Three-dimensional transoesophageal echocardiography for cardiac output in critically ill patients: A pilot study of ultrasound versus the thermodilution method

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Three-dimensional transesophageal echocardiography for cardiac output in intensive critically ill patients: a pilot study ultrasound versus thermodilution method

Intérêt de l'échocardiographie Trans-œsophagienne tridimensionnelle pour évaluer le débit cardiaque chez les patients admis en réanimation : étude pilote.

Abbreviated title: Three-dimensional transesophageal echocardiography for cardiac output

Abbreviated title: Evaluation du débit cardiaque par échocardiographie Trans-œsophagienne 3D

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Summary

Background: Three-dimensional transesophageal echocardiography (3D-TEE) is a new noninvasive tool for quantitative assessment of left ventricular (LV) volumes and ejection fraction (EF).

Aim: The objective of this pilot study was to evaluate the feasibility and accuracy of 3D-TEE for the estimation of cardiac output (CO) using transpulmonary thermodilution with the PiCCO (Pulse index Contour Continuous Cardiac Output) system as the reference method in intensive care unit (ICU) patients.

Methods: Fifteen ICU patients on mechanical ventilation prospectively underwent PiCCO catheter implantation and 3D-TEE. 3D-TEE LV end-diastolic and LV end-systolic volumes were determined using a semi-automated software. CO was calculated as the product of LV stroke volume (end-diastolic – end-systolic volumes) multiplied by heart rate. CO was also determined invasively by transpulmonary theromodilution as reference method.

Results: Among 30 hemodynamic evaluations, 29 (97%) LV 3D-TEE datasets were suitable for CO calculation. The mean 3D-TEE image acquisition and post processing times were 46 and 155 seconds respectively. There was a correlation (r=0.78, p<0.0001) between PiCCO and 3D-TEE CO. The 3D-TEE CO mean bias was 0.38 L/min with -1.97 to 2.74L/min limits of agreement.

Conclusions: Noninvasive estimation of CO by 3D-TEE is feasible in ICU patients. This new semi-automated modality is an additional promising tool for noninvasive hemodynamic assessment of ICU patients. However, the wide limits of agreement with thermodilution observed in this pilot study require further investigations in larger cohorts of patients.

Key words: 3D; TEE; cardiac output; ultrasound; intensive care unit.

Résumé

Contexte: L'échocardiographie trans-oesophagienne tridimensionelle (ETO-3D) est une nouvelle modalité non invasive d'évaluation des volumes et de la fraction d'éjection du ventricule gauche (VG).

Objectif : Evaluer la faisabilité et la performance de l'ETO-3D comparativement à la thermodilution transpulmonaire par méthode PiCCO pour la mesure du débit cardiaque (DC).

Méthodes: Dans cette étude pilote, quinze patients sous ventilation mécanique admis en réanimation et bénéficiant d'un monitorage hémodynamique invasif par le système PiCCO ont été prospectivement évalués par ETO-3D. Les volumes télé-diastolique et télé-systolique du VG ont été mesurés en utilisant un logiciel semi-automatique spécifique. Le DC a ensuite été calculé en multipliant le volume d'éjection systolique du VG (volume télé-diastolique–volume télé-systolique) par la fréquence cardiaque. Le DC a également été mesuré de façon invasive par thermodilution transpulmonaire.

Résultats: Parmi les 30 évaluations hémodynamiques effectuées, 29 (97%) acquisitions ETO-3D étaient exploitables. Les temps moyens nécessaires pour l'acquisition et l'analyse des données ETO-3D étaient respectivement de 46 et 155 secondes. Les mesures de DC effectuées par ETO-3D et par méthode invasive étaient corrélées ($r=0,78$, $p<0,0001$). Le biais moyen entre les 2 méthodes de mesure était de 0,38 L/min, les limites d'agrément étaient de -1.97 à 2,74 L/min.

Conclusions: L'évaluation non-invasive du DC par ETO-3D est faisable.Cette nouvelle modalité ultrasonore est un outil prometteur pour l'évaluation hémodynamique des patients admis en réanimation. Les relatives larges limites d'agrément observées dans cette étude pilote comparativement à la theromdilution nécessitent toutefois d'être évaluer sur de plus larges populations de patients.

