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Volumetric preload measurement by thermodilution: a comparison with transoesophageal echocardiography

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Background. End-diastolic volume indices determined by transpulmonary thermodilution and pulmonary artery thermodilution may give a better estimate of left ventricular preload than pulmonary capillary wedge pressure monitoring. The aim of this study was to compare volume preload monitoring using the two different thermodilution techniques with left ventricular preload assessment by transoesophageal echocardiography (TOE).

Methods. Twenty patients undergoing elective cardiac surgery with preserved left–right ventricular function were studied after induction of anaesthesia. Conventional haemodynamic variables, global end-diastolic volume index using the pulse contour cardiac output (PiCCO) system ($GEDVI_{PiCCO}$), continuous end-diastolic volume index ($CEDVI_{PAC}$) measured by a modified pulmonary artery catheter (PAC), left ventricular end-diastolic area index (LVEDAI) using TOE and stroke volume indices (SVI) were recorded before and 20 and 40 min after fluid replacement therapy. Analysis of variance (Bonferroni–Dunn), Bland–Altman analysis and linear regression were performed.

Results. $GEDVI_{PiCCO}$, $CEDVI_{PAC}$, LVEDAI and $SVI_{PiCCO/PAC}$ increased significantly after fluid load ($P<0.05$). An increase >10% for $GEDVI_{PiCCO}$ and LVEDAI was observed in 85% and 90% of the patients compared with 45% for $CEDVI_{PAC}$. Mean bias (2 SD) between percentage changes (Δ) in $GEDVI_{PiCCO}$ and ΔLVEDAI was -3.2 (17.6)% and between $\Delta CEDVI_{PAC}$ and ΔLVEDAI -8.7 (30.0)%. The correlation coefficient (r^2) for $\Delta GEDVI_{PiCCO}$ *vs* ΔLVEDAI was 0.658 and for $\Delta CEDVI_{PAC}$ *vs* ΔLVEDAI 0.161. The relationship between $\Delta GEDVI_{PiCCO}$ and ΔSVI_{PiCCO} was stronger ($r^2=0.576$) than that between $\Delta CEDVI_{PAC}$ and ΔSVI_{PAC} ($r^2=0.267$).

Conclusion. GEDVI assessed by the PiCCO system gives a better reflection of echocardiographic changes in left ventricular preload, in response to fluid replacement therapy, than CEDVI measured by a modified PAC.

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Optimization of perioperative volume status for improved cardiac performance, especially in patients with a potentially limited left ventricular reserve, requires adequate preload monitoring. In contrast to the widely used cardiac filling pressures, end-diastolic volume estimates of the left ventricle are better indicators of end-diastolic left ventricular fibre length, i.e. preload according to the Frank–Starling law.[1 2] Therefore, assessment of left ventricular volume by radionuclide angiography, magnetic resonance imaging and echocardiography would be the preferred techniques.[3] However, these methods are either not practicable in a perioperative setting or cannot be routinely performed for logistic and economical reasons. Hence, there has been recent interest in alternative, catheter-related, volume estimates using thermodilution.

Two different techniques, transpulmonary and pulmonary artery thermodilution, are used in commercially available monitoring devices. The PiCCO system (Pulse Contour Cardiac Output system; Pulsion Medical Systems, Munich, Germany) uses integrated transpulmonary thermodilution to

measure the volumetric preload parameter global end-diastolic volume index (GEDVI) and includes the total volumes of cardiac atria and ventricles as well as part of the systemic vascular blood volume. Compared with conventional pressure-derived preload assessment, volumetric preload determination by the PiCCO system has been shown to better reflect left ventricular filling.[4 5] Pulmonary artery thermodilution, on the other hand, determines right ventricular end-diastolic volume index (RVEDVI). This volume index also showed a better correlation with cardiac performance than cardiac filling pressures in studies performed in critically ill patients.[6–8] A recent modification of pulmonary artery thermodilution catheters allows the automatic and continuous determination of RVEDVI, the continuous end-diastolic volume index (CEDVI; Swan-Ganz Continuous Cardiac Output/End Diastolic Volume Thermodilution Catheter; CCOmbo CCO/SvO2/CEDV catheter 774HF75; Edwards Lifesciences, Irvine, CA, USA).

The aim of this study was to compare volumetric preload as measured by transpulmonary thermodilution ($GEDVI_{PiCCO}$) and monitored by pulmonary artery thermodilution ($CEDVI_{PAC}$) with left ventricular preload estimates assessed by transoesophageal echocardiography (TOE). Our hypothesis was that both volume preload parameters would comparably reflect left ventricular preload monitored by TOE.

