The accuracy of preload assessment by different transesophageal echocardiographic techniques in patients undergoing cardiac surgery

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Abstract

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Accuracy of preload assessment
by different transesophageal echocardiographic techniques
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Abstract

Objectives: Aim of this study was to compare different approaches to assess left ventricular preload by transesophageal echocardiography (TEE): Left ventricular end-diastolic volume index (LVEDVI) determined using the method of disc summation (LVEDVI<sub>Md</sub>) and left ventricular end-diastolic area index (LVEDAI) were compared to LVEDVI assessed by the modified Simpson Formula (LVEDVI<sub>Si</sub>). Global end-diastolic volume index (GEDVI) and stroke volume index (SVI) measured by the PiCCO plus system (Pulsion Medical Systems, Germany) were used as TEE-independent reference variables.

Design: Prospective observational study.

Setting: Community hospital.

Participants: 22 patients undergoing elective cardiac surgery.

Interventions: Following induction of anesthesia hemodynamic assessment by TEE and the PiCCO plus system was made 20 (T<sub>1</sub>) and 10 min (T<sub>2</sub>) before, as well as 10 (T<sub>3</sub>) and 20 min (T<sub>4</sub>) after a fluid trial. At each time point LVEDVI<sub>Md</sub>, LVEDAI, LVEDVI<sub>Si</sub>, GEDVI and SVI were determined.

Measurements and Main Results: The fluid trial resulted in a significant increase of all preload variables measured at T<sub>3</sub>. At T<sub>4</sub>, all preload variables but LVEDVI<sub>Md</sub> showed a significant decrease. Mean bias±2SD for %changes (Δ) of LVEDVI<sub>Md</sub>-ΔLVEDVI<sub>Si</sub> was +1.5±59.0% and for Δ LVEDAI-ΔLVEDVI<sub>Si</sub> +0.9±23.6%. The correlation between LVEDVI<sub>Md</sub> and LVEDVI<sub>Si</sub> was significantly weaker than between LVEDAI and LVEDVI<sub>Si</sub> (p<0.001). Comparing TEE measurements with GEDVI and SVI, strong correlations were observed for LVEDAI and LVEDVI<sub>Si</sub> only.

Conclusion: The method of disc summation cannot be recommended for preload assessment during a fluid challenge in cardiac surgery patients. By contrast, single plane area
measurements provided reliable information when compared to the application of the modified Simpson Formula.

**Keywords**

Cardiac preload assessment, end-diastolic volume, end-diastolic area, Simpson formula, method of discs summation, trans-esophageal echocardiography, trans-pulmonary thermodilution, off-pump coronary artery bypass grafting
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Introduction

Preload optimization is a prerequisite for adequate cardiac performance and sufficient organ perfusion in the perioperative period. Preload, defined as end-diastolic myocardial fiber length or fiber tension can only be determined in an experimental setting\(^1\). In clinical practice, measurement of central venous pressure and pulmonary artery occlusion pressure are being used as surrogates for cardiac preload despite the fact that they have been shown to poorly reflect left ventricular preload\(^2,3\). In an attempt to better assess cardiac preload, transesophageal echocardiography (TEE) is being increasingly used to estimate the volume status of patients. Furthermore, alternative parameters measuring end-diastolic volumes by transpulmonary thermodilution (PiCCO\textsubscript{plus} system, Pulsion Medical Systems; Germany) have been introduced into clinical practice recently. These volumetric indices have been shown to better reflect preload compared to central venous pressure and pulmonary capillary occlusion pressure and to correlate well with volumetric preload assessment by echocardiography\(^4-7\).

