

Intraoperative Transesophageal Echocardiography for the Detection of Cardiac Preload Changes Induced by Transfusion and Phlebotomy in Pediatric Patients

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Background: Intraoperative blood volume changes are difficult to monitor in pediatric patients. The authors tested the hypothesis that transesophageal echocardiography would identify changes in cardiac filling resulting from manipulations of blood volume.

Methods: Eleven patients (3–15 kg) were studied following sternal closure after repair of congenital heart lesions. Transesophageal echocardiography of the midpapillary left ventricular short axis view and hemodynamics were recorded at baseline (T1), during withdrawal of blood until the systolic blood pressure decreased by 5 mmHg (T2) and 10 mmHg (T3), and after reinfusion of the blood (T4). The identical cycle of blood withdrawal and reinfusion was repeated after administration of calcium chloride (10 mg/kg; T5–T8).

Results: Manually traced transesophageal echocardiography images of the left ventricular end-diastolic area decreased from 4.64 ± 1.50 cm² at T1 to 4.03 ± 1.25 cm² at T2 to 3.78 ± 1.35 cm² at T3, and increased to 4.42 ± 1.75 cm² at T4. Nearly identical results were obtained at T5–T8. End-systolic areas significantly decreased from 1.96 ± 0.86 cm² at T1 to 1.52 ± 0.73 cm² at T2 to 1.41 ± 0.62 cm² at T3, and increased to 1.87 ± 0.88 cm² at T4. An experienced anesthesiologist–echocardiographer blinded to study events was able to identify mild reductions in blood volume (T2, T3, T6, T7) from recorded cine-loop video recordings with high sensitivity (80–95%) and specificity (80%).

Conclusions: Transesophageal echocardiography is a potentially useful monitor of cardiac filling changes in pediatric patients. (Key words: Anesthesia, pediatric; children; infants. Hypovolemia. Measurement techniques: transesophageal echocardiography.)

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IN addition to documenting surgical problems and their corrections, transesophageal echocardiography (TEE) may be used to make quantitative and qualitative assessments of cardiac function in the perioperative period.¹ This type of measurement could be important in the pediatric patient, because the use of monitoring devices is limited by the size of the patient, the anatomic features of congenital heart lesions, and the relative invasiveness of the devices.

Assessment of Intraoperative Blood Volume Changes

The intraoperative assessment of blood volume changes in pediatric cardiac surgical patients is traditionally performed using central venous pressure (CVP), left atrial pressure, pulmonary arterial pressure, and visual observation of the heart. In pediatric patients, cardiac output is more heart rate-dependent than preload-dependent.² Nevertheless, close attention to the blood volume status is required in pediatric patients during procedures with major blood volume shifts, such as cardiac surgery. Transesophageal echocardiography may allow additional assessment of blood volume status in this age group, supplementing currently available monitoring. The purpose of this study was to measure the ability of manually traced and visually observed two-dimensional TEE images to detect changes in cardiac areas that occur during intraoperative manipulations of blood volume in pediatric cardiac surgical patients.

Materials and Methods

Patient Population

The study protocol was approved by the Institutional Review Board and informed consent was obtained from the parent or legal guardian before surgery. Pediatric

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patients, ranging in weight from 3 to 15 kg, scheduled to undergo elective surgical repair of congenital heart disease requiring cardiopulmonary bypass (CPB) were included in the study. Patients with residual interatrial or interventricular connections after CPB were excluded from the study. Only patients who were hemodynamically stable, normotensive, and receiving minimal or no inotropic support ($\leq 5 \mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ of dopamine) were included in the study.

Study Protocol

All patients had an Aloka (Corometrics, Wallingford, CT) pediatric transesophageal echocardiography probe inserted after induction of anesthesia. The study was conducted after the completion of CPB, protamine administration, and closure of the sternum. In all patients, the intravascular blood volume status was restored after CPB by transfusing blood remaining in the CPB circuit and citrated whole blood. After sternal closure, blood was administered in 10-ml/kg increments until no further increase was seen in arterial blood pressure with additional volume. A 5-min equilibration period was permitted before initiation of the study.