Patients and methods

Patient selection

With local ethics committee approval and written informed consent, 20 patients undergoing elective off-pump coronary artery bypass grafting were enrolled. Exclusion criteria were preoperative dysrhythmias, reduced left and right ventricular function (ejection fraction <40%), valvular heart disease, intracardiac shunts, pulmonary artery hypertension, severe peripheral vascular disease and a history of oesophageal or gastrointestinal disease precluding the use of transoesophageal echocardiography.

Anaesthetic technique

After application of the routine haemodynamic monitoring (pulse oximetry, five-lead ECG and non-invasive blood pressure monitoring; CMS, Philips Medical Systems, Andover, MA, USA) a peripheral radial arterial and an i.v. line were inserted and lactated Ringer's solution 2 ml kg^{-1} h^{-1} i.v. was given continuously. Anaesthesia was induced using fentanyl 10–30 μg kg^{-1} i.v., lidocaine 1.5 mg kg^{-1} i.v. and propofol up to 2 mg kg^{-1} i.v., and was maintained with additional propofol (1.5–3 mg kg^{-1} h^{-1}) and fentanyl (10 μg kg^{-1} i.v.). Muscle paralysis was achieved with pancuronium bromide (0.1 mg kg^{-1} i.v.). The trachea was intubated and the lungs mechanically ventilated without positive end-expiratory pressure using an inspired oxygen of 50% and tidal volume of 8 ml kg^{-1} to maintain end-expiratory PCO_2 at 4–4.5 kPa during the study period. Thus, effective applied mean tidal volumes were 610 (73) ml and peak airway pressure ranged from 14 to 24 cm H_2O (mean=18 [2] cm H_2O).

Haemodynamic monitoring and transoesophageal echocardiography

A 4 F thermistor-tipped arterial catheter (Pulsiocath thermodilution catheter; Pulsion Medical Systems, Munich, Germany) was inserted in the left femoral artery; its tip advanced to the abdominal aorta, and it was connected to the $PiCCO_{plus}$ (version 5.2.2; Pulsion Medical Systems). Cardiac output (CO_{PiCCO}), stroke volume (SV_{PiCCO}) and global end-diastolic volume ($GEDVI_{PiCCO}$) were determined using a triplicate injection of 15 ml ice-cold normal saline through an additional 7 F central venous catheter introduced in the right subclavian vein. $GEDVI_{PiCCO}$ is calculated from the difference of mean indicator transit time and exponential indicator down-slope time and from the cardiac index obtained from transpulmonary thermodilution. The basis of this method has been described in detail previously.[9 10] The PiCCO system also displays intrathoracic blood volume index (ITBVI) as an additional volume preload variable. This variable is calculated from $GEDVI_{PiCCO}$ based on a fixed algorithm, established from data obtained from earlier double-indicator transpulmonary thermodilution. The bolus thermodilution measurements were made by the same observer to avoid interobserver variation.

A 7.5 F pulmonary artery catheter (Swan-Ganz Continuous Cardiac Output/End Diastolic Volume Thermodilution Catheter CCOmbo CCO/SvO2/CEDV catheter 774HF75 Edwards Lifesciences) was introduced into the right internal jugular vein and attached to the Vigilance monitor for measurement of cardiac output (CO_{PAC}), stroke volume (SV_{PAC}) and continuous end-diastolic volume ($CEDVI_{PAC}$). $CEDVI_{PAC}$ is determined by analysis of the thermal washout curve using plateau and exponential curve analysis by analogy to the determination of right-ventricular ejection fraction and right-ventricular end-diastolic volume assessment by the fast-response thermistor-tipped pulmonary artery catheter. Details of this method have been published elsewhere.[11] Central venous and pulmonary capillary wedge pressures were measured using standard transducers (CMS; Philips Medical Systems).

TOE was performed using a Philips Sonos 5500 system with an Omniplane III-TOE probe (Philips Medical Systems). The probe was positioned to obtain the transgastric midpapillary short-axis view of the left ventricle. Left ventricular end-diastolic area (LVEDA) and left ventricular end-systolic area (LVESA) were measured by manual planimetry of the area circumscribed by the leading edge of the endocardial border in this position. LVEDA was determined as the largest left ventricular cross-sectional area after the electrocardiographic T wave and LVESA as the smallest left

ventricular cross-sectional area after the R wave. All TOE measurements were performed, recorded and calculated by an experienced operator blinded to the results of the haemodynamic measurements.