There are different approaches to assess preload using TEE either by measuring and calculating left ventricular end-diastolic area or volume\(^8-10\). Left ventricular end-diastolic volume is considered superior and calculation is typically based on the assumption that the ventricles consist of a sum of small cylinders and a truncated ellipse (Simpson algorithm). The modified Simpson Formula incorporates this algorithm and left ventricular end-diastolic volumes can be reliably assessed in patients without gross geometrical ventricular distortions\(^11\). Because three positions of the TEE probe are required, this method is time-consuming,
distracting and therefore unsuitable in a perioperative setting. Alternatively, preload measurements may be performed by the semi-automated *method of disc summation*. This approach relies also on the Simpson algorithm and calculates volume from multiple diameters perpendicular to a longitudinal ventricular axis. It is assumed to be the method of choice for volume calculation in the presence of considerable distortions of the left ventricle and can be performed in a single plane view, but conflicting results have been reported using this echocardiographic approach. In daily practice in the operating room, however, the left ventricle is predominantly visualized in a short axis view and *left ventricular area* is typically used as a surrogate of cardiac preload assessment by anesthesiologists.

The aim of this prospective study was to compare the two most convenient techniques - the left ventricular end-diastolic volume determined by the *method of disc summation* and the *left ventricular end-diastolic area* - with the left ventricular end-diastolic volume measurement using the *modified Simpson formula* in patients with preserved left ventricular function undergoing cardiac surgery. Global end-diastolic volume and stroke volume were determined by the PiCCOplus system to serve as TEE independent reference measurements.
Methods

Patients

With local ethics committee approval and written informed consent patients with preserved left ventricular function undergoing elective off-pump coronary artery bypass grafting were studied. Patients with preoperative dysrhythmias, reduced left and right ventricular function (ejection fraction < 40%), valvular heart disease, intracardiac shunts, pulmonary artery hypertension or severe arterial occlusion disease (contraindication for the placement of a PiCCO catheter) were excluded. Sample size of \( \geq 20 \) patients was selected on the hypothesis of an expected response of 10% of hemodynamic variables to fluid replacement (level of significance = 0.05%, power = 90%) according to a previously performed study \(^6\).

Anesthetic technique

After arrival of the patient in the operating room, routine hemodynamic monitoring was applied (pulse oximetry, 5-lead ECG and non-invasive blood pressure monitoring; CMS, Philips Medical Systems, Andover, MA) and the radial artery cannulated for invasive blood pressure measurements. Lactated Ringer's solution was given continuously at a rate of 2 ml kg\(^{-1}\) hr\(^{-1}\) iv. Anesthesia was induced by fentanyl (10-30 \( \mu \)g kg\(^{-1}\) iv) and propofol (up to 2 mg kg\(^{-1}\) iv) and was maintained with additional propofol (1.5-3 mg kg\(^{-1}\) h\(^{-1}\)) and fentanyl (10 \( \mu \)g kg\(^{-1}\) iv). Pancuronium bromide (0.1 mg kg\(^{-1}\) iv) was given for muscle relaxation. The patient’s trachea was intubated and the lungs were mechanically ventilated without positive end-expiratory pressure using an inspired O\(_2\)-concentration of 50% and tidal volumes of 7-8 ml kg\(^{-1}\) to maintain end-expiratory PCO\(_2\) at 4 – 4.5 kPa.

Transpulmonary thermodilution

A 4F thermistor-tipped arterial catheter (Pulsiocath thermodilution catheter) was inserted into the left femoral artery, its tip advanced to the abdominal aorta, and connected to the stand-alone PiCCO\(_{\text{plus}}\) computer (Version 5.2.2; Pulsion Medical Systems, Munich, Germany).
Stroke volume and global end-diastolic volume were determined by a triplicate 20 ml ice-cold normal saline injection through a 7F central venous catheter. The determination of global end-diastolic volume has been described in detail elsewhere (4-7).

**Preload assessment by transesophageal echocardiography (TEE)**

TEE was done using a Philips SONOS 5500 system with an Omniplane III - TEE probe (Philips Medical Systems, Andover, MA; USA) at end-expiration. All measurements were performed by the same experienced examiner after adjustment of dynamic range and gain controls as well as optimization of image resolution by harmonic B-color imaging. Echocardiographic preload variables were calculated off-line by this examiner blinded to patient data and all hemodynamic information.