Echocardiographic and hemodynamic recordings were performed at the following time sequence: after a baseline measurement was performed (T1), blood was withdrawn from the central venous catheter until the systolic blood pressure had decreased by 5 mmHg (T2) and 10 mmHg (T3) from the baseline value, respectively. All the withdrawn blood was returned to the patient and a return-to-baseline interval was recorded (T4). After T4, a 10-mg/kg intravenous bolus of calcium chloride was injected. After a 60-s equilibration period, a second baseline (T5) was recorded. Blood was withdrawn from the central venous catheter until the systolic blood pressure had decreased by 5 mmHg (T6) and 10 mmHg (T7) from the second baseline recording. All the withdrawn blood was returned to the patient, and a return-to-baseline interval was recorded (T8).

Echocardiographic Images

Echocardiographic imaging of the left ventricle was performed at the midpapillary muscle short axis view. The image obtained was a tomographic plane with a round cross-section of the left ventricle and with the papillary muscles transected at the same level. This view was maintained throughout the study period. Ten-second video recordings were obtained at each study interval for later analysis.

The TEE images were traced off-line using a dedicated Aloka 870 Ultrasonograph (Corometrics). Two investigators, blinded to the study interval, traced left ventricular end-diastolic area (LVEDA) and end-systolic area (LVESA). Left ventricular areas were measured by tracing the endocardial borders of the myocardium using the video monitor and trackball and a leading edge-to-leading edge convention. The papillary muscles were included within the area of the left ventricle. Three separate tracings of systole and diastole during consecutive cardiac cycles were made by each investigator for each study interval. LVEDA and LVESA were calculated from the combined data of observer 1 and observer 2 using the mean of the six end-diastolic and end-systolic tracings, respectively, at each study interval. Stroke area (SA = LVEDA - LVESA) and ejection fraction area (EFA = SA/LVEDA) were computed from the mean values of LVEDA and LVESA at each study interval.

In addition to the above, an experienced echocardiographer was tested to determine whether blood volume changes could be detected by observation of short repeating segments (cine-loops) of the video image. The investigator was first shown a cine-loop identified as a baseline (T1 or T5) image. The same investigator then was shown the cine-loop from T2, T3, T4, T6, T7, or T8 in a blinded, randomized fashion. The investigator classified the unknown cine-loops as either hypovolemic or normovolemic in comparison with the baseline cine-loop. Each cine-loop was compared with its respective baseline (*i.e.*, T6 was compared with T5, and T4 was compared with T1), and each cine-loop was shown to the investigator only once.

Hemodynamic Measurements

All hemodynamic measurements were made using electronic transducers zeroed to the level of the right atrium. The patients' position was not changed during the study. Hemodynamics were recorded on a multi-channel recorder (Hewlett-Packard, Waltham, MA) for later analysis. The end-expiratory point was marked on the paper tracing, and this point was used for the calculation of hemodynamic parameters. Heart rate, mean arterial pressure, systolic blood pressure, diastolic blood pressure, and CVP were determined from the paper tracing.

Data Analysis

For the purposes of the cine-loop analysis, T2 and T6 were defined as level 1 hypovolemia. T3 and T7 were

defined as level 2 hypovolemia. T4 and T8 were defined as normovolemia. A correct interpretation of T4 or T8 as normovolemia was considered a true-negative, and an incorrect interpretation was considered a false-positive. A correct interpretation of T2, T3, T6, or T7 as hypovolemia was considered a true-positive, and an incorrect interpretation was considered a false-negative. These data were analyzed by calculating the following:

$$\text{sensitivity} = \frac{\text{True positives}}{\text{True positives} + \text{False negatives}},$$

$$\text{specificity} = \frac{\text{True negatives}}{\text{True negatives} + \text{False positives}},$$

positive predictive value

$$= \frac{\text{True positives}}{\text{True positives} + \text{False positives}},$$

negative predictive value

$$= \frac{\text{True negatives}}{\text{True negatives} + \text{False negatives}},$$

for correctly interpreting the cine-loop as hypovolemic or normovolemic. There were twice as many hypovolemic cine-loops as normovolemic cine-loops. Thus, to prevent bias, positive and negative predictive value calculations were performed individually for level 1 and level 2 hypovolemia.