Experimental protocol

After induction of anaesthesia and a 15 min period of haemodynamic stabilization, haemodynamic measurements were performed before (T_0) and 20 min (T_1) and 40 min (T_2) after a volume load. Hydroxyethyl starch solution 6% (HES 130/0.4; Voluven®; Fresenius Kabi, Stans, Switzerland) was given i.v. in a dose of 10 ml kg^{-1} (ideal body weight) over a period of 20 min (mean volume, 730 [60] ml). At each time point heart rate, MAP, mean pulmonary arterial pressure (MPAP), central venous pressure (CVP), pulmonary capillary wedge pressure (PCWP) and PiCCO measurements and the CO_{PAC} readings were recorded. TOE was performed simultaneously. Surgery started after measurements at T_2 were completed.

Data analysis

A sample size of >15 patients was calculated on the hypothesis of an expected 10% change in haemodynamic variables after fluid replacement (level of significance=0.05%; power=90%) according to initial observations using the different methods of preload assessment.

All haemodynamic measurements were recorded as the mean of three consecutive readings at intervals of 3 min. Ejection fraction (%) was calculated *post hoc* from TOE measurements: $100\times LVEDA^{-1}\times(LVEDA–LVESA)$. All haemodynamic values were indexed to body surface area (BSA) by means of the Du Bois formula ($BSA=body\ weight\ [kg]^{0.425}\times body\ length[cm]^{0.725}\times 71.84$). Statistical analysis was performed using Statview 5.01® Software (SAS Institute, Cary, NC, USA). Analysis of variance (ANOVA) with *post hoc* Bonferroni–Dunn correction was done for comparison of haemodynamic data during the study period (T_0–T_2). Two-tailed Student's *t*-test was used to determine differences in preload changes and stroke volume changes between methods. Bland–Altman analysis[12] was performed to compare the preload and stroke volume changes assessed by all three techniques and absolute values of cardiac output determined by the two thermodilution methods. The Pearson correlation was established for absolute values and changes between preload and stroke volume indices. Relationships between the corresponding values obtained from one method and relationships between values recorded from the different methods were calculated to exclude the possibility of mathematical coupling;[13] Fisher's *z* transformation and a Hotelling–Williams test were used to compare correlation coefficients for statistical difference. A *P*-value <0.05 was considered statistically significant. Unless otherwise stated, data are presented as mean (SD).

Table 1 Haemodynamic variables during the study. **P*<0.05 compared with T_0; †*P*<0.05 compared with T_1

	T_0	T_1	T_2
Heart rate (beats min^{-1})	60 (6)	59 (5)	60 (6)
MAP (mm Hg)	69 (2)	77 (5)*	72 (3)†
MPAP (mm Hg)	15 (3)	22 (4)*	21 (4)*
CVP (mm Hg)	6 (3)	10 (4)*	10 (6)*
PCWP (mm Hg)	8 (2)	13 (3)*	13 (5)*
SVRI (dyne s^{-1} cm^{-5} m^2)	2055 (296)	1714 (341)*	1703 (351)*
CI_{PiCCO} (litre min^{-1} m^{-2})	2.5 (0.3)	3.1 (0.5)*	3.0 (0.5)*
SVI_{PiCCO} (ml m^{-2})	42 (6)	53 (10)*	50 (9)*†
$GEDVI_{PiCCO}$ (ml m^{-2})	664 (87)	777 (125)*	720 (113)*†
$ITBVI_{PiCCO}$ (ml m^{-2})	809 (108)	963 (154)*	878 (140)*†
CI_{PAC} (litre $min^{-1}m^{-2}$)	2.3 (0.3)	3.0 (0.6)*	3.0 (0.6)*
SVI_{PAC} (ml m^{-2})	42 (6)	51 (10)*	49 (9)*
$CEDVI_{PAC}$ (ml m^{-2})	121 (30)	135 (30)*	133 (27)*
Sv_{O_2} (%)	82 (7)	84 (6)	83 (6)
EF (%)	50.6 (9.5)	51.1 (11.2)	50.9 (9.1)
LVEDAI (cm^2 m^{-2})	6.8 (1.3)	8.1 (1.6)*	7.6 (1.6)*†

HR, heart rate; MAP, mean arterial pressure; MPAP, mean pulmonary arterial pressure; CVP, central venous pressure; PCWP, pulmonary capillary wedge pressure; SVRI, systemic vascular resistance index; CI, cardiac index; SVI, stroke volume index; $GEDVI_{PiCCO}$, global end-diastolic volume index; $CEDVI_{PAC}$, continuous end-diastolic volume index; Sv_{O_2}, mixed venous oxygen saturation; EF, ejection fraction; LVEDAI, left ventricular end-diastolic area index. T_0, before fluid load; T_1, 20 min after fluid load; T_2, 40 min after fluid load.