**Methods of disc summation**

The TEE probe was positioned in the mid-esophagus and retroflexed to visualize the ventricular apex in the two-chamber view. Visualization of the mitral valve annulus and apex were optimized by adjustment of acoustic power and gray levels, prerequisites for an optimal determination of length of the left ventricle. Endocardial boundaries of the left ventricle were determined according to the guidelines of the American Society of Echocardiography and volumes calculated by the software integrated in the Philips SONOS 5500 system.

**Modified Simpson Formula**

The initial position of the probe (mid-esophageal, two-chamber view) was also used for left-ventricular volume determination by the methods of disc summation. The probe was then advanced to obtain two cross sectional areas in the trans-gastric short axis view at mitral and papillary muscle level. For the calculation of the left-ventricular end-diastolic volume using the modified Simpson Formula, ventricular length (L) was defined as the distance from the leading endocardial edge at the ventricular apex to the midpoint of the mitral annulus. Left ventricular end-diastolic area was measured at the mitral and mid-papillary level.
(LVEDA\textsubscript{mitral}, LVEDA\textsubscript{papillary}) by manual planimetry of the area circumscribed by the leading edge of the endocardial border in the short axis view. End diastole was determined as the largest left ventricular dimension after the electrocardiographic R wave. The left-ventricular end-diastolic volume (LVEDV) was calculated according to the following formula\textsuperscript{18}:

\[
\text{LVEDV} = L \times 3^{-1} + L \times 6^{-1} \times (\text{LVEDA}_{\text{mitral}}) + L \times 6^{-1} \times (\text{LVEDA}_{\text{mitral}} + \text{LVEDA}_{\text{papillary}}) + L \times 9^{-1} \times (\text{LVEDA}_{\text{papillary}})
\]

Left-ventricular end-diastolic area

For comparative analysis, left-ventricular end-diastolic area assessed at mid-papillary level in the trans-gastric short axis view was used.

Study sequence

Following induction of anesthesia and hemodynamic stabilization, measurements were performed 20 (T\textsubscript{1}) and 10 min (T\textsubscript{2}) before as well as 10 (T\textsubscript{3}) and 20 min (T\textsubscript{4}) after a fluid bolus (10 ml kg\textsuperscript{-1} of 6% hydroxyethyl starch solution HES 130/0.4, Voluven\textsuperscript{®}, Fresenius Kabi, Stans, Switzerland; administered over a time period of 20 min). At each time point TEE was performed, and standard hemodynamic measurements (heart rate [HR], mean arterial pressure [MAP], central venous pressure [CVP], and SV as well as GEDV) were assessed simultaneously. All measurements were recorded as mean of 3 consecutive readings at intervals of 3 min.

Statistical analysis

TEE and PiCCO variables were post-hoc indexed to body surface area by means of the Du Bois formula: BSA = body weight[kg]\textsuperscript{0.425} x body length[cm]\textsuperscript{0.725} x 71.84 (left-ventricular end-diastolic volume index assessed by the method of disc summation = LVEDVI\textsubscript{Md}, left-ventricular area index at mid-papillary level = LVEDAI and left-ventricular end-diastolic volume index determined by the modified Simpson formula = LVEDVI\textsubscript{Si}; global end-diastolic volume index = GEDVI, stroke volume index = SVI).
Statistical analysis was performed using Statview 5.01® Software (SAS Institute Inc. Cary, USA). ANOVA with post-hoc Bonferroni/Dunn correction was calculated for comparison of hemodynamic data during the study period. Bland-Altman analysis was done to compare % changes of LVEDVIMd and LVEDAI with those of LVEDVISi as well as % changes of all TEE preload measurements with GEDVI. Pearson correlations comparing all variables assessed by TEE and the PiCCOplus system were established for absolute values and % changes. Fisher’s z transformation and Hotelling-Williams test was used to compare correlation coefficients for statistical difference. A p-value <0.05 was considered statistically significant.
Results

86 complete sets of data were obtained for statistical analysis from 22 patients (5 women and 17 men, ages = 67±8 years, body mass index = 28±4 kg m⁻², ejection fraction = 64±9 %), in one patient low quality of echocardiographic images at the last two measurement time points made reliable measurements impossible.