Mots-clés : 3D; ETO; ultrasons; débit cardiaque; réanimation

List of abbreviations

2D, two-dimensional;

3D, Three-dimensional;

CO, cardiac output;

CV, coefficient of variation;

ICC, intra-class correlation coefficient;

ICU, intensive care unit;

LV, left ventricular;

LVEF, left ventricular ejection fraction;

LVOT, left ventricular outflow tract

SAPS, simplified acute physiology score;

TEE, transesophageal echocardiography

INTRODUCTION

Cardiac output (CO) measurement is an important parameter required for hemodynamic management of critically ill mechanically ventilated patients. The thermodilution by Swan-Ganz catheter is still considered as the reference method in clinical setting.[1] More recently, transpulmonary thermodilution was established as an alternative to pulmonary catheter.[2] However, this method is also invasive and requires artery and central venous catheterization which can lead to severe complications.[1]

Transesophageal echocardiography (TEE) is increasingly used for the hemodynamic management of patients admitted in intensive care unit (ICU).[3] While the transthoracic examination of mechanically ventilated patients may be challenging, TEE is safeand provides accurate heart imaging in most of these patients.[4] TEE training is an essential part of advanced critical care echocardiography learning.[3]

Recently, a new generation of TEE probes has been introduced allowing real time three-dimensional (3D) imaging of the heart.[5] Currently, 3D-TEE is available for routine practice in several echocardiography machines integrating both traditional modalities and 3D imaging. In addition, image acquisition has been simplified and recent software using semi-automated approach have dramatically reduced the 3D dataset off-line post-processing time.[5]

The accuracy of 3D ultrasound for left ventricular (LV) systolic and diastolic volumes measurements and for LV ejection fraction (LVEF) calculation is superior to conventional two-dimensional (2D) approach when using MRI as gold standard method.[5][6][7] However, the value of this technology for the estimation of CO in ICU setting is still poorly investigated. This new semi-automated ultrasound modality offering the advantage to provide the most reliable ultrasound quantitative assessment of LVEF may have a suitable role in CO assessment especially in cases where conventional ultrasound Doppler method is not applicable (beam misalignment for example).

The main objective of this pilot study was to evaluate the feasibility and accuracy of 3D-TEE for the estimation of CO using transpulmonary thermodilution as the reference method in ICU mechanically ventilated patients.

METHODS

Patients

Fifteen ICU patients on mechanical ventilation who had received a PiCCO (Pulse index Contour Continuous Cardiac Output) hemodynamic monitoring device were prospectively included in the study. Exclusion criteria were age <18 years, non-sinus rhythm, contraindication for TEE,[8] tricuspid, aortic or mitral valve regurgitation >2/4, extracorporeal membrane oxygenation support and mechanical mitral valve prosthesis.

In addition to hemodynamics measurements, the following data were recorded: age, gender, simplified acute physiology score (SAPS II),[9] and primary reason for ICU admission.

All patients were on continuous IV sedation combined with neuromuscular blocking agents during hemodynamic and TEE measurements.

The study was approved by the institutional committee on human research of our institution. Written informed consent was obtained from an appropriate designee of each patient before participation.

Invasive CO measurements

A 5-F thermistor-tipped catheter was placed in the femoral artery and connected to the PiCCO System (Pulsion Medical System, Munich, Germany). From a central venous catheter positioned in the internal jugular or subclavian vein, 20 ml of cold saline solution (<8°) were injected using the distal lumen and CO was calculated with transpulmonary thermodilution method.[1] The mean of three consecutive CO measurements was used. PiCCO measurements were performed by an intensivist independently and unaware of the echocardiography results.

TEE

The ultrasound esophageal probe was first introduced. Immediately after PiCCO measurements, TEE examination was then acquired in all patients by two experienced physicians (>1000 exams) using the IE33 system (Philips Medical Systems, Andover, MA, USA) equipped with a 3D-TEE probe (X7-2t). The images were transferred to a workstation equipped with the QLAB software version 8.1 for post-processing. All the examinations were analyzed off-line blinded to invasive measurements. All projections were obtained according to echocardiography guidelines.[5][8] All measurements were averaged over 3 cardiac cycles. Ectopic and post-ectopic beats were disregarded.