Results

Four women and 16 men, ages 67.2 (8.4) yr [range 52–78 yr], body mass index=28.2 (4.1) kg m^{-2}, ejection fraction=64.9 (9.7)% were enrolled into the study. Fluid bolus led to a significant change in all monitored haemodynamic variables, with the exception of heart rate (T_1; *P*<0.05) (Table 1). Basic haemodynamic variables, cardiac index (CI), stroke volume index (SVI), end-diastolic volume indices assessed by both catheter systems and TOE variables increased but systemic vascular resistance decreased. Compared with T_1, the haemodynamic measurements at T_2 showed significant decreases in MAP, $GEDVI_{PiCCO}$, SVI_{PiCCO} and LVEDAI.

A significantly different pattern of preload index changes assessed by PAC was observed 20 and 40 min after fluid administration compared with preload changes monitored by PiCCO and TOE. Between T_0 and T_1, an increase >10% was observed in nine patients (45%) for $CEDVI_{PAC}$ compared with 17 (85%) for $GEDVI_{PiCCO}$ and 18 (90%) for LVEDAI (%change Δ $GEDVI_{PiCCO}$=16.8 [6.9]%, $\Delta CEDVI_{PAC}$=11.1 [8.1]%, ΔLVEDAI=20.5 [10.1]%; *P* $\Delta GEDVI_{PiCCO}$ *vs* ΔLVEDAI=0.117, *P* $\Delta CEDVI_{PAC}$ *vs* ΔLVEDAI=0.018). Between T_1 and T_2, $CEDVI_{PAC}$ decreased by >10% in only one patient (5%), but in seven (35%) and eight (40%) patients for $GEDVI_{PiCCO}$ and LVEDAI, respectively ($\Delta GEDVI_{PiCCO}$=−6.2 [7.5]%, $\Delta CEDVI_{PAC}$=0.2 [10.1]%, ΔLVEDAI=−6.7 [7.0]%; *P* $\Delta GEDVI_{PiCCO}$ *vs* ΔLVEDAI=0.547, *P* $\Delta CEDVI_{PAC}$ *vs* ΔLVEDAI=0.011). Bland and Altman analysis of the preload changes induced between T_0 and T_1 showed lower mean bias and lower limits of agreement for LVEDAI–$GEDVI_{PiCCO}$ compared with LVEDAI–$CEDVI_{PAC}$

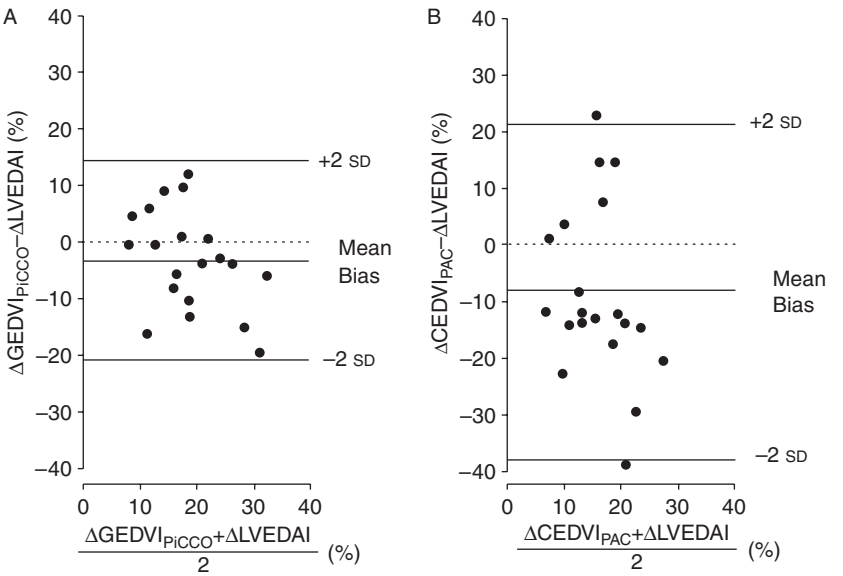

Fig 1 Bland–Altman analysis of changes in cardiac preload indices between T_0 and T_1. (A) $GEDVI_{PiCCO}$ *vs* LVEDAI: mean bias (2 SD)=−3.2 (17.6)%. (B) $CEDVI_{PAC}$ *vs* LVEDAI: mean bias (2 SD)=−8.7 (30.0)%. T_0, before fluid load; T_1, 20 min after fluid load; $GEDVI_{PiCCO}$, global end-diastolic volume index (assessed by PiCCO); LVEDAI, end-diastolic area index; $CEDVI_{PAC}$, continuous end-diastolic volume index (assessed by PAC); Δ, change in response to fluid replacement therapy (%).

