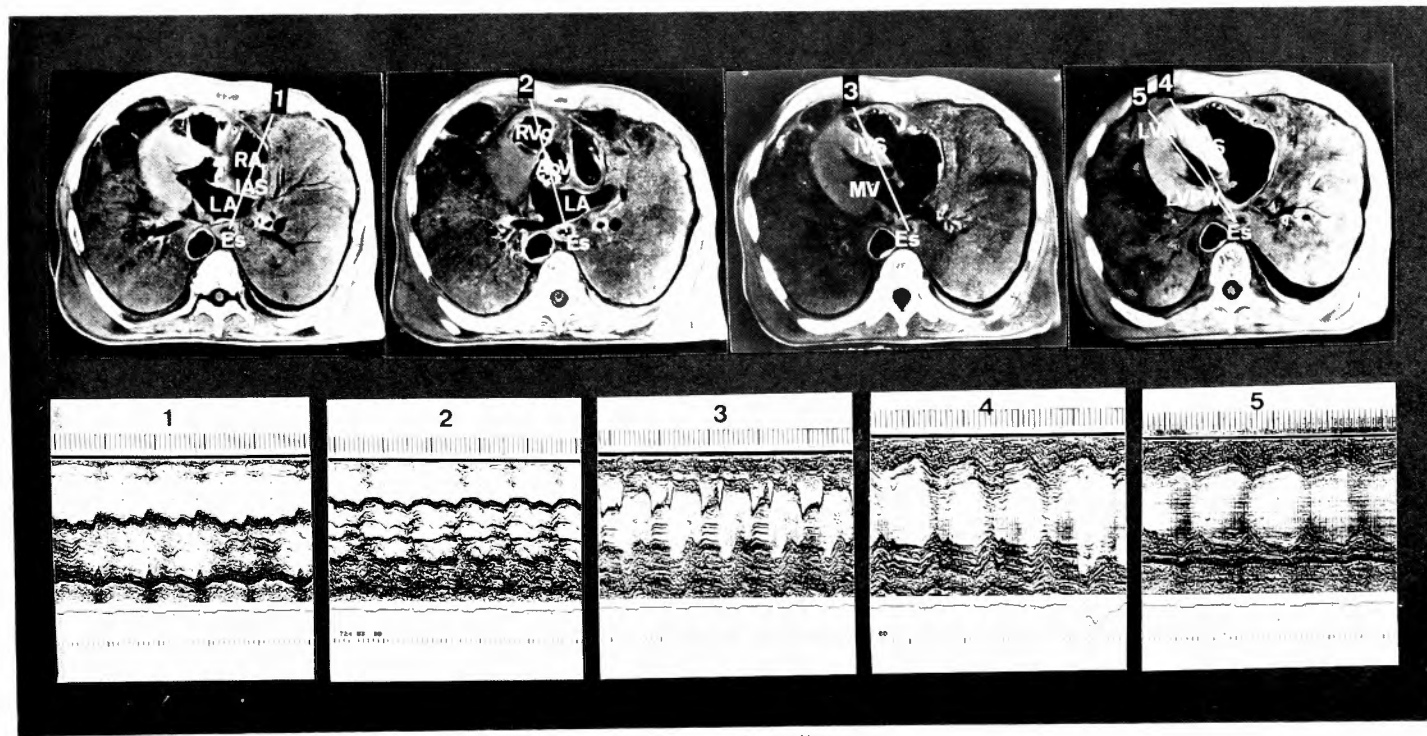


Fig. 27. Transverse sections of the heart with corresponding echocardiograms. IAS: interatrial septum, AoV: aortic valve, MV: mitral valve, IVS: interventricular septum, LVAW: left ventricular anterior wall, LVPW: left ventricular posterior wall, ES: esophagus.

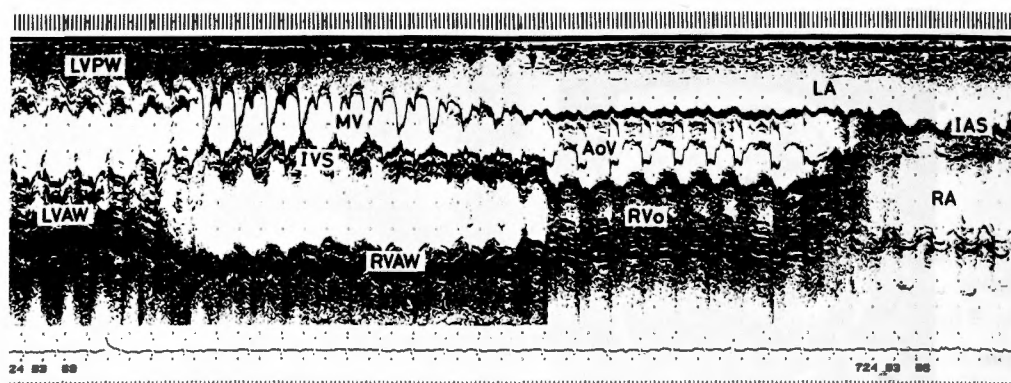


Fig. 28. M-mode scan of the heart by withdrawing and rotating the transducer from position 5 to position 1.

surgery^{34,35)}, probably because of the direct contact of the transducer with the heart via the esophageal wall without interference by lung tissue or bony structures.

MATSUZAKI et al.³¹⁾ found close correlations of C-E amplitude ($r=0.848$), diastolic descent rate ($r=0.883$), end-diastolic dimension ($r=0.852$) and end-systolic dimension ($r=0.886$) between anterior and transesophageal echocardiographies. FRAZIN et al.¹³⁾ also noted good correlations of aortic dimension ($r=0.69$), left atrial dimension ($r=0.96$) and diastolic descent rate ($r=0.97$) between these two methods. In this study, high correlations were noted for aortic dimension ($r=0.836$), left atrial dimension ($r=0.984$), C-E amplitude ($r=0.977$) and diastolic descent rate ($r=0.978$) between these two methods; most plots were located along the $Y=X$ line except those of aortic dimension. Variations in aortic dimension are thought to result from changes in beam angulation accompanying aortic enlargement. In patients without paradoxical movement of the interventricular septum, the end-diastolic dimension on transesophageal echocardiography correlated well with that on anterior echocardiography, with a tendency towards greater values in the former. Thus transesophageal echocardiography is a valuable clinical tool, especially in aged patients with chronic obstructive lung disease, and in patients during and soon after cardiac surgery.

Use in Evaluation of left Ventricular Function.

Systolic function:

Altered left ventricular function after cardiac surgery is the result of mechanical effects (altered perload and afterload) and reduction in myocardial contractility due to trauma by the operative procedure, anesthesia and cardiopulmonary bypass, including cardiac arrest.

In Group I, all indices were well maintained and the postoperative course was uneventful. However, in Group II, EF, mVcf and PSP/ESD, which increased immediately after operation, probably due to the effect of inotropic agents, were significantly reduced 6 to 12 hours after operation. STI increased to 0.44 ± 0.10 , and some patients had STI over 0.6. Even one month postoperatively, these indices were inadequate, while SV increased. These results suggest that mitral stenosis causes severe myocardial suppression, as previously observed^{10,11,22,23)}. In

Group III, SV was significantly reduced immediately after operation. Subsequent increase of mVcf and PSP/ESD, and decrease of EF resulted from reduction of left ventricular volume overload. The postoperative systolic indices in Group III, with moderate myocardial damage, were between those of Groups I and II. STI was relatively high compared with the other systolic indices. The reason for this is probably that the mechanical aortic valve prosthesis needs a longer isometric contraction time, and a larger aortic orifice, due to aortic regurgitation, results in a shorter left ventricular ejection time. In Group IV, EF, mVcf and PSP/ESD increased after operation; postoperative myocardial depression was milder than in Group II and III, despite the depression 3 to 6 hours after operation, probably due to catecholamine release,^{16,55)} and one month after operation, left ventricular function was slightly better than before operation. The improvement of left ventricular function following A-C bypass surgery is thought to be the result of improved myocardial contractility and/or dyskinetic movement of the affected ventricular wall due to restoration of coronary blood flow to the ischemic myocardium.

The effect of A-C bypass surgery has been demonstrated by the improvement of NYHA activity class²⁹⁾, EF²⁾ and STI¹⁶⁾, and by myocardial scintigraphy.^{20,42)} However, it is not suitable to evaluate overall left ventricular function following A-C bypass surgery, because there are various changes caused by factors such as the previous presence and the perioperative extension of infarction and the severity of the peripheral coronary arterial lesion.