Doppler method

From 120° mid-esophageal two-dimensional long axis zoom of aortic valve, LV outflow tract (LVOT) diameter was measured. Using pulsed wave Doppler mode, LVOT time–velocity integral was recorded from transgastric view. Guided both by the 2D image and color Doppler, the Doppler sound beam was placed as parallel as possible to the LVOT flow. CO was calculated as recommended (Doppler CO).[10]

3D method

From 2D LV mid-esophageal four-chamber view at 0°, the real-time biplane imaging modality (X-plane mode) was used to obtain a simultaneous visualization of two orthogonal LV views and therefore to adjust the probe position and acoustic window. During a temporary interruption of ventilator support at end-expiration (5 to 10 seconds depending on patient’s heart rate), 3D LV full-volume data set was then reconstructed using R-wave gated method over 4 to 6 consecutive cardiac cycles and acquired. Sector size and depth were adjusted to achieve optimal visualization of the LV at the highest possible frame rate (mean value 28 ± 5 frames/s). During post-processing the full-volume LV data set was organized off-line into four-, two-chamber and short-axis views. Mitral annular and apical points were placed manually on these images in end-diastole and end-systole. LV endocardial borders were then detected automatically by the software and adjusted manually if needed. The software then used sequence analysis to track the endocardium in all frames and determine LV end-diastolic volume, LV end-systolic volume and LV ejection fraction. CO was calculated as the product of LV stroke volume (end-diastolic – end-systolic volume) multiplied by heart rate (Figure 1).

Statistical analysis

Continuous variables are presented as medians with interquartile range. Qualitative variables are presented as counts and percentages. CO obtained from PiCCO and from 3D-TEE were compared using Pearson's correlation coefficient and the Bland–Altman method.

In addition, the percentage error (2 standard deviations/mean CO) for TEE estimation of CO with PiCCO-derived measurement as the gold standard was calculated.

Intra-observer and inter-observer variabilities for measurement of CO were assessed in a subset of 10 patients. The coefficient of variation (CV) and the intra-class correlation coefficient (ICC) were determined.

MedCalc Statistical Software version 14.12.0 (MedCalc Software, Ostend, Belgium) was used for calculation.

RESULTS

Clinical characteristics of the patients are listed in Table 1.

Thirty hemodynamic evaluations were obtained in 15 patients. At least 12 hours separated two investigations in patients undergoing multiple evaluations.

3D-TEE estimation of CO was feasible in 29/30 (97%) cases. Abnormal LV segmental contraction was observed in 9 (31%) cases. The mean 3D-TEE image acquisition and post processing times were 46 ± 19 and 155 ± 35 seconds respectively. The CO derived from

PiCCO and 3D-TEE CO were correlated (r=0.78, p<0.0001); the coefficient of correlation between PiCCO and Doppler CO was 0.72, p<0.0001 (Figure 2).

Compared to PiCCO, the 3D-TEE CO mean bias was 0.38 L/min (95% confidence interval, -0.07 to 0.84L/min), with a standard deviation of the difference between paired measurements of 1.2 L/min, giving limits of agreement of -1.97 to 2.74L/min and a percentage error of 44%. Compared to PiCCO, the Doppler CO mean bias was 0.48 L/min (95% confidence interval, -0.07 to 1.03 L/min), with a standard deviation of the difference between paired measurements of 1.45 L/min, giving limits of agreement of -2.37 to 3.33 L/min and a percentage error of 53% (Figure 3).

For intra-observer variability the CV and the ICC were respectively 3.9% and 0.99 (95% confidence interval, 0.91 to 0.99) for 3D-TEE CO, and 9.3% and 0.96 (95% confidence interval, 0.81 to 0.99) for Doppler CO. For inter-observer variability the CV and the ICC were respectively 9.5% and 0.95 (95% confidence interval, 0.76 to 0.99) for 3D-TEE CO, 5.1% and 0.94 (95% confidence interval, 0.71 to 0.99) for Doppler CO.

DISCUSSION

In this pilot study, 3D-TEE appears to be a feasible method for CO measurement in ICU mechanically ventilated patients. The latest generation 3D echocardiography equipment and software permitted acquisition of good quality images in 97% of the cases with relatively short recording and off-line post processing times (46 and 155 seconds respectively) that make this technique suitable for routine clinical use at the bedside. Furthermore 3D-TEE also provides the most reliable ultrasound assessment of LVEF. This new semi-automated modality is a promising additional tool for noninvasive hemodynamic assessment of ICU patients. However, in this study including a limited number of observations the percentage error and the limits of agreement are relatively wide compared to invasive measurement of CO. The 3D-TEE needs further evaluations in larger cohorts of patients.