Effect of fluid challenge

The fluid challenge (between T₂ and T₃) resulted in a significant rise of mean arterial pressure, SVI and CVP. In parallel, the echocardiographic variables LVEDVIₘᵩ, LVEDAI and LVEDVIₛᵢ as well as GEDVI assessed by the PiCCOplus system increased significantly. A significant reduction of MAP and SVI was observed at 30 min after the fluid bolus (T₄) compared to the measurements at 15 min after fluid bolus (T₃). Changes of CVP were not significant. Only LVEDVIₛᵢ, LVEDAI and GEDVI but not LVEDVIₘᵩ decreased significantly (Table 1).

Comparison of LVEDVIₘᵩ and LVEDAI with LVEDVIₛᵢ

Bland-Altman analysis of % changes (Δ) caused by the fluid challenge during the study period revealed a mean bias±2SD of +1.5±59.0% for ΔLVEDVIₘᵩ-ΔLVEDVIₛᵢ and of +0.9±23.6 % for ΔLVEDAI-ΔLVEDVIₛᵢ (Figure 1A and B). Mean bias±2SD for absolute values of LVEDVIₘᵩ-LVEDVIₛᵢ was -2.2± 28.2 ml m⁻². The correlations between absolute values and % changes (Δ) between LVEDVIₘᵩ and LVEDVIₛᵢ were significantly weaker than between LVEDAI and LVEDVIₛᵢ (p ΔLVEDVIₘᵩ-ΔGEDVI vs ΔLVEDVIₛᵢ = 0.004, p ΔLVEDVIₘᵩ-ΔLVEDAI-ΔLVEDVIₛᵢ = 0.003; Table 2 and 3, Figure 2 and 3).

Comparison of TEE variables with GEDVI and SVI

Comparing the TEE preload variables LVEDVIₘᵩ, LVEDAI and LVEDVIₛᵢ with GEDVI, largest mean bias and limits of agreement was observed for ΔLVEDVIₘᵩ - ΔGEDVI (+4.1±51.8%, Figure 4 A). By contrast, bias and limits of agreement were similar for
\( \Delta \text{LVEDAI} - \Delta \text{GEDVI} \ (\pm 3.7 \pm 23.8\%) \) and \( \Delta \text{LVEDV}_{\text{Si}} - \Delta \text{GEDVI} \ (\pm 2.7 \pm 27.8\%, \text{Figure 4 B and C}) \). Weak correlations for absolute values and \% of \( \text{LVEDV}_{\text{Md}} - \text{GEDVI} \) were observed (Table 2 and 3). Correlations of \( \text{LVEDAI} - \text{GEDVI} \) and \( \text{LVEDV}_{\text{Si}} - \text{GEDVI} \) showed no statistically significant difference (\( p_{\text{LVEDAI-GEDVI vs. LVEDV}_{\text{Si}}-\text{GEDVI}} = 0.675, p_{\Delta \text{LVEDAI-\Delta GEDVI vs. \Delta \text{LVEDV}_{\text{Si}}-\Delta \text{GEDVI}}} = 0.849 \)). They were significantly stronger than the correlation of \( \text{LVEDV}_{\text{Md}} - \text{GEDVI} \) (\( p_{\text{LVEDV}_{\text{Md}}-\text{GEDVI vs. LVEDV}_{\text{Si}}-\text{GEDVI}} = 0.006, p_{\Delta \text{LVEDV}_{\text{Md}}-\Delta \text{GEDVI vs. \Delta \text{LVEDAI-\Delta GEDVI}}} = 0.001 \)).