Echocardiographic intraobserver variability (precision) was determined for each observer by calculating the average percentage of the absolute value of the difference between the three individual tracings and the mean value for LVESA and LVEDA:

$$\frac{(|\text{LVESA}_1 - \overline{\text{LVESA}}|) + (|\text{LVESA}_2 - \overline{\text{LVESA}}|) + (|\text{LVESA}_3 - \overline{\text{LVESA}}|)}{\overline{\text{LVESA}}} \div 3 \times 100\%,$$

$$\frac{(|\text{LVEDA}_1 - \overline{\text{LVEDA}}|) + (|\text{LVEDA}_2 - \overline{\text{LVEDA}}|) + (|\text{LVEDA}_3 - \overline{\text{LVEDA}}|)}{\overline{\text{LVEDA}}} \div 3 \times 100\%.$$

The interobserver variability (bias) was determined by calculating the difference between the mean measurements for the two observers divided by the average of the two numbers:

$$\frac{\text{Observer 1} - \text{Observer 2}}{(\text{Observer 1} + \text{Observer 2}) \div 2} \times 100\%.$$

Means and standard deviations were calculated for intraobserver and interobserver variability at each study interval and for the entire study.

Continuous data were analyzed using analysis of variance and Scheffé's multiple contrasts. $P < 0.05$ was considered statistically significant. All analyses were two-tailed.

Results

Blood Volume Changes

Quantitative Data. Eleven patients (aged 6 to 36 months) successfully completed the protocol, and at no time did the mean arterial pressure decrease below 50 mmHg. Demographic data are presented in table 1. The LVEDA and LVESA data are presented in figure 1. There were significant reductions ($P < 0.05$) in LVEDA and LVESA with both levels of hypovolemia. Baseline (mean of T1 and T5) LVEDA was $4.53 \pm 1.60 \text{ cm}^2$, and the baseline LVESA was $2.11 \pm 0.94 \text{ cm}^2$. During level 1 hypovolemia (mean of T2 and T6), the LVEDA decreased to $4.29 \pm 1.43 \text{ cm}^2$, and the LVESA decreased to $1.83 \pm 0.83 \text{ cm}^2$. During level 2 hypovolemia (mean of T3 and T7), the LVEDA decreased to $3.96 \pm 1.41 \text{ cm}^2$ and the LVESA decreased to $1.78 \pm 0.75 \text{ cm}^2$. Systolic blood pressure and CVP also decreased significantly ($P < 0.05$) with both levels of hypovolemia, and the data are summarized in table 2.

Cine-Loop Data. In a comparison of the baseline images (T1 and T5) with images obtained after reinfusion of the blood (T4 and T8), there were 16 true-negatives and 4 false-positives. In comparing baseline images (T1 and T5) with level 1 hypovolemia (T2 and T6), there were 16 true-positives and 4 false-negatives. At level 2 hypovolemia (T3 and T7), there were 19 true-positives and 1 false-negative. There was a sensitivity of 88% in detecting hypovolemia at both levels. At normovolemia, there was a specificity of 80%. At level 1 hypovolemia, the sensitivity was 80%, the positive predictive value was 80%, and the negative predictive value was 80%. At level 2 hypovolemia, the sensitivity was 95%, the positive predictive value was 83%, and the negative predictive value was 94%.

Variability

For observer 1, the intraobserver variability for LVEDA and LVESA across all measurement intervals was 6% and 9%, respectively. For observer 2, the intraobserver

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Table 1. Demographic Data

Patient No.	Age	Weight (kg)	Sex	Diagnosis	Procedure
1	5 d	3	M	Right atrial tumor	Tumor debulking of right heart
2	19 mo	10	M	Tetralogy of Fallot	Tetralogy of Fallot repair
3	13 mo	11	M	Atrial septal defect	Atrial septal defect repair
4	36 mo	15	M	Atrial septal defect	Atrial septal defect repair
5	22 mo	10	F	Tetralogy of Fallot	Tetralogy of Fallot repair
6	32 mo	10	F	Atrial septal defect	Atrial septal defect repair
7	29 mo	11	M	Subaortic membrane	Subaortic membrane excision
8	6 mo	5	F	AV canal defect	AV canal repair
9	10 mo	5	M	AV canal defect	AV canal repair
10	17 mo	11	M	RVOT obstruction	RVOT repair
11	42 mo	11	M	Tetralogy of Fallot	Tetralogy of Fallot repair

AV = atrioventricular; RVOT = right ventricular outflow tract.

variability for LVEDA and LVESA across all measurement intervals was 5% and 9%, respectively. The interobserver (bias) variability across all measurement intervals was 13% for LVEDA and 46% for LVESA. The intraobserver (precision) and interobserver (bias) data for individual study intervals are presented in table 3.