Echocardiographic measurement is also applicable during pericardectomy for constrictive pericarditis. Increased SV, EF, mVcf and PSP/ESD, and decreased STI were observed after pericardectomy.

It is generally recognized that parameters measured by anterior echocardiography correlate well with those by angiocardiography. However, correlation is not always good after open heart surgery, because of the paradoxical movement of the interventricular septum. With transesophageal echocardiography, the left ventricular dimension can be measured between the anterior and posterior free wall, excluding the interventricular septum³⁴⁾. A high correlation was noted in SV between transesophageal echocardiography and thermo-dilution ($r=0.849$), and there were also high correlations between EF and CI ($r=0.763$), and mVcf and CI ($r=0.789$). Therefore transesophageal echocardiography appears to be suitable for the evaluation of left ventricular function soon after open heart surgery³⁵⁾.

Moreover, EF showed a greater value as compared with CI than has generally been accepted, and there were variations of CI between 0.5 and 0.6 of EF. These findings demonstrate that left ventricular anterior and posterior free walls are indeed hyperkinetic due to compensation for the paradoxical movement of the interventricular septum and that there may be a participation of diastolic characteristics and/or the Frank-Starling mechanism in the given CI, which makes it possible to maintain the CI with a relatively low EF by increasing the left ventricular end-diastolic dimension.

STI was first described by WEISLER et al. in 1968⁵⁶⁾. This index consists of two factors; LVET and PEP. LVET correlates well with SV, and PEP correlates inversely with myocardial contractility^{56,57)}. Therefore, PEP/LVET is being used as a parameter of left ventricular

contractility independent of heart rate in the field of internal medicine^{17,57)}. Kawabe introduced this parameter for estimating postoperative left ventricular function, using the radial arterial pressure curve, electrocardiogram and phonocardiogram²⁶⁾. However, in the low cardiac output state, the radial artery is frequently contracted in various degrees. Thus, this state might result in a delay and an obscure dicrotic notch in the radial arterial pressure curve. The simultaneous recording of electrocardiogram and echocardiogram would provide a more accurate measurement. Indeed, there was an inverse correlation ($r = -0.625$) between STI and CI in this study, and the usefulness of this parameter was confirmed even after cardiac surgery.

Recent animal experiments have shown that the slope of the end-systolic pressure/end-systolic volume ratio (E max) might better characterize the left ventricular contractility independent of the magnitude of load⁵¹⁾. Clinically, E max was obtained by plotting dicrotic arterial pressure against end-systolic volume before and after changing the afterload^{21),44)}. However, in the early postoperative period, when cardiac function is very unstable, it seems to be unwise to change the load. Currently, the simple peak systolic pressure/end-systolic volume ratio was also found to be a sensitive parameter of left ventricular contractility independent of the load^{33,37,45)}.

The author obtained the end-systolic dimension by transesophageal echocardiography and the peak systolic pressure from the radial arterial pressure curve and used the more simple ratio of peak systolic pressure/end-systolic dimension instead of E max.

According to FUJII et al.¹⁴⁾, there is a close relationship between E max and EF ($r = 0.79$). In this study, the PSP/ESD ratio correlated well with EF ($r = 0.756$). Thus, this simple ratio also appears to be a useful parameter of postoperative left ventricular contractility.

Diastolic characteristics:

Until recently, left ventricular function was estimated from the pump function and muscle contractile mechanics, which provided a picture only of cardiac contractility. Since the observation by SONNENBLICK et al.⁴⁷⁾, special attention has been paid to the cardiac diastolic characteristics. Several investigations have been reported in normal and diseased hearts^{4,27,54)}. Alterations in left ventricular compliance based on intraoperative echocardiography have also been reported^{30,48,49)}.

Although there are some parameters suitable for determining left ventricular diastolic characteristics, they are almost too complicated for clinical use.

Left ventricular compliance is defined as dV/dP , where dV is equal to diastolic volume change, and dP is equal to change in left ventricular diastolic pressure. SMITH et al.⁴⁶⁾ modified this expression by normalizing it with the end-systolic volume and used it clinically with good results. In this study, the author used this "normalized compliance" because of its simplicity and reliability. Here dV was obtained from SV ; ESV was measured by echocardiography. Mean pulmonary capillary wedge pressure was used as dP with the assumption that left ventricular end-diastolic pressure approximates mean pulmonary capillary wedge pressure, and left ventricular pressure falls to zero at the beginning of diastole.

"Normalized compliance" had a high preoperative value of 0.44 ± 0.21 in Group I, but it fell to 0.26 ± 0.19 immediately after operation. Nevertheless, the lowest value was 0.26 ± 0.19 ,

suggesting that the influence of operative procedures and bypass techniques, including artificial fibrillation, is minimal.

On the contrary, a low preoperative value of 0.08 ± 0.04 rose to 0.12 ± 0.05 after left ventricular filling disturbance was reduced by operation in Group II, although it remained low for 24 hours. In Groups III and IV also, "normalized compliance" was low for 24 hours postoperatively, and there were no significant differences among Group II, III and IV. This result suggests that cardioplegic cardiac arrest influences the diastolic characteristics of the left ventricle despite myocardial protection, and the influence continues during the first 24 hours or longer.

Alterations of "normalized compliance" were significant in Group V. Low preoperative values due to left ventricular filling disturbances were significantly improved following pericardectomy and continued satisfactorily throughout the postoperative course.

In addition, "normalized compliance" correlated well with EF ($r=0.728$), suggesting that myocardial distensibility is affected by EF, a reliable index of left ventricular contractility, as well⁴⁷. And the fact that even patients with EF over 0.5 and low "normalized compliance" frequently had LOS implies that cardiac output in this period is also greatly dependent on the diastolic characteristics of the left ventricle.

Other Applications.

Intraoperative use:

The usefulness of M-mode echocardiography during operation has been reported by some authors. MATSUMOTO et al.³⁰ first introduced transesophageal echocardiography for continuous intraoperative monitoring of left ventricular function. Ishihara in his animal study showed that there was a close relationship between E-F slope and % closing volume of the mitral valve, and echocardiography was suitable to evaluate mitral reconstructive surgery for mitral regurgitation²⁴. Figure 29 depicts changes in echocardiographic measurements before and after reconstructive surgery of the mitral valve. In the patient with severe residual regurgitation (case 2),

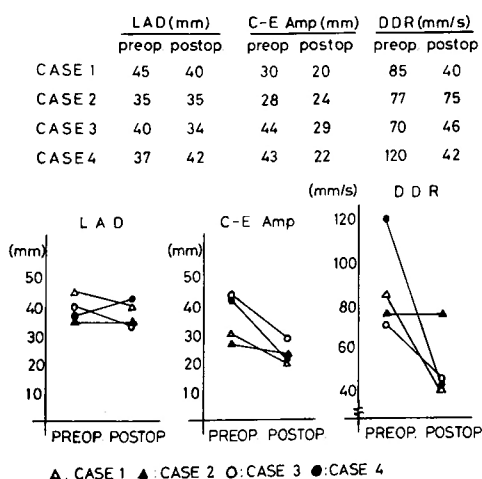


Fig. 29. Echocardiographic study before and immediately after reconstructive surgery for mitral regurgitation.

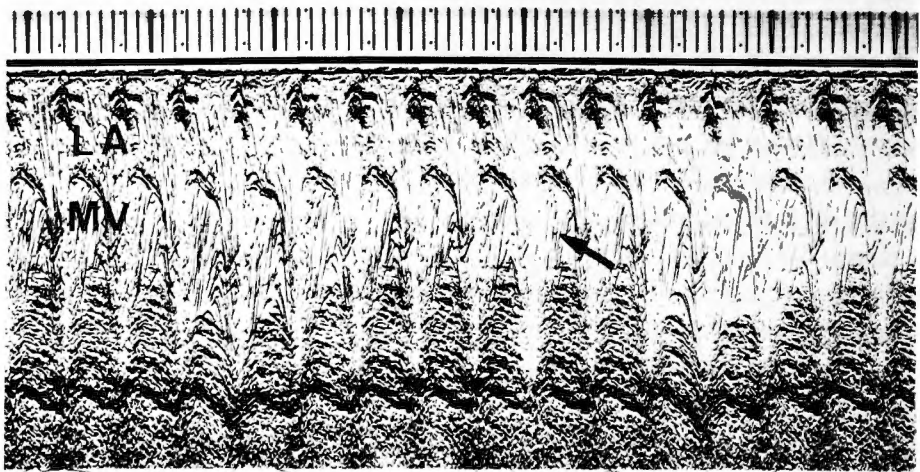


Fig. 30. Intraoperative contrast echocardiogram showing severe mitral regurgitation (arrow).