A similar pattern was observed for the correlation between TEE variables and SVI (Table 2 and 3).
Discussion

In the present study, we investigated different echocardiographic approaches to assess left ventricular filling during a fluid trial in patients with preserved left ventricular function before cardiac surgery. In our series of measurements, left ventricular end-diastolic volumes assessed by the modified Simpson formula and TEE independent variables measured by transpulmonary thermodilution (PiCCOplus System) were used as reference variables to assess the performance of the echocardiographic method of disc summation and the determination of left ventricular end-diastolic area. The results indicate that the method of disc summation underestimated absolute values of left ventricular end-diastolic volumes and was not able to follow preload changes as compared with the modified Simpson formula or global end-diastolic volume assessed by the PiCCOplus System. By contrast, assessment of the left ventricular end-diastolic area provided information as accurate as the complex volume estimation by the modified Simpson formula.

Strongest correlations for absolute values and trends were observed between the echocardiographic reference technique (modified Simpson formula) and the variables assessed by the PiCCO plus system. For the calculation of the modified Simpson formula two ventricular areas at the base of the ventricle and at mid-papillary level in a short axis view as well as the longitudinal axis in a mid-esophageal two-chamber have to be determined. This technique has been validated against radio-nuclide angiography or magnetic resonance imaging\textsuperscript{11,19,20} and may provide adequate information on ventricular volumes primarily in patients with preserved left ventricular function. However, the following prerequisites should be met for optimal results\textsuperscript{13}: First, respiration should be suspended preferentially at end-expiration to reduce translational motion; second, image resolution has to be optimized using harmonic B-color imaging after adjusting dynamic range and gain controls; third, apical foreshortening needs to be avoided and contrast enhancement of the endocardial border should be maximized in order to reduce extrapolation during manual tracing\textsuperscript{21}. These goals
may be best achieved in hemodynamically stable patients during an echocardiographic evaluation in the cardiologist's office or the cardiac catheterization laboratory, but not necessarily in patients with rapid hemodynamic changes in the busy environment of an operating room. Therefore, careful interpretation of results obtained in the perioperative period are mandatory.

In contrast to the modified Simpson formula, the method of disc summation allows a fast single plane volume assessment. In order to calculate left ventricular volume multiple LV diameters are automatically measured after endocardial border tracing from the endocardium of the anterior wall to the inferior wall in a line perpendicular to the longitudinal axis of the ventricle from the basis to the apex. Thus, mathematical assumptions are reduced and adjustment for geometrical ventricular distortions improved. However, studies evaluating this method consistently report an underestimation of left-ventricular volumes determined by other imaging techniques. Our data show that this method in fact failed to provide adequate information of cardiac filling when compared with the modified Simpson formula and the assessment by the PiCCO system. This finding may primarily be explained by the fact that measurements during this study were performed in one TEE view only. The approach assumes the left ventricle having a symmetrical geometry with an ideally centered longitudinal axis which is coupled to the diameter measurement, i.e. the determination of different areas. For the modified Simpson formula, however, areas and longitudinal axis are both measured separately. Therefore, apical foreshortening may have a larger impact on the method of disc summation. Furthermore, difficulties placing the single plane at the largest possible end-diastolic area may be difficult resulting in a deviation of the “ideal” longitudinal axis. Thus, smaller circle areas and consequently smaller volumes would be determined.

Considering these limitations, the method of disc summation may be used for reliable volume assessment under optimal conditions most preferably in two TEE planes. However, it cannot be recommended for repeated preload monitoring in a perioperative setting.
The assessment of the left-ventricular end-diastolic area allows a simple qualitative and quantitative preload monitoring in a single plane view at mid-papillary level \(^{12,16,17,23}\). Easy identification of the papillary muscles as typical landmarks allows reproducible determination, which is crucial for repeated measurements in guiding fluid therapy. In consistence with previous work \(^{4,6,23-25}\) changes of left-ventricular end-diastolic area reliably reflected changes of stroke volume and global end-diastolic volume measured by transpulmonary thermodilution in our study. The performance was comparable to the volume measurements by the modified Simpson formula. This can be primarily attributed to the physiological finding that 90% of ventricular volume changes are based on radial shortening and only 10% on longitudinal shortening \(^{26}\). Moreover, the LVEDA at mid-papillary level is used for the calculation of the LVEDV by the modified Simpson formula and therefore, the close relationship of LVEDA and LVEDVs changes is not surprising.