Discussion

Detection of Blood Volume Changes Using Transesophageal Echocardiography

Because of the steep slope of the Frank-Starling curve in pediatric patients, it is important to monitor intravascular blood volume during procedures that involve major blood volume shifts, such as cardiac surgery. Normally, intravascular volume is monitored in pediatric cardiac surgery using central venous and/or left

atrial pressures and visual observation of the heart. The current study was designed to determine the utility of visually observed and manually traced TEE images for the intraoperative assessment of clinical changes in blood volume.

This investigation demonstrated that a decrease in blood volume of approximately 5–8% reduced LVEDA, CVP, and systolic blood pressure. Although all the changes in ventricular areas, CVP, and systolic blood pressure were significant, the absolute changes in CVP were small in numeric terms. A decrease in CVP from 10 to 9 mmHg could be attributed to physiologic variability, respiratory variation, or changes in transducer height relative to the patient. Therefore, hypovolemia presenting with changes in CVP may go undetected in the clinical setting, though it may represent a considerable intravascular volume change. Using TEE, however, qualitative and quantitative measurements dem-

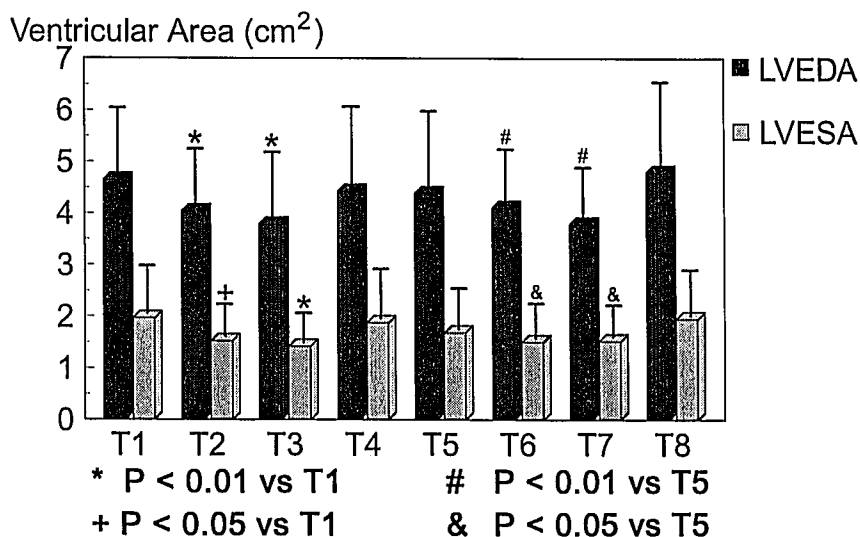


Fig. 1. Mean \pm SD of left ventricular end-diastolic area (LVEDA) and left ventricular end-systolic area (LVESA) for study intervals T1–T8. The data represent the average of multiple manual endocardial tracings of observers 1 and 2.

Table 2. Hemodynamic Data

	T1	T2	T3	T4	T5	T6	T7	T8
HR (beats/min)	133 ± 16	139 ± 20	138 ± 16	135 ± 17	135 ± 17	136 ± 15	137 ± 15	136 ± 15
MAP (mmHg)	70 ± 4	63 ± 4	57 ± 4	69 ± 6	73 ± 9	66 ± 7	62 ± 7	75 ± 13
DBP (mmHg)	55 ± 4	49 ± 4	45 ± 4	53 ± 4	56 ± 6	52 ± 5	49 ± 5	58 ± 9
SBP (mmHg)	93 ± 7	84 ± 5	76 ± 5	90 ± 10	97 ± 12	89 ± 11	83 ± 11	99 ± 16
BVR (ml/kg)	0	3.8 ± 2.5	5.9 ± 2.3	0	0	4.0 ± 2.1	6.8 ± 2.2	0
CVP (mmHg)	10 ± 3	9 ± 3	9 ± 3	10 ± 3	11 ± 3	9 ± 2	9 ± 2	11 ± 3

HR = heart rate; MAP = mean arterial pressure; DBP = diastolic blood pressure; SBP = systolic blood pressure; BVR = blood volume removed; CVP = central venous pressure.

onstrated changes in left ventricular filling. The two observers found 5% decrease in LVEDA with the first level of hypovolemia (T2 and T5) and 13% decrease in LVEDA with the second level of hypovolemia (T3 and T7).

Manual off-line tracings are not a practical way to determine blood volume changes in the operating room. An experienced anesthesiologist–echocardiographer who was blinded to the events of the study was able to determine decreases in blood volume with high sensitivity (80–95%) and specificity (80%) when analyzing off-line images. This situation differed from the clinical scenario in that the observer was shown the baseline image immediately before assessing the unknown images. These comparisons could be made online in the operating room using split-screen and cine-loop technology. It is conceivable, however, that an anesthesiologist could commit more errors interpreting images in the operating room environment because of distractions related to other aspects of patient care.

Preliminary investigations have been performed using two-dimensional automated border detection systems (ABD). The preliminary results of Gorcsan *et al.*³ demonstrated that ABD accurately detected true changes in ventricular volume in canine hearts using the midpapillary left ventricular short axis view. While varying the left ventricular volume using an intraventricular

balloon, the borders of the left ventricle were measured using the ABD system. Automated border detection echo area was correlated to absolute volume changes with an *r* value of 0.98. Another preliminary study done by Gorcsan *et al.* used ABD to measure the left ventricular cavity area in four adult patients using the same view.⁴

The ABD technology could be more difficult to apply to pediatric TEE. The image quality is impaired by the reduced number of ultrasonic crystals. In addition, there seems to be accentuated respiratory movement of the heart relative to the esophagus in pediatric patients. This would complicate ABD information acquisition by moving the heart outside of the “region of interest” that must be manually identified by the echocardiographer.

The variability inherent in repeated manual endocardial border tracings and the poor resolution of echocardiographic images were probably the two major sources of error in this study. This can be seen in the contrast between the numeric results of observer 1 and observer 2. LVESA was often difficult to measure because the endocardial borders of the contracting ventricle appeared to collapse upon themselves and could no longer be visualized. This difficulty was reflected in the high interobserver variability that occurred with LVESA measurements.

As the resolution quality of TEE images improves, the

Table 3. Intraobserver and Interobserver Variability (%)

	T1	T2	T3	T4	T5	T6	T7	T8
Intraobserver 1 EDA	5 ± 3	5 ± 3	6 ± 5	6 ± 4	5 ± 2	5 ± 3	6 ± 3	6 ± 3
Intraobserver 2 EDA	4 ± 3	5 ± 4	5 ± 5	5 ± 5	5 ± 4	8 ± 4	5 ± 2	3 ± 1
Intraobserver 1 ESA	6 ± 4	9 ± 6	11 ± 4	11 ± 7	6 ± 4	9 ± 7	12 ± 8	11 ± 7
Intraobserver 2 ESA	10 ± 6	9 ± 5	9 ± 8	9 ± 7	8 ± 6	9 ± 7	8 ± 6	8 ± 6
Interobserver EDA	12 ± 20	12 ± 10	16 ± 11	9 ± 6	7 ± 6	19 ± 11	13 ± 9	13 ± 9
Interobserver ESA	41 ± 27	45 ± 30	53 ± 33	37 ± 23	38 ± 38	52 ± 37	58 ± 43	40 ± 34

Values are mean ± SD.

EDA = left ventricular end-diastolic area; ESA = left ventricular end-systolic area.

intraoperative utility of TEE for detection of blood volume changes in pediatric patients should increase. Another important innovation that will improve volume status detection is split-screen cine-loop capability. With this technology, it should be possible to directly compare two images (acquired at different times) on the same screen to facilitate the visual detection of changes in intravascular volume.

It was one of the authors' original intentions to assess the hemodynamic effects of calcium chloride by plotting LVESA against arterial systolic pressure during rapid variations in ventricular preload before and after an intravenous bolus of calcium chloride. The difficulties inherent in measuring LVESA with the current pediatric TEE system and the minimal hemodynamic response to calcium chloride prevented this attempt to approximate end-systolic pressure-volume relationship determinations in pediatric patients. These patients had received citrated blood products after CPB but were probably not acutely hypocalcemic at the point when calcium chloride was administered. The minimal hemodynamic response to calcium chloride (table 2) also could have been due to the low dose of calcium chloride administered.

In conclusion, intraoperative pediatric TEE was used to detect changes in intracardiac volume a group of infants and young children. Both manual (off-line) tracings of the end-diastolic area of the left ventricle and visual comparison of cine-loop images to baseline images during acute decreases in blood volume were effective methods of identifying cardiac filling changes in this age group.

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