the diastolic descent rate decreased minimally. Figure 30 is an intraoperative contrast echocardiogram obtained by direct infusion of cold saline into the left atrium, showing severe mitral regurgitation. Therefore, evaluation of mitral reconstructive surgery, as well as of open mitral commissurotomy²⁵⁾, might be possible by transesophageal echocardiography immediately after the heart begins to beat.

The sensitivity of echocardiography to microbubbles is now well recognized, having been applied extensively in contrast echocardiography¹⁹⁾. Figure 31 shows echograms recorded after cardiopulmonary bypass. Contrast echoes are seen in the left atrium, left ventricle and aorta for 10 minutes or longer after the closure of cardiac chambers. These contrast echoes are thought to be microbubbles which enter the cardiac chambers during operation⁵⁾. There is a slight possibility of producing focal microemboli, so this air should be evacuated when transesophageal echocardiography demonstrates many microbubbles.

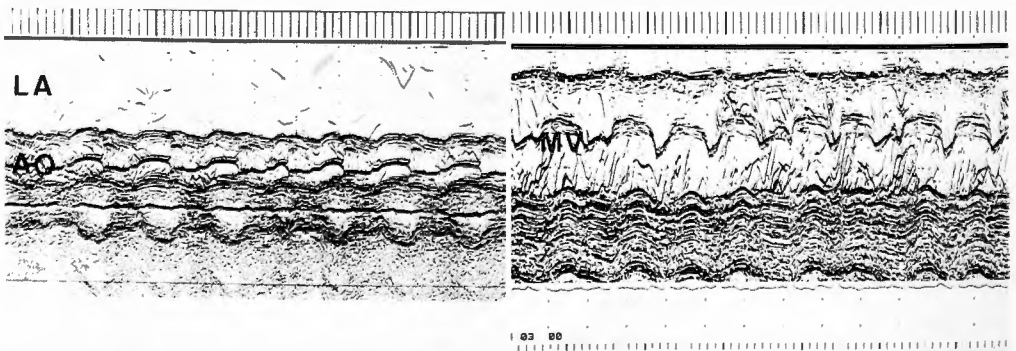


Fig. 31. Echograms recorded after cardio-pulmonary bypass showing microbubble echoes.

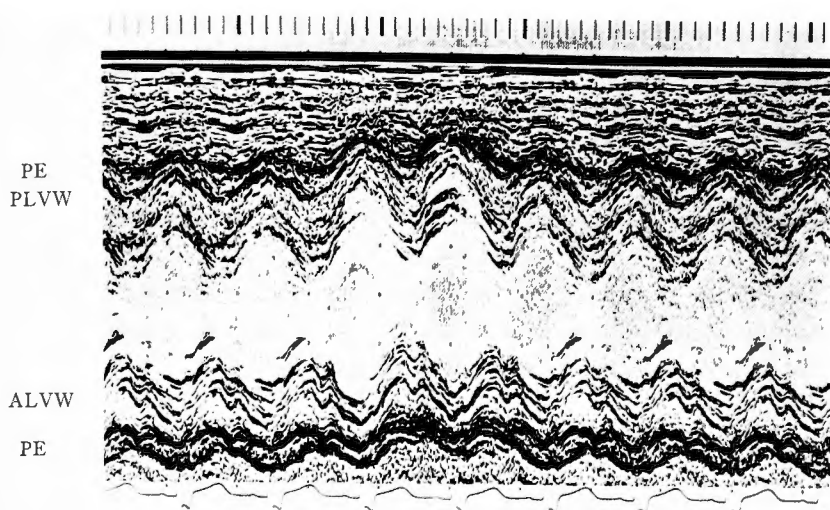


Fig. 32. Transesophageal M-mode echocardiogram of pericardial effusion.
ALVW: anterior left ventricular wall, PLVW: posterior left ventricular wall.
PE: pericardial effusion.

Cardiac tamponade:

Cardiac tamponade is one of the common complications in cardiac surgery. Echocardiography is generally accepted as a useful method of detecting pericardial effusion. The conventional anterior approach is frequently of little use in the early postoperative period, because of the poor quality of its image. Figure 32 is a transesophageal echocardiogram of pericardial effusion. Effusion is well identified in front of the anterior left ventricular wall and behind the posterior left ventricular wall. Therefore, This method is useful in the early detection of cardiac tamponade.

Summary

Transesophageal M-mode echocardiography provided a clear echogram as a mirror image of the anterior echocardiogram. It had a higher rate of detection of various echograms than anterior echocardiography, not only in aged patients with chronic obstructive lung disease, but also in patients during and soon after cardiac surgery. Moreover, various measurements by this method correlated well with those obtained by anterior echocardiography.

Transesophageal echocardiography was performed in 20 patients undergoing cardiac operation in order to assess its value during and soon after cardiac surgery. Their diseases were: atrial septal defect (5), partial endocardial cushion defect (1), ventricular septal defect (1), mitral stenosis (6), mitral regurgitation (1), aortic regurgitation (2), ischemic heart disease (2), and constrictive pericarditis (2).

SV measured by transesophageal echocardiography correlated well with that obtained by thermo-dilution, and there were high correlations between EF and CI, and between mVcf and

CI, while STI correlated inversely with CI. PSP/ESD also correlated well with EF.

Observing the change in these indices offered much information concerning left ventricular systolic function after cardiac surgery. Moreover, measurement of pulmonary capillary wedge pressure, combined with the left ventricular volume determined by this method, provided the left ventricular diastolic characteristics ("normalized compliance").

In addition, intraoperative evaluation of mitral reconstructive surgery, prevention of focal micro-embolism and early detection of cardiac tamponade were thought to be possible.

Therefore, continuous monitoring by transesophageal echocardiography appears to be valuable for intra- and post-operative management of cardiac surgery, especially in anticipation of low cardiac output syndrome and other serious complications.

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和文抄録

経食道的Mモード心エコー法：心臓手術後早期に
おける左心機能評価への応用大阪市立大学医学部外科学第二講座（主任：酒井克治教授）
京都大学医学部外科学第二講座（主任：日笠頼則教授）

村 口 和 彦

経食道超音波探触子を作成し、経食道的心エコー法の臨床的有用性について、心臓病、非心臓病患者を含む30例で検討した。

探触子は Aerothec-10 mm-5 MHz を用い、選択的気管支造影用 catheter の先端に装着し、使用した。これにより探触子の食道内挿入・回転・屈曲は容易であった。得られた心エコー図は、前胸壁心エコー図の鏡面像に一致し、また探触子が食道壁を介して直接に心臓後壁に接するため、本法は画質や各種エコー図の検出率において優れていた。その上、各種計測値は前胸壁心エコー法によるそれらと非常に高い相関を示し、本法が臨床上有用である事が実証された。特に、従来しばしば記録が困難であった心臓手術中・術後早期への本法の応用は、極めて有意義であると思われる。

そこで、心臓手術中・術後早期への応用の有用性を検討するために、20心臓手術例の術中・術後早期に経食道的心エコー法を施行した。

本法は、手術野を妨げる事なく術中の使用も可能であり、しかも画質は術中・術後とも良好であった。また、本法による SV は熱希釈法によるそれと、EF および mVcf は CI と良好な相関を示し、本法が開心術後の左室収縮能の評価に有用である事が示唆された。一方、STI は CI と逆相関を、PSP/ESP は EF と正の相関を示し、これらの指標も左室収縮能を良く反映するものと考えられた。本法による左室容積変化と平均肺動脈契入圧の関係からは、左室 Compliance の術後変化をも観察可能であり、したがって、経食道的心エコー法は、心臓手術後の左心機能の観察に優れた手段である。

さらに、僧帽弁形成術の術中評価や空気塞栓症の予防および心タンポナーデの早期発見の可能性も示唆され、本法は、心臓手術中・術後管理に有用な非侵襲的手段として今後注目されるものと思われる。