Doppler-echocardiography assessment of CO can be performed using several techniques. Doppler-based CO is the most frequently used ultrasound approach in ICU patients.[11] However, this method requires two measurements obtained from two different acoustic windows. Using TEE, LVOT diameter should be measured from the mid-esophageal long axis view while pulsed wave Doppler LVOT flow should be acquired from the transgastric view. This Doppler derived CO approach is vulnerable to several measurements errors, mainly related to Doppler beam non-optimal alignment with aortic flow.[10] Another method relies on two-dimension assessment of systolic and diastolic volumes based on the Simpson method. However, this technique has several limitations mainly related to the use of calculation formulas which postulate normal LV shape.[7] Indeed, this is an important issue in ICU patients who frequently have segmental LV dysfunction, as observed in 31% of the cases included in our study.

Alternatively, accurate 3D-ultrasound LV measurement of end-diastolic and end-systolic volumes has been validated using MRI as the gold standard method.[6][7] Thus, 3D-TEE might provide more reliable semi-automated quantitative assessment of actual systolic function than the simple and frequently used fractional area change visually evaluated in transgastric short axis view or in four-chamber view of the cardiac chambers,[12] since this monoplane two-dimension approach might be biased in patients with inhomogeneous systolic contraction. Moreover, the 3D-TEE LV full-volume approach without any geometrical assumption has the potential to provide accurate estimation of stroke volume and CO. Using previous generations of machines and software, the feasibility of the technique has been reported for CO measurement in the operating room in stable patients just before bypass surgery.[13] However, the post-processing time to obtain CO was >400 sec in that study. Our study showed that the post-processing time was more than halved using latest generation software, making the technique more applicable for clinical use at the patient's bedside. In order, to make sure that the echo analyses were completely blinded from PiCCO and clinical data, the echo post-processing was performed off-line in our study. Using the same software, the 3D-TEE volume dataset processing is feasible on-line on the echocardiography machine.

In this pilot study including a limited number of observations the percentage error and the limits of agreement between 3D-TEE and invasive measurement of CO were relatively wide. Thus, 3D-TEE could not be considered as interchangeable with invasively measured CO and needs further evaluations in larger cohorts of patients. However, the percentage error with invasive data was smaller and the limits of agreements were narrower using 3D-TEE compared to Doppler method. To date 3D-TEE should be considered as a promising valuable noninvasive alternative to conventional ultrasound examination offering the advantage to provide the most reliable ultrasound quantitative assessment of LVEF.

We acknowledge several limitations to the present study. First, current availability and cost of the 3D-ultrasound technology is still an obstacle to the large diffusion of the technique in ICUs worldwide. However, Doppler-echocardiography platforms including one compact ultrasound system that allow real time 3D-TEE imaging are now available and may rapidly diffuse in the ICU environment. Second, sinus rhythm is required for 3D LV data set reconstruction over several cardiac cycles. For an accurate estimation of LV stroke volume in patients with arrhythmias, next generation of echocardiography machines should allow a single-beat LV full-volume acquisition with a high frame rate. Third, the 3D data acquisitions and post-processing were performed in this study by two experts used to TEE. It would be of interest to assess in next studies the feasibility of the techniques by less experienced physicians. Finally, the ability of 3D-TEE to track CO changes after a therapeutic intervention was not assessed and requires to be investigated in next studies.

CONCLUSIONS

Noninvasive estimation of CO by 3D-TEE is feasible in ICU mechanically ventilated patients. This new semi-automated modality appears to be a promising valuable noninvasive alternative to conventional ultrasound examination offering the advantage to provide the most reliable ultrasound quantitative assessment of LVEF. This new technology needs to be investigated in larger population of ICU patients.

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CONFLICTS OF INTERESTS

N.H. has performed consulting/advisory activities for Philips. The other authors have no competing interests to declare related to the present study.

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FIGURES

Figure 1: Post-processing of 3D-TEE LV dataset. The dedicated software determine semi-automatically LV end-diastolic volume, LV end-systolic volume and LV ejection fraction. CO was calculated as the product of LV stroke volume (end-diastolic – end-systolic volume) by heart rate.