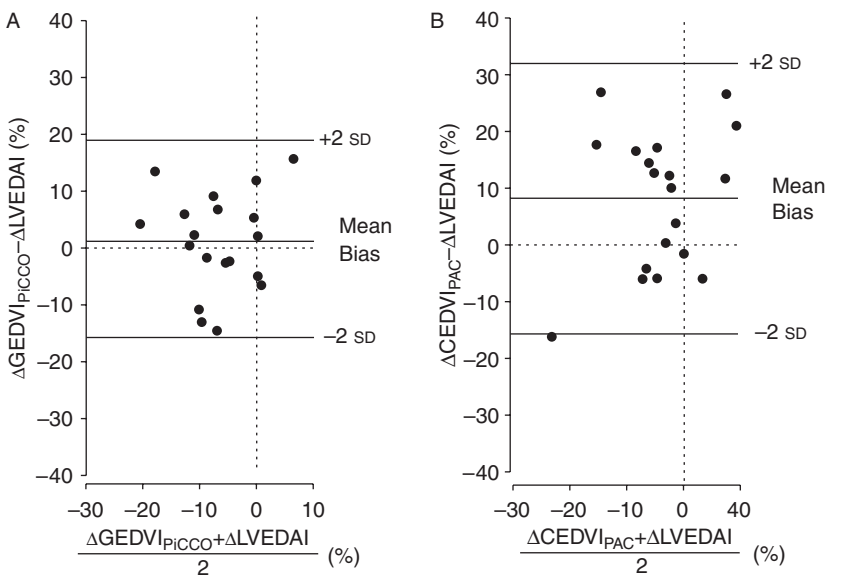

Fig 2 Bland–Altman analysis of changes in cardiac preload indices between T_1 and T_2. (A) $GEDVI_{PiCCO}$ *vs* LVEDAI: mean bias (2 SD)=1.2 (17.9)%. (B) $CEDVI_{PAC}$ *vs* LVEDAI: mean bias (2 SD)=7.7 (24.0)%. T_1, 20 min after fluid load. T_2, 40 min after fluid load. $GEDVI_{PiCCO}$, global end-diastolic volume index (assessed by PiCCO); LVEDAI, end-diastolic area index; $CEDVI_{PAC}$, continuous end-diastolic volume index (assessed by PAC); Δ, change in response to fluid replacement therapy (%).

(Fig. 1A, B). Between T_1 and T_2, these differences were less pronounced (Fig. 2A, B). Comparing cardiac and stroke volume indices assessed by both thermodilution techniques during the study period, the mean bias (2 SD) was −0.04 (1.15) litre min^{-1} m^{-2} for CI_{PiCCO}–CI_{PAC} and −1.2 (18.2) ml m^{-2} for SVI_{PiCCO}–SVI_{PAC}. There was a good correlation between SVI_{PiCCO} and SVI_{PAC} and between ΔSVI_{PiCCO} and ΔSVI_{PAC} (r^2=0.768 and 0.617, respectively [P<0.001]).

Linear regression analysis between the preload indices assessed by the different methods and between preload indices and stroke volume indices showed significant correlations for all volume, but not for the pressure preload indices (Table 2). Correlations for $GEDVI_{PiCCO}$ and LVEDAI with stroke volume indices were stronger than for $CEDVI_{PAC}$. The relationship between $CEDVI_{PAC}$ and LVEDAI was weaker than the relationship between $GEDVI_{PiCCO}$ and LVEDAI (Fig. 3). Regression analysis of preload and stroke volume

Table 2 Correlation coefficients (r^2) between absolute values of cardiac preload and stroke volume indices. *Issue of possible mathematical coupling: $GEDVI_{PiCCO}$–SVI_{PiCCO} *vs* $GEDVI_{PiCCO}$–SVI_{PAC}, P=0.755; $CEDVI_{PAC}$–SVI_{PiCCO} *vs* $CEDVI_{PAC}$–SVI_{PAC}, P=0.753; †compare Figure 3. Italics indicate the corresponding P-value for each correlation coefficient (r^2)

	Stroke volume indices		Preload indices			
	SVI_{PiCCO}	**SVI_{PAC}**	**$CEDVI_{PAC}$**	**LVEDAI**	**CVP**	**PCWP**
Preload indices						
$GEDVI_{PiCCO}$	0.395*	0.346	0.131	0.357†	0.042	0.073
	<0.001	*<0.001*	*0.005*	*<0.001*	*0.814*	*0.203*
$CEDVI_{PAC}$	0.248	0.245*		0.100†	0.032	0.022
	<0.001	*<0.001*		*0.009*	*0.671*	*0.874*
LVEDAI	0.347	0.362			0.059	0.016
	<0.001	*<0.001*			*0.657*	*0.899*
CVP	0.012	0.004				0.175
	0.818	*0.961*				*0.002*
PCWP	0.066	0.039				
	0.627	*0.776*				

SVI, stroke volume index; $GEDVI_{PiCCO}$, global end-diastolic volume index; $CEDVI_{PAC}$, continuous end-diastolic volume index; LVEDAI, left ventricular end-diastolic area index; CVP, central venous pressure; PCWP, pulmonary capillary wedge pressure.

Table 3 Correlation coefficients (r^2) between change in cardiac preload and stroke volume indices. Δ, change in response to fluid replacement therapy (%). *Issue of possible mathematical coupling: $\Delta GEDVI_{PiCCO}$–ΔSVI_{PiCCO} *vs* $\Delta GEDVI_{PiCCO}$–SVI_{PAC}, P=0.812; $\Delta CEDVI_{PAC}$–ΔSVI_{PAC} *vs* $\Delta CEDVI_{PAC}$–ΔSVI_{PiCCO}, P=0.288; †compare Figure 4. Italics indicate the corresponding P-value for each correlation coefficient (r^2)

	Δ Stroke volume indices		Δ Preload indices			
	SVI_{PiCCO}	**SVI_{PAC}**	**$CEDVI_{PAC}$**	**LVEDAI**	**CVP**	**PCWP**
Δ Preload indices						
$GEDVI_{PiCCO}$	0.576*	0.557	0.294	0.658†	0.015	0.029
	<0.001	*<0.001*	*0.005*	*<0.001*	*0.661*	*0.365*
$CEDVI_{PAC}$	0.191	0.267*		0.161†	0.001	0.038
	0.005	*<0.001*		*0.014*	*0.895*	*0.249*
LVEDAI	0.512	0.454			0.012	0.042
	<0.001	*<0.001*			*0.703*	*0.203*
CVP	0.034	0.001				0.259
	0.272	*0.894*				*<0.001*
PCWP	0.060	0.048				
	0.125	*0.191*				

SVI, stroke volume index; $GEDVI_{PiCCO}$, global end-diastolic volume index; $CEDVI_{PAC}$, continuous end-diastolic volume index; LVEDAI, left ventricular end-diastolic area index; CVP, central venous pressure; PCWP, pulmonary capillary wedge pressure.

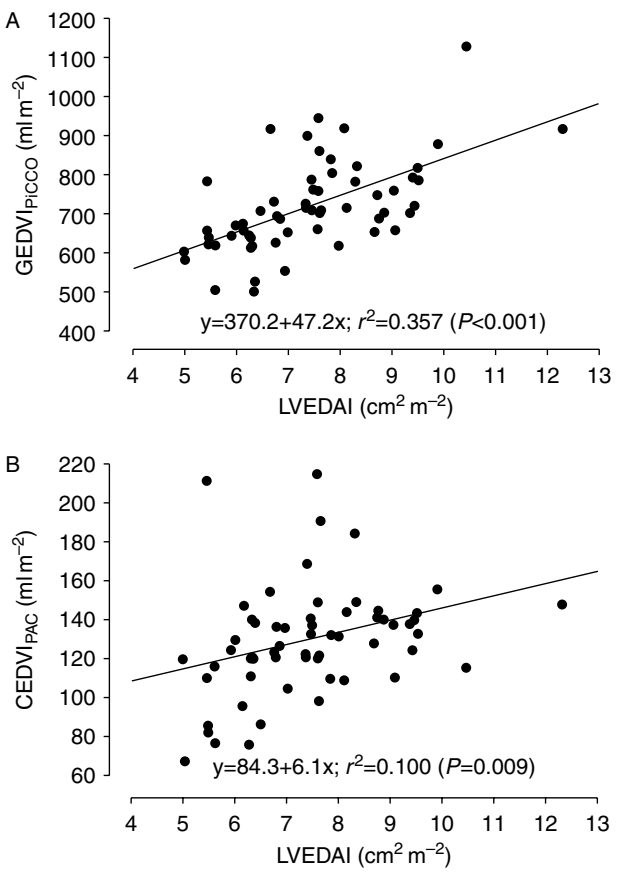

Fig 3 Correlation between cardiac preload indices. (A) $GEDVI_{PiCCO}$ *vs* LVEDAI. (B) $CEDVI_{PAC}$ *vs* LVEDAI. $GEDVI_{PiCCO}$, global end-diastolic volume index (assessed by PiCCO); LVEDAI, left ventricular end-diastolic area index; $CEDVI_{PAC}$, continuous end-diastolic volume index (assessed by PAC). Analysis of pooled data (T_0–T_2).

index changes (Table 3) as well as for volume preload index changes and changes observed by TOE (Fig. 4) showed higher correlation coefficients than for absolute values. Assessment of mathematical coupling of $GEDVI_{PiCCO}$–SVI_{PiCCO} with $GEDVI_{PiCCO}$–SVI_{PAC} and of $CEDVI_{PAC}$–SVI_{PAC} with $CEDVI_{PAC}$–SVI_{PiCCO} revealed no significant difference.

Discussion

These results, obtained in patients with preserved left ventricular function, indicate that global end-diastolic volume index assessed by the PiCCO system ($GEDVI_{PiCCO}$) gives a better reflection of echocardiographic changes of left ventricular end-diastolic area index (LVEDAI) in response to fluid replacement therapy than continuous end-diastolic volume index measured with a modified pulmonary artery catheter ($CEDVI_{PAC}$). Furthermore, the relationship of absolute values and changes of $GEDVI_{PiCCO}$ with stroke volume index (SVI) was stronger than for the respective values of $CEDVI_{PAC}$ with SVI. For both thermodilution techniques, mathematical coupling appeared to be unlikely.

As with previously published results, conventional pressure preload parameters did not adequately reflect left ventricular filling,[1,2,4–8] indicating superiority of volumetric monitoring of cardiovascular volume status over conventional preload pressure monitoring. In clinical practice, when logistic and financial considerations limit the use of echocardiography and other imaging technologies, thermodilution-based volume assessment must be regarded as the preferred method. However, to our knowledge, a comparison of the different commercially available

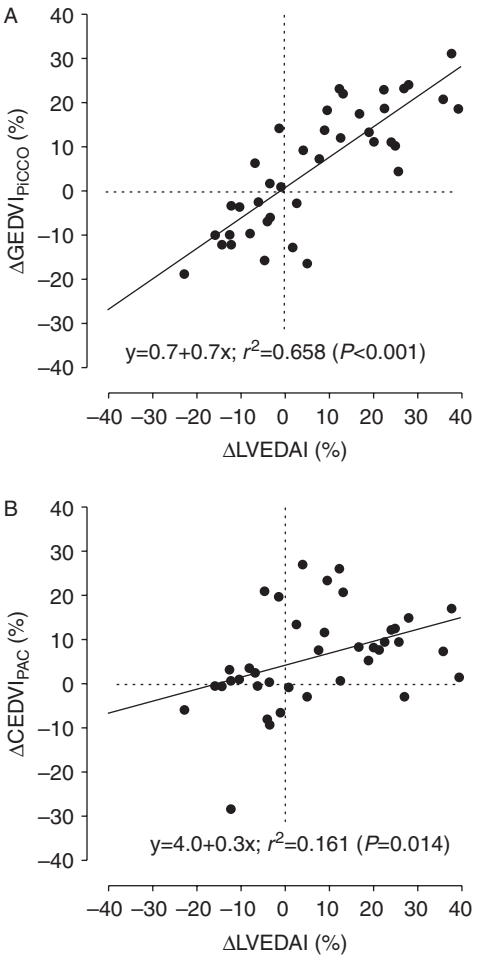

Fig 4 Correlation between changes of cardiac preload indices. (A) $GEDVI_{PiCCO}$ *vs* LVEDAI. (B) $CEDVI_{PAC}$ *vs* LVEDAI. $GEDVI_{PiCCO}$, global end-diastolic volume index (assessed by PiCCO); LVEDAI, end-diastolic area index; $CEDVI_{PAC}$, continuous end-diastolic volume index (assessed by PAC); Δ, changes in response to fluid replacement therapy (%). Analysis of pooled data (changes between T_0 and T_1 and changes between T_1 and T_2).

volumetric preload assessment techniques has not been performed.

Transpulmonary thermodilution integrated in the PiCCO system does not require pulmonary artery catheter placement and thus avoids the related risks.[14] Based on the injection site (usually central venous access) and the detection site (thermistor in the distal descending aorta) the measured volume includes the total volumes of the heart and the aortic blood volume (GEDVI). In most studies published during the last decade, GEDVI and the closely related intrathoracic blood volume index (ITBVI), which includes the central blood volumes of GEDVI and the pulmonary blood volume, were both assessed by a double-indicator (iced water and indocyanine green injection) dilution technique using the COLD system (Pulsion Medical Systems). These studies were performed in a variety of clinical settings (critically ill,[15] sepsis,[16] cardiac surgery,[17] neurosurgery[18]). Results indicate that these volume preload indices are closely correlated to volume status and to changes in cardiac output in response to changes in circulating blood volume. Moreover, this method of volumetric preload assessment has been shown to be a measure of cardiac preload equivalent to preload assessment by TOE.[19] However, the results raised concerns of mathematical coupling which can occur if two variables calculated from the same measurement are compared, allowing correlations between the variables to be artificially improved.[20] This issue has been addressed in studies by changing cardiac output using dobutamine[21] or β-antagonists.[22] In our study, independent changes in cardiac output and volume preload indices mean that correlations between measured volumes and cardiac output were unlikely to be attributed primarily to mathematical coupling.