In order to address this coupling between the different TEE approaches hemodynamic measurements based on transpulmonary thermodilution using the PiCCOplus system - i.e. global end-diastolic volume and stroke volume - were performed. Global end-diastolic volume (GEDV) includes the total volumes of cardiac cavities as well as part of the systemic vascular blood volume based depending on the injection site (typically central venous access) and the detection site (typically a thermistor in the distal descending aorta). Therefore, considerable higher values of GEDV than the echocardiographic volume estimates have to be expected. This variable has shown to better correlate with volume status and stroke volume changes in response to altered circulating blood volumes than conventional cardiac filling pressures \(^{5,7,27}\). Moreover, GEDV proved to be an equivalent indicator of cardiac preload when compared to TEE preload assessment \(^{4,6}\). Stroke volume measured by trans-pulmonary thermodilution, on the other hand, was repeatedly validated against the clinical standard, i.e. pulmonary artery thermodilution, in different clinical settings \(^{27-29}\).
Some limitations of this study have to be considered: First, echocardiographic end-diastolic volume estimates were not compared to volumes measured by radio-nuclide angiography, contrast ventriculography, or magnetic resonance imaging, the most appropriate techniques for preload assessment \(^{11,22}\). Unfortunately, the perioperative use of these techniques is not suitable due to technical limitations. Therefore, accuracy of absolute volumes measured by TEE could not be defined. Second, TEE measurements were performed in patients with preserved left ventricular function only. It is likely that measurements in patients with strongly disturbed ventricular function, pulmonary artery hypertension or valvular disease may result in different findings \(^{13}\). Furthermore, TEE assessment was done by one experienced examinator throughout the study period. Based on the known inherent interobserver variability \(^{30}\), TEE performed by different observers could have shown an increased variability of echocardiographic measurements.

In conclusion, the echocardiographic method of disc summation assessed in a single plane failed to adequately measure preload changes during a fluid trial in patients with preserved left ventricular function before cardiac surgery. Therefore, this technique cannot be recommended as alternative echocardiographic method for preload estimation in the perioperative setting. By contrast, single-plane assessment of left ventricular end-diastolic area was able to provide information as accurate as the modified Simpson formula.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CVP</td>
<td>central venous pressure</td>
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<td>GEDV</td>
<td>global end-diastolic volume</td>
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<td>GEDVI</td>
<td>global end-diastolic volume index</td>
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<td>HR</td>
<td>heart rate</td>
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<td>LVEDA</td>
<td>left ventricular end-diastolic area</td>
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<td>LVEDVI</td>
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<td>MAP</td>
<td>mean arterial pressure</td>
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<tr>
<td>Md</td>
<td>method of disc summation</td>
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<td>Si</td>
<td>modified Simpson Formula</td>
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<td>SVI</td>
<td>stroke volume index</td>
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<td>SVRI</td>
<td>systemic vascular resistance index</td>
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<tr>
<td>TEE</td>
<td>transesophageal echocardiography</td>
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**Figure legends**

**Figure 1:**

Title:

Bland-Altman analysis for \( \% \text{ changes (} \Delta \text{)} \) of LVEDVI\textsubscript{Md} (A) and of LVEDAI (B) vs. \( \Delta \text{LVEDVI}_{\text{Si}} \)

Footnote:

\( \Delta = \% \text{ changes, LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, Md = Method of discs, Si = Modified Simpson Formula.} \)

\( \Delta \text{LVEDVI}_{\text{Md}} - \Delta \text{LVEDVI}_{\text{Si}} : \text{mean bias (±2SD)} = +1.5 ± 59.0\% \), \( \Delta \text{LVEDAI} - \Delta \text{LVEDVI}_{\text{Si}} : \text{mean bias (±2SD)} = +0.9 ± 23.6 \% \).

**Figure 2:**

Title:

Pearson correlations for absolute values of LVEDVI\textsubscript{Md} (A) and LVEDAI (B) vs. LVEDVI\textsubscript{Si}

Footnote:

LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, Md = Method of discs, Si = Modified Simpson Formula.

**Figure 3:**

Title:

Pearson correlation for \( \% \text{ changes (} \Delta \text{)} \) of LVEDVI\textsubscript{Md} (A) and LVEDAI (B) vs. \( \Delta \text{LVEDVI}_{\text{Si}} \)

Footnote:
$\Delta = \%$ changes, LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, Md = Method of discs, Si = Modified Simpson Formula.

**Figure 4:**

**Title:**
Bland-Altman analysis for $\%$ changes ($\Delta$) of LVEDVIMd (A), LVEDAI (B) and LVEDVISi (C) vs. GEDVI

**Footnote:**
$\Delta = \%$ changes, GEDVI = global end-diastolic volume index, LVEDVI = left ventricular end-diastolic volume index, LVEDAI = left ventricular end-diastolic area index, Md = Method of discs, Si = Modified Simpson Formula. $\Delta$LVEDVIMd-$\Delta$GEDVI: mean bias ($\pm$2SD) = $+0.9\pm23.6\%$, $\Delta$LVEDAI-$\Delta$GEDVI: mean bias ($\pm$SD) = $+0.9\pm23.6\%$, $\Delta$LVEDVISi-$\Delta$GEDVI: mean bias ($\pm$2SD) = $+1.5\pm59.0\%$. 

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Table 1: Hemodynamic variables

<table>
<thead>
<tr>
<th></th>
<th>T₁</th>
<th>T₂</th>
<th>T₃</th>
<th>T₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (beats min⁻¹)</td>
<td>60±8</td>
<td>60±8</td>
<td>59±7</td>
<td>60±7</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>70±3</td>
<td>69±3</td>
<td>76±6*§</td>
<td>74±5*§#</td>
</tr>
<tr>
<td>CVP (mmHg)</td>
<td>6±3</td>
<td>7±2</td>
<td>13±3*§</td>
<td>12±4*§</td>
</tr>
<tr>
<td>SVRI (dyne se cm⁻5 m⁻²)</td>
<td>2141±290</td>
<td>2098±275</td>
<td>1680±283*§</td>
<td>1693±298*§</td>
</tr>
<tr>
<td>SVI (ml m⁻²)</td>
<td>40±8</td>
<td>41±7</td>
<td>53±10*§</td>
<td>49±9*§#</td>
</tr>
<tr>
<td>GEDVI (ml m⁻²)</td>
<td>661±106</td>
<td>650±105</td>
<td>748±120*§</td>
<td>704±109*§#</td>
</tr>
<tr>
<td>LVEDVI_Md (ml m⁻²)</td>
<td>48±14</td>
<td>47±14</td>
<td>56±18*§</td>
<td>52±14</td>
</tr>
<tr>
<td>LVEDAI (cm² m⁻²)</td>
<td>6.9±1.0</td>
<td>6.8±0.9</td>
<td>7.8±1.1*§</td>
<td>7.6±1.6*§#</td>
</tr>
<tr>
<td>LVEDVI_Si (ml m⁻²)</td>
<td>49±10</td>
<td>48±9</td>
<td>62±10*§</td>
<td>54±10*§#</td>
</tr>
</tbody>
</table>

CVP = central venous pressure, GEDVI = global end-diastolic volume index, HR = heart rate, LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, MAP = mean arterial pressure, Md = Method of disc summation, Si = Modified Simpson Formula, SVI = stroke volume index, SVRI = systemic vascular resistance index. T₁ = 20 min before fluid load; T₂ = 10 min before fluid load, T₃ = 10 min after fluid load; T₄ = 20 min after fluid load. *p<0.05 for comparison with T₁; §p<0.05 for comparison with T₂; #p<0.05 for comparison with T₃.
Table 2: Correlation coefficients ($r^2$) between absolute values of cardiac preload assessed by transesophageal echocardiography (TEE) and hemodynamic variables determined by the PiCCOplus system.