CO, cardiac output; EDV, end-diastolic volume; ESV, end-systolic volume; LV, left ventricular; LVEF, left ventricular ejection fraction; SV, stroke volume

Figure 2: Linear correlation between PiCCO and 3D-TEE (left) and between PiCCO and Doppler method (right).

3D TEE, Three-dimensional trans-esophageal echocardiography; CO, cardiac output.

Figure 3: Bland–Altman analysis of the agreement between PiCCO CO and 3D-TEE (left) and between PiCCO and Doppler method (right).

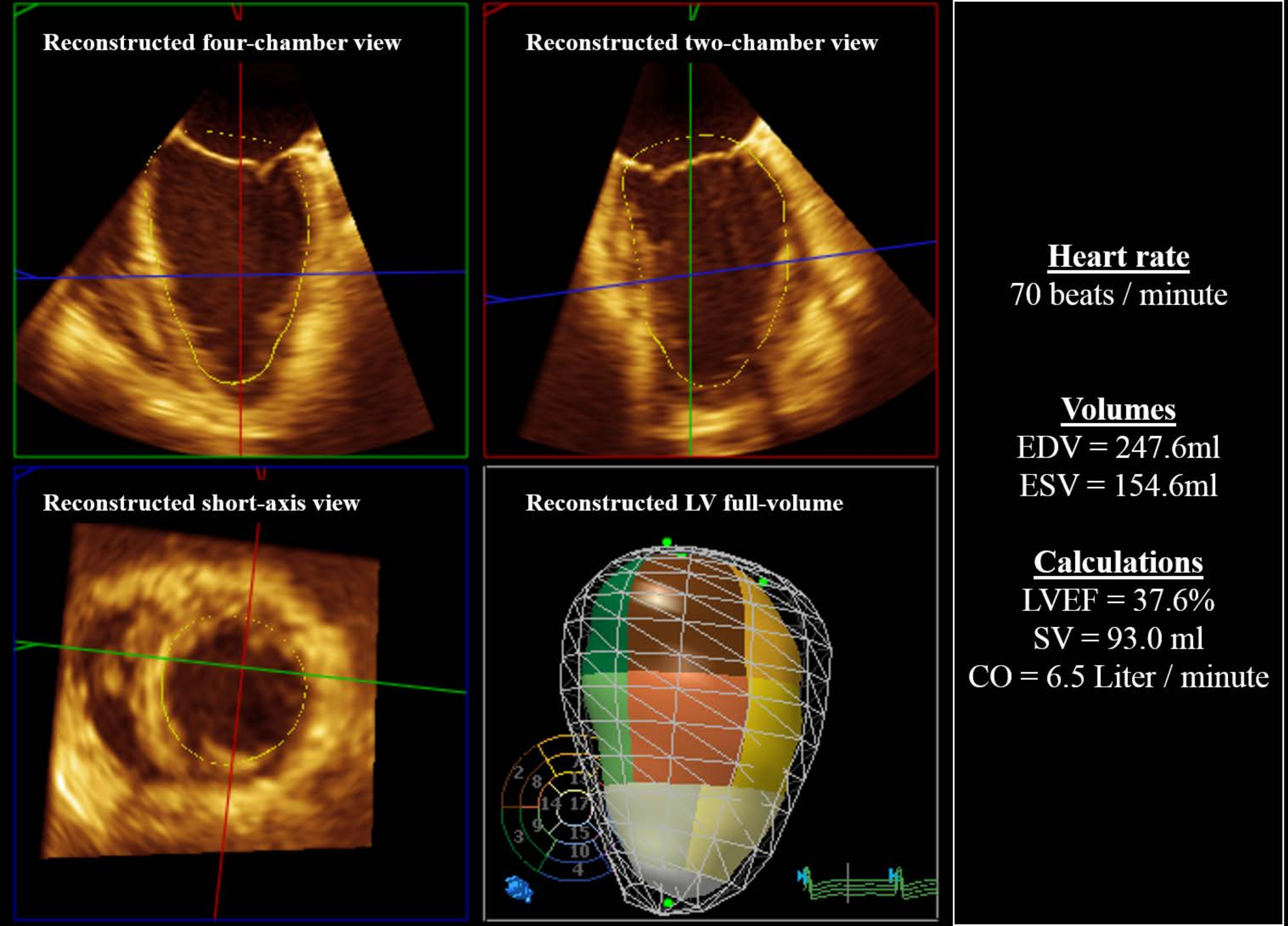
3D-TEE, Three-dimensional trans-esophageal echocardiography; CO, cardiac output.