Recently, the time-consuming and expensive double-indicator technique (COLD system) has been replaced by a single-indicator technique (PiCCO system). Using the PiCCO system, GEDVI is measured and ITBVI is calculated from GEDVI based on a fixed algorithm established with data from the double-indicator technique. Adequate accuracy and precision between end-diastolic volume assessment by the COLD system and the PiCCO system has been demonstrated.[23] Furthermore, the superiority of the PiCCO system as a left ventricular preload monitoring compared with conventional pressure preload assessment was confirmed[4,5] and the influence of mathematical coupling was again found to be negligible.[10]

In contrast to the global end-diastolic volume assessed by the PiCCO system, continuous end-diastolic volume index ($CEDVI_{PAC}$) is measured using a pulmonary artery catheter and the continuous cardiac output measurement technique; thus, end-diastolic volume of the right heart is determined. Earlier versions of a modified pulmonary artery catheter (mounted with fast reacting thermistors) assessed right ventricular end-diastolic volume (RVEDVI) by the iced water bolus method. RVEDVI has been validated against radionuclide angiography, contrast ventriculography and echocardiography of the right heart.[11,24] Several studies on RVEDVI, used as left ventricular preload substitute in critically ill patients, showed a superior relationship between this preload variable and cardiac output compared with standard pressure measurement[8,25] and mathematical coupling was also not a factor.[25–27] However, difficulties in correct catheter placement prevented wider clinical use of this technique. The modified pulmonary artery catheter (CCOMBO-EDV) gives access to continuous volumetric preload assessment of the right heart.

To our knowledge, the present data on $CEDVI_{PAC}$ represent the first clinical experience with this technique. $CEDVI_{PAC}$ reflected left ventricular preload better than the conventional cardiac filling pressures and the results are comparable with previous clinical investigations of RVEDVI as volume preload index. However, a poorer relationship between $CEDVI_{PAC}$ and echocardiographic preload assessment and poorer performance in comparison with $GEDVI_{PiCCO}$ or stroke volume indices highlight major

limitations in using right-heart catheterization for volumetric left ventricular preload assessment. Right ventricular function differs considerably from left ventricular function. The major determinant of left ventricular function is myocardial wall tension, whereas for the right it is ventricular afterload, which is primarily controlled by pulmonary vascular resistance and indirectly by left ventricular function and various pulmonary factors.[28] Based on clinical experience, excluding the right ventricle from the circulation, the right heart may act as a conductance vessel and therefore the influence of right ventricular end-diastolic volume on cardiac performance may be limited.[29] Furthermore, $CEDVI_{PAC}$ readings may be influenced by interventricular dependence, right ventricular dysfunction and increased right ventricular afterload. Therefore, the relationship between right ventricular preload assessment and cardiac output readings may be weak. However, our findings do not preclude a valid assessment of right heart end-diastolic volumes. In addition, delayed reactivity to rapid changes of intravascular volume by the pulmonary artery catheter compared with the PiCCO system could explain different findings for $CEDVI_{PAC}$ and $GEDVI_{PiCCO}$. However, stroke volume changes in this study assessed with both the PiCCO system and the pulmonary artery catheter were comparable.

Certain limitations of the clinical utility of $CEDVI_{PAC}$ monitoring have to be considered. $CEDVI_{PAC}$ was assessed here as a substitute for left ventricular preload only and has not been validated as right ventricular preload parameter against radionuclide angiography or magnetic resonance imaging. However, valid echocardiographic monitoring of right heart volume based on anatomical structures is questionable due to lack of suitable mathematical models. Moreover, $CEDVI_{PAC}$ has not been tested in patients with clinical left- or right-heart failure and its value in this context is unknown. The limitations of transoesophageal echocardiography as the gold standard for monitoring left ventricular preload have to be emphasized. Quantitative assessment of left ventricular end-diastolic area by transoesophageal echocardiography may not necessarily reflect volume status due to myocardial wall motion abnormalities in patients undergoing cardiac surgery, and may be altered by dislocation of the probe from the midpapillary level.[30]

In conclusion, the present study, comparing two thermodilution-based volumetric preload assessment tools with echocardiographic preload monitoring, indicates that GEDVI assessed by the PiCCO system better reflects left ventricular preload than CEDVI measured by a modified pulmonary artery catheter.

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