<table>
<thead>
<tr>
<th></th>
<th>TEE</th>
<th>PiCCOplus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LVEDVI&lt;sub&gt;Md&lt;/sub&gt;</td>
<td>GEDVI&lt;sub&gt;Si&lt;/sub&gt;</td>
</tr>
<tr>
<td>LVEDVI&lt;sub&gt;Si&lt;/sub&gt;</td>
<td>0.215*&lt;br&gt;$&lt;0.001$</td>
<td>0.034&lt;br&gt;0.090</td>
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<tr>
<td>LVEDAI</td>
<td>0.514*&lt;br&gt;$&lt;0.001$</td>
<td>0.261&lt;br&gt;$&lt;0.001$</td>
</tr>
<tr>
<td>LVEDVI&lt;sub&gt;Si&lt;/sub&gt;</td>
<td>-</td>
<td>0.340&lt;br&gt;$&lt;0.001$</td>
</tr>
</tbody>
</table>

GEDVI = global end-diastolic volume index, LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, Md = Method of discs, Si = Modified Simpson Formula, SVI = stroke volume index. (* Figure 3)
**Table 3:** Correlation coefficients ($r^2$) between % changes ($\Delta$) of cardiac preload assessed by transesophageal echocardiography (TEE) and hemodynamic variables determined by the PiCCOplus system.

<table>
<thead>
<tr>
<th>TEE</th>
<th>ΔLVEDVI$_{Md}$</th>
<th>ΔLVEDAI</th>
<th>ΔLVEDVI$_{Si}$</th>
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</thead>
<tbody>
<tr>
<td>ΔLVEDVI$_{Si}$</td>
<td>0.077*</td>
<td>0.747*</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.029</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PiCCOplus</th>
<th>ΔGEDVI</th>
<th>ΔLVEDAI</th>
<th>ΔLVEDVI$_{Si}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔGEDVI</td>
<td>0.163</td>
<td>0.529</td>
<td>0.510</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ΔSVI</td>
<td>0.122</td>
<td>0.554</td>
<td>0.575</td>
</tr>
<tr>
<td></td>
<td>0.005</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

$\Delta$ = % changes, GEDVI = global end-diastolic volume index, LVEDAI = left ventricular end-diastolic area index, LVEDVI = left ventricular end-diastolic volume index, Md = Method of discs, Si = Modified Simpson Formula, SVI = stroke volume index. *(Figure 4)
References


Figure 1

A: ΔLVEDVI_{ld} vs. ΔLVEDVI_{si}

B: ΔLVEDDI + ΔLVEDVI_{si}

Diagrams showing scatter plots with lines indicating mean bias and ±2SD.
Figure 2

A  

LVEDVI_{M0} vs. LVEDVI_{Si}  

\[ y = 16.9 + 0.6x; r^2 = 0.215 \]

B  

LVEDAI vs. LVEDVI_{Si}  

\[ y = 3.2 + 0.1x; r^2 = 0.514 \]
Figure 3

A.

$\Delta \text{LVEDVI}_{\text{left}}$ vs. $\Delta \text{LVEDVI}_{\text{si}}$

$y = -0.1 + 0.4x; \ r^2 = 0.077$

B.

$\Delta \text{LVEDAI}$ vs. $\Delta \text{LVEDVI}_{\text{si}}$

$y = 2.1 + 0.7x; \ r^2 = 0.747$
Figure 4

A. $\Delta LVEDVI_{LVEDVI} \text{ vs. } \Delta GEDVI$

B. $\Delta LVDAI \text{ vs. } \Delta GEDVI$

C. $\Delta LVEDVI_{S\text{LVEDVI}} \text{ vs. } \Delta GEDVI$