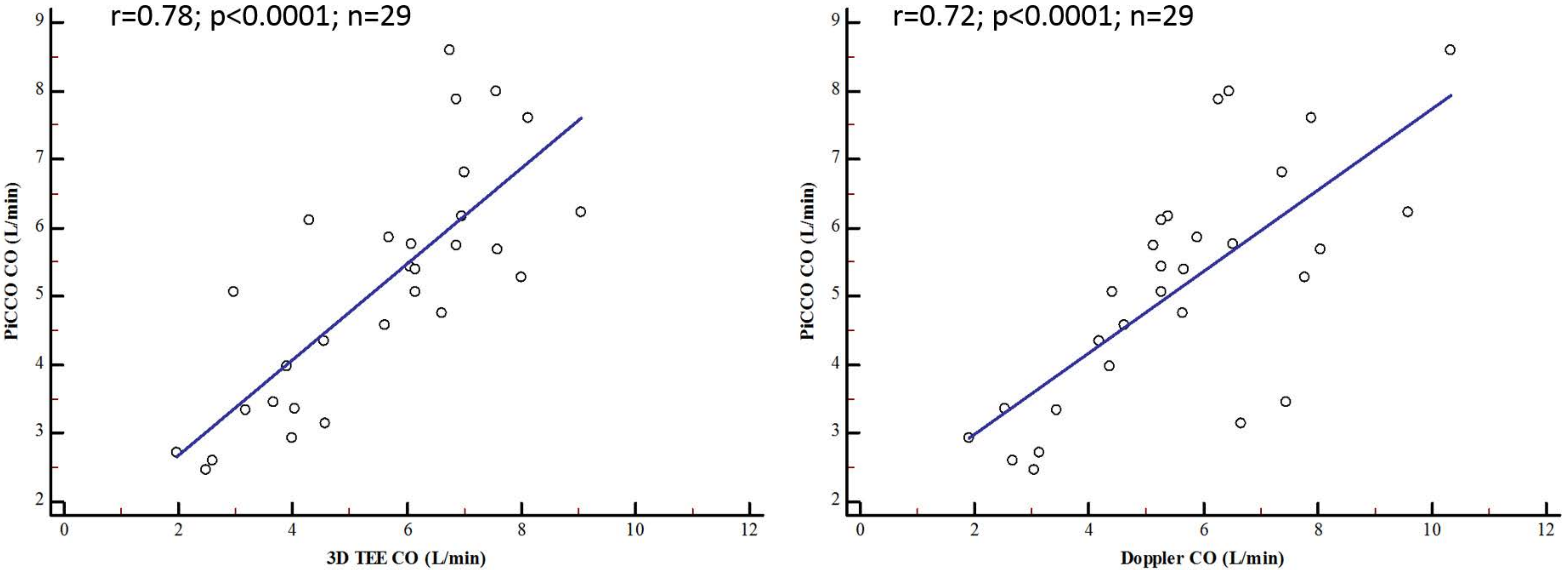
Table 1: Patients characteristics at the inclusion in the study (n=15)

Variable	Value
Age (years)	61 [48-68]
Men	10 (67)
Simplified acute physiology score (SAPS II)	68 [59-75]
Reason for ICU admission	
-Septic shock	3 (20)
-Cardiogenic shock	3 (20)
-Cardiac arrest	2 (13)
-Post operative multi-organ failure	2 (13)
-Heart transplantation	2 (13)
-Acute respiratory distress syndrome	1 (7)
-Pancreatitis	1 (7)
-Pulmonary Embolism	1 (7)
Ventilator parameters	
-tidal volume (ml)	480 [428-500]
-breathing rate (breath/minute)	20 [20-30]
- positive end-expiratory pressure (cm H_2O)	6 [4-8]
-Fraction of inspired oxygen (%)	40 [40-55]
Patients on cathecholamines at admission	15 (100)
Norepinephrine dose (mg/h)	1.05 [0.5-1.6]
Dobutamine dose (µg/kg/min)	10 [5-15]
Heart rate (beats/minute)	85 [77-99]
Systolic blood pressure (mmHg)	124 [108-134]
Diastolic blood pressure (mmHg)	63 [58-70]
Mean blood pressure (mmHg)	83 [76-91]

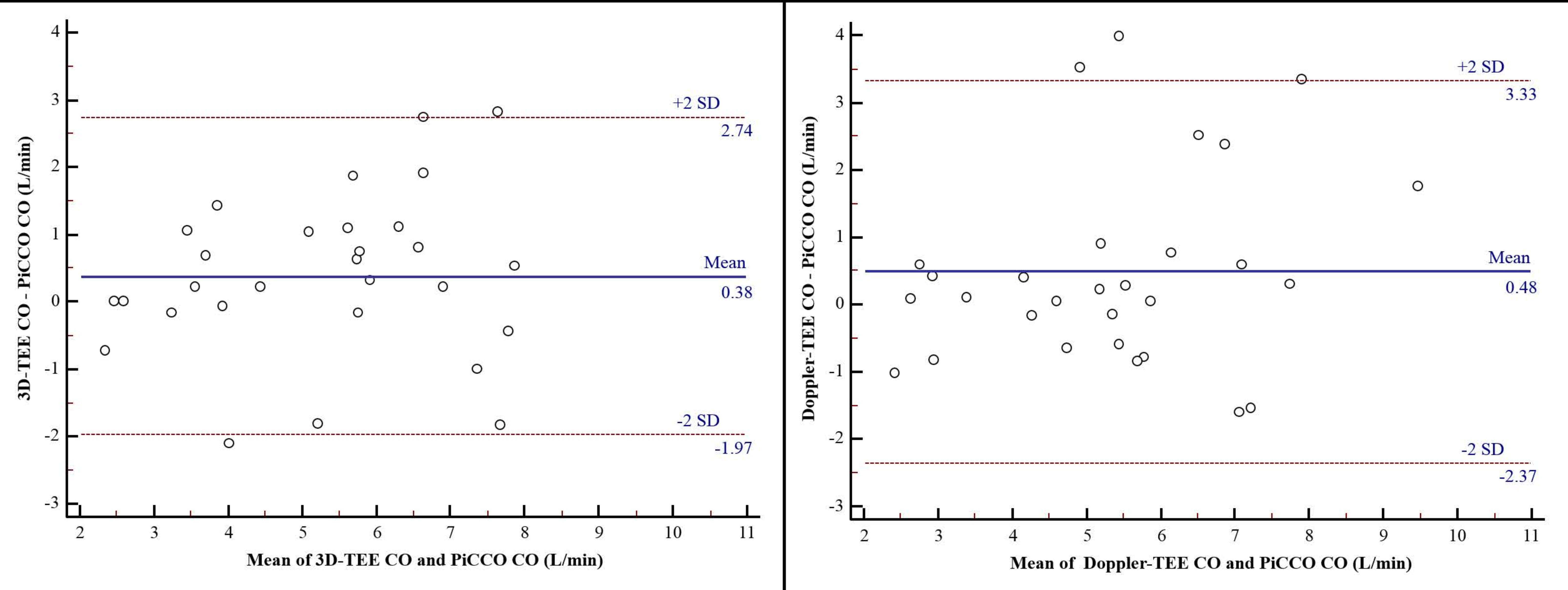
Renal replacement therapy	6 (40)
Left ventricular end-diastolic volume (ml) Left ventricular end-systolic volume (ml) Left ventricular ejection fraction (%)	131 [98-159] 48 [25-114] 53 [29-73]

Data are expressed as median and interquartile range or number (%).
ICU, intensive care unit


Reconstructed four-chamber view
Reconstructed two-chamber view
Reconstructed short-axis view
Reconstructed LV full-volume
Heart rate
70 beats / minute
Volumes
EDV = 247.6ml
ESV = 154.6ml
Calculations
LVEF = 37.6%
SV = 93.0 ml
CO = 6.5 Liter / minute



r=0.78; p<0.0001; n=29
PiCCO CO (L/min)
3D TEE CO (L/min)
r=0.72; p<0.0001; n=29
PiCCO CO (L/min)
Doppler CO (L/min)



3D-TEE CO - PiCCO CO (L/min)
Mean of 3D-TEE CO and PiCCO CO (L/min)
+2 SD
2.74
Mean
0.38
-2 SD
-1.97
Doppler-TEE CO - PiCCO CO (L/min)
Mean of Doppler-TEE CO and PiCCO CO (L/min)
+2 SD
3.33
Mean
0.48
-2 SD
-2.37