



The diagnostic accuracy of estimated continuous cardiac output compared with transthoracic echocardiography

Précision diagnostique de l'estimation continue du débit cardiaque par rapport à l'échocardiographie transthoracique

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Abstract

Purpose *Estimated continuous cardiac output (esCCO) is a new and noninvasive cardiac output (CO) monitoring device using pulse wave transit time. The aim of this study was to assess rapid changes in CO using esCCO (ΔCO_{esCCO}) without invasive calibration and to compare the results with those using transthoracic Doppler echocardiography (ΔCO_{TTE}).*

Methods *Fifty-four consecutive patients were enrolled in this study following elective cardiac surgery. The CO_{esCCO} and CO_{TTE} were collected during four consecutive steps: 1) at baseline, 2) during passive leg raising (PLR), 3) at return to baseline, and 4) after a fluid challenge. The relationship between ΔCO_{esCCO} and ΔCO_{TTE} induced by*

PLR and a fluid challenge was assessed and a polar plot analysis was performed. Relationship, Bland-Altman analysis, and percentage error for absolute values of CO_{esCCO} and CO_{TTE} were also performed.

Results *Twenty-four patients were excluded from the analysis. No correlation was found between ΔCO_{esCCO} and ΔCO_{TTE} during PLR ($r = 0.07$; $P = 0.732$; $n = 30$) and after a fluid challenge ($r = 0.24$; $P = 0.394$; $n = 14$). The polar plot analysis showed that 21 data points (87%) of significant changes in CO were above the 30° radial sector lines and confirmed that esCCO was unable to track changes in CO. A weak positive relationship was found between absolute values of CO_{esCCO} and CO_{TTE} ($r = 0.28$; $P = 0.004$). Bias, precision, and limits of agreement were $0.25 \text{ L}\cdot\text{min}^{-1}$, $2.4 \text{ L}\cdot\text{min}^{-1}$, and -4.4 to $4.9 \text{ L}\cdot\text{min}^{-1}$, respectively. The percentage error was 80%.*

Conclusions *Estimated continuous cardiac output without external calibration seems unable to assess rapid changes in CO following cardiac surgery and was not interchangeable with transthoracic Doppler echocardiography.*

Author contributions All authors contributed to the concept and design of the study, reviewed the analysis, and participated in the preparation of the submitted manuscript. *Xavier Balaire* performed the transthoracic echocardiography. *Marc-Olivier Fischer* and *Charles Le Mauff de Kergal* performed data acquisition. *Clément Boisselier* requested ethical and administrative authorization. *Marc-Olivier Fischer*, *Jean-Luc Hanouz*, and *Jean-Luc Fellahi* designed the study, performed statistical analysis, and wrote the manuscript.

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Résumé

Objectif *L'estimation continue du débit cardiaque (esCCO) est une nouvelle technique de monitoring continu et non invasif du débit cardiaque utilisant la vitesse de propagation de l'onde de pouls. L'objectif de l'étude était de comparer les variations rapides de mesure de débit cardiaque entre l'esCCO (ΔCO_{esCCO}) sans calibration invasive et l'échocardiographie Doppler transthoracique (ΔCO_{ETT}).*

Méthodes *Cinquante-quatre patients consécutifs ont participé à l'étude après avoir subi une chirurgie cardiaque non urgente. Les données de CO_{esCCO} et CO_{ETT} ont été récoltées au cours de quatre étapes consécutives: 1) état de base, 2) épreuve de lever de*

jambes passif (ELJ), 3) retour à l'état de base, et 4) après remplissage vasculaire. La relation entre la ΔCO_{esCCO} et la ΔCO_{ETT} induites par l'ELJ et le remplissage vasculaire a été évaluée et une analyse par diagramme polaire a été réalisée. La corrélation, l'analyse de Bland-Altman et le pourcentage d'erreur pour les valeurs absolues de CO_{esCCO} et CO_{ETT} ont également été réalisés.

Résultats Vingt-quatre patients ont été exclus de l'analyse. Aucune corrélation n'a été observée entre la ΔCO_{esCCO} et la ΔCO_{ETT} pendant l'ELJ ($r = 0,07$, $P = 0,732$, $n = 30$) ni après remplissage vasculaire ($r = 0,24$, $P = 0,394$, $n = 14$). L'analyse en diagramme polaire a démontré que 21 points (87 %) parmi les variations de débit cardiaque significatives se trouvaient au dessus de la zone radiale de 30° , confirmant que l'esCCO n'était pas assez précise pour détecter les changements de débit cardiaque. Une faible relation positive a été observée entre les valeurs absolues de CO_{esCCO} et CO_{ETT} ($r = 0,28$, $P = 0,004$). Le biais, la précision et les limites d'agrément étaient $0,25 \text{ L}\cdot\text{min}^{-1}$, $2,4 \text{ L}\cdot\text{min}^{-1}$, et $-4,4$ à $4,9 \text{ L}\cdot\text{min}^{-1}$, respectivement. Le pourcentage d'erreur était de 80 %.

Conclusion L'esCCO sans calibration externe semble non utilisable pour évaluer les variations rapides du débit cardiaque après une chirurgie cardiaque et l'esCCO n'était pas interchangeable avec l'échocardiographie Doppler transthoracique.

Advanced hemodynamic monitoring, including measurement of cardiac output (CO), has been shown to decrease morbidity and mortality in moderate- to high-risk patients during the perioperative period.¹ Nevertheless, intermittent bolus pulmonary artery thermodilution, considered to be the reference approach for CO monitoring, is a highly invasive method and not feasible for regular use in routine practice.² Among noninvasive CO monitoring devices, Doppler transthoracic echocardiography (TTE) has been validated as a reference method in critical care,³⁻⁵ however, TTE is time-consuming and requires expensive equipment and operator training. Moreover, the poor echogenicity of numerous critically ill patients decreases its efficiency at the bedside.³ New noninvasive convenient technologies could significantly improve the use of CO monitoring in high-risk patients and adherence of practitioners to the international guidelines.^{2,6} Recently, the Japanese company, Nihon Kohden, marketed a device (i.e., estimated continuous cardiac output [esCCO], Tokyo, Japan) that estimates CO by measuring pulse wave transit

time (PWTT) derived from an electrocardiogram, digital pulse oximeter, and noninvasive brachial pressure. Two proof-of-concept studies using an external calibration with bolus pulmonary artery thermodilution and invasive arterial pressure showed encouraging results.^{7,8} Another study conducted in the intensive care unit (ICU) to compare noninvasive esCCO without external CO calibration with TTE was less straightforward.⁹ Further validation studies using different comparators and conducted in various subgroups of high-risk patients are highly desirable before recommending a wider use of esCCO at the bedside, in the ICU, or in the operating room.

Accordingly, the aim of this study conducted in cardiac surgical ICU patients was to compare noninvasive esCCO without external CO calibration with TTE during rapid changes in CO. We tested the hypothesis that esCCO could be an acceptable and convenient noninvasive alternative to TTE in that setting.

Methods

Patient population

The study was conducted in accordance with the Statement for Reporting Studies of Diagnostic Accuracy (the STARD initiative).¹⁰ Fifty-four consecutive adult patients admitted to the ICU following elective cardiac surgery with cardiopulmonary bypass were prospectively investigated at the University Hospital of Caen (Caen, France) from November 2012 to March 2013. Institutional approval was obtained from the local ethics committee (Comité de Protection des Personnes Nord-Ouest III, CHU de Caen, avenue de la Côte de Nacre, BP 95182, 14033 Caen Cedex 9, France, Number A12-D22-VOL.13, June 9, 2012). Authorization was granted to waive written informed consent because data were collected during routine care that conformed to standard procedures currently used in our institution. Nevertheless, verbal consent was obtained from all study participants. All patients scheduled for elective cardiac surgery with cardiopulmonary bypass (coronary artery bypass grafting, aortic and/or mitral valve replacement or repair, or combined cardiac surgery) were eligible for the study. The patients were enrolled if, according to the judgment of the attending anesthesiologist, they presented an indication of fluid loading during the postoperative period in the ICU. Patients undergoing emergent surgery (less than 24 hr), redo surgery, off-pump coronary artery bypass grafting, and complex unusual procedures were not included in the study. Additional exclusion criteria included patients with irregular heart rhythm when study hemodynamic data were

gathered, patients with poor echogenicity, and/or patients with a poor-quality esCCO signal.

Perioperative management

General anesthesia and postoperative management followed the institutional standard. In the operating theatre, a Leadercath 20G (Vygon) radial artery catheter (Ecouen, France) and a jugular central venous catheter were inserted after induction of general anesthesia. Intra- and postoperative fluid management were left to the discretion of the attending anesthesiologist who was not involved in the study protocol and was guided by routine clinical and hemodynamic parameters. At the time of the study, patients either breathed spontaneously or received tracheal intubation and lung ventilation (volume-controlled regimen or assisted ventilation).

Transthoracic echocardiography cardiac output (CO_{TTE}) calculation

A single trained operator (X.B.) blinded to the esCCO measurements performed transthoracic echocardiography using a standard transthoracic probe (S5-1, Philips Healthcare, Bothell, WA, USA) and a dedicated unit (CX Cart 50, Philips Healthcare, Bothell, WA, USA). The CO_{TTE} was calculated using the sub-aortic velocity-time integral (VTI_{SA}), the diameter of the left ventricular outflow tract (LVOT), and heart rate (HR) using the following formula: $CO_{TTE} = (VTI_{SA} \times (\text{diameter of LVOT})^2 \times \pi/4) \times HR$. The diameter of the LVOT was measured in the parasternal long axis view, and the VTI_{SA} was measured on the five-chamber apical view using pulsed Doppler and averaged over three consecutive measurements. Two mandatory quality criteria were essential for patient enrollment in the study: the Doppler click of aortic valve closure and a dual spectrum VTI_{SA} (Fig. 1), confirming the right position of the pulsed-wave Doppler cursor and its repeatability over the study period.¹¹

esCCO cardiac output (CO_{esCCO}) calculation

In all patients, an electrocardiograph, a noninvasive brachial pressure device, and a digital oximeter were connected to the Vismo monitor (Nihon Kohden, Tokyo, Japan), and a second investigator (C.L.M.D.K.) carried out a noninvasive calibration. After recording patient characteristics, including age, sex, height, weight, and noninvasive brachial pressure, the esCCO device determined a reference value for calibration. The signal quality index was displayed continuously on the monitor. The esCCO calculated the stroke volume (SV) continuously using the negative correlation between SV

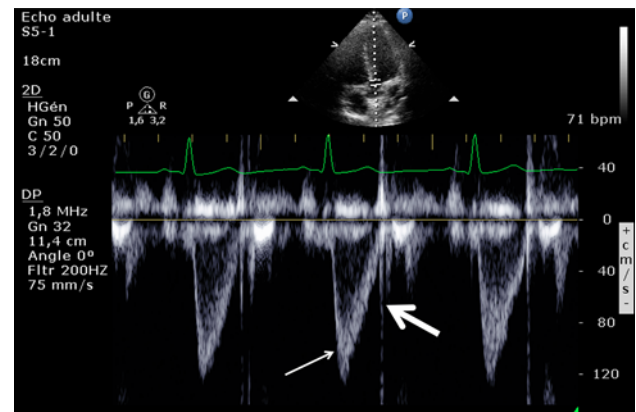


Fig. 1 Example of a systolic still-frame image of the heart in the apical five-chamber view illustrating the Doppler recording sub-aortic velocity-time integral and the presence of the two quality criteria necessary to include the patient: the Doppler click of the aortic valve closure (large arrow) and a dual spectrum of VTI_{SA} (fine arrow). These criteria helped confirm the right position of the pulsed-wave Doppler cursor and its reproducibility over the study period

and PWTT. The PWTT was calculated by averaging 64 consecutive heart beats. The CO_{esCCO} was performed with the formulas previously described⁷: 1) $CO = SV \times HR$; 2) $SV = K \times PP$ where K was the experimental constant and PP the pulse pressure; and 3) $PP = (\alpha \times PWTT) + \beta$ where α and β were experimental constants. The PWTT represented the sum of the pre-ejection period and the delay in pulse wave arrival time from the ascending aorta to the site of the peripheral pulse oximeter sensor. The PWTT was calculated as the interval between the R wave on the electrocardiogram and the arrival of the peripheral SpO_2 pulse wave.

Study protocol

Patients were enrolled postoperatively following the attending anesthesiologist's decision to administer a fluid challenge (6% hydroxyethyl starch 500 mL 130/0.4) over 15 min. For each patient, measurements were recorded: 1) at baseline in the 45° semi-recumbent position; 2) during passive leg raising (PLR), which consisted of simply pivoting the entire bed using an automatic pivotal motion, as previously described;¹² 3) at return to baseline in the 45° semi-recumbent position; and 4) ten minutes after a fluid challenge in PLR responders only. The positive response to PLR was defined by an increase in $CO_{TTE} \geq 10\%$.¹³ The highest value of CO_{TTE} was observed within the first 90 sec following the PLR maneuver.¹⁴ The highest value of CO_{esCCO} was recorded during the period ranging from the beginning of the PLR to two minutes after the highest value of CO_{TTE} , in accordance with the fact that PWTT was calculated by averaging 64 consecutive heart beats.⁷ The

same method was applied after the fluid challenge. Finally, a positive response to the fluid challenge was defined by an increase in CO_{TTE} of at least 15%.¹⁵ At each step, all hemodynamic parameters (including CO_{TTE} , CO_{esCCO} , and PWTT) were recorded. During the recording of study data, ventilator settings, sedation, and vasoactive drugs remained unchanged. The noninvasive brachial pressure was measured only at the time of the initial calibration, as recommended by the manufacturer.

Endpoints

The primary endpoint was the relationship between rapid changes in CO ($\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$) following PLR. Secondary endpoints were 1) the relationship and agreement between absolute values of CO_{TTE} and CO_{esCCO} and 2) the ability of $\Delta\text{CO}_{\text{esCCO}}$ to track rapid changes in $\Delta\text{CO}_{\text{TTE}}$.

Statistical analysis

On the basis of a previous report⁹ and according to our primary endpoint, we calculated that 29 patients were necessary to show a correlation coefficient $r = 0.50$ between $\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$ with a 5% type I error rate and a 20% type II error rate. Data are expressed as mean (SD) or median [25th-75th percentile] for non-normally distributed variables (Kolmogorov-Smirnov test) or numbers and percentages, as appropriate. Continuous variables were analyzed with the unpaired Mann-Whitney U test. Categorical variables were analyzed with the Fisher's exact test or the K χ -2 test, as appropriate. Changes in hemodynamic parameters after PLR and the fluid challenge were compared using the paired Wilcoxon

test. The relationships between $\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$ and the absolute values of CO_{TTE} and CO_{esCCO} were determined by linear regression. A modified Bland-Altman analysis for repeated measurements was used to compare bias, precision (SD of bias), and limits of agreement (LOA) (bias \pm 1.96 SD) between CO_{TTE} and CO_{esCCO} .¹⁶ The percentage error to determine acceptable limits of agreement between both devices was calculated using the formula given by Critchley and Critchley.¹⁷ Trends were analyzed using polar plotting of CO changes among consecutive time points, as previously described.^{18,19} A P value of < 0.05 was considered to be statistically significant and all P values were two-tailed. Statistical analyses were performed using MedCalc[®] Software bvba version 12.5.0 (Mariakerke, Belgium) and Deltagraph[®] version 5.6 (RockWare Inc., Golden, CO, USA).

Results

Twenty-four of the 54 consecutive adult patients enrolled in the study were excluded because of poor echogenicity ($n = 8$), the absence of the two predefined TTE criteria of quality ($n = 14$), and the absence of an esCCO signal ($n = 2$) (Fig. 2). The intra-observer variability for CO measurement assessed from five consecutive TTE exams was 4%. When present, the esCCO signal quality index was excellent at each time in all patients, indicating that CO_{esCCO} was valid for analysis. No complication related to the use of esCCO was observed over the study period. Baseline characteristics for the remaining 30 patients are indicated in Table 1. Patients were included on postoperative day 0 [0-1]. At the time of the study, 16 (53%) patients breathed

Fig. 2 The flow chart of the study. esCCO = estimated continuous cardiac output; FC = fluid challenge; PLR = passive leg raising; TTE = transthoracic Doppler echocardiography

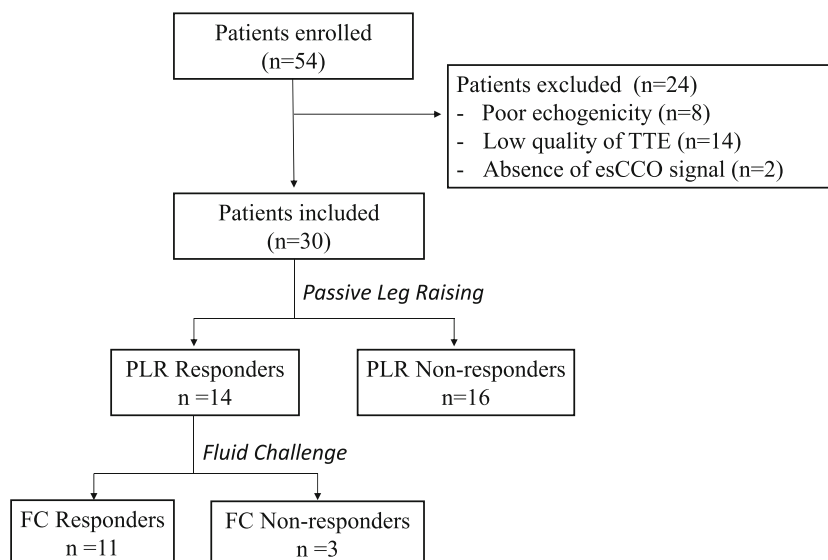


Table 1 Patients baseline characteristics ($n = 30$)

	Total cohort ($n = 30$)
Age (yr)	67 (12)
Sex (M/F)	20/10
Body mass index ($\text{kg}\cdot\text{m}^{-2}$)	29 (5)
EuroSCORE II (%)	1.04 [0.76-1.69]
Hypertension	24 (80)
Peripheral vascular disease	2 (7)
Diabetes mellitus	2 (7)
Postoperative LVEF (%)	56 (10)
<i>Type of surgery</i>	
CABG	5 (17)
Valvular surgery	21 (70)
Combined surgery	4 (13)
Length of CPB (min)	84 (41)
<i>Ventilatory patterns</i>	
Mechanical ventilation	14 (47)
Spontaneous ventilation	16 (53)
<i>Inotropic and vasoactive requirement</i>	
Dobutamine*	6 (20)
Norepinephrine [†]	7 (23)

Values are mean (SD) or median [25th-75th percentile] or number (%)

*From 2-5 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. [†]From 0.01-0.12 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. CABG = coronary artery bypass grafting; CPB = cardiopulmonary bypass; LVEF = left ventricular ejection fraction

spontaneously and 14 (47%) patients received tracheal intubation and lung ventilation (volume-controlled regimen = 9; assisted ventilation = 5).

The $\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$ were compared during PLR ($n = 30$) and after the fluid challenge ($n = 14$). Responders to PLR ($n = 14$) increased CO_{TTE} by 25 (14)% on average while CO_{esCCO} varied by -1 (4)% ($P < 0.001$). Responders to the fluid challenge ($n = 11$) increased CO_{TTE} by 38

(21)% on average, while CO_{esCCO} varied by 3 (12)% ($P = 0.09$). The CO_{TTE} increased significantly after both PLR and the fluid challenge, whereas no significant difference was observed in CO_{esCCO} (Table 2). No statistical correlation was found between $\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$ during PLR ($n = 30$; $Y = -1.49 + 0.03X$; $R^2 = 0.00$; $r = 0.07$; $P = 0.732$), and after the fluid challenge ($n = 14$; $Y = 7.64 - 0.13X$; $R^2 = 0.06$; $r = 0.24$; $P = 0.394$) (Figs. 3A and 3B, respectively).

The range of CO_{TTE} absolute values was 2.9-13.6 $\text{L}\cdot\text{min}^{-1}$ [6.1 (2.3) $\text{L}\cdot\text{min}^{-1}$], while the range of CO_{esCCO} absolute values was 2.7-8.8 $\text{L}\cdot\text{min}^{-1}$ [5.9 (1.5) $\text{L}\cdot\text{min}^{-1}$]; $P = 0.730$. A weak positive relationship was found between the absolute values of CO_{TTE} and CO_{esCCO} ($n = 104$; $Y = 9.55 + 0.44x$; $R^2 = 0.079$; $r = 0.28$; $P = 0.004$). The bias, precision, and LOA between CO_{TTE} and CO_{esCCO} were 0.25 $\text{L}\cdot\text{min}^{-1}$, 2.4 $\text{L}\cdot\text{min}^{-1}$, and -4.4 to 4.9 $\text{L}\cdot\text{min}^{-1}$, respectively (Fig. 4). The percentage error between CO_{TTE} and CO_{esCCO} was 80%, meaning that both methods were not interchangeable.

After the 0.5 $\text{L}\cdot\text{min}^{-1}$ central exclusion zone, polar plot analysis showed that 21 data points (87%) were above the 30° radial sector lines, confirming the low trending of esCCO to track rapid changes in CO (Fig. 5).

Discussion

The main finding of the study was the inability of esCCO to detect rapid changes of CO in adult patients undergoing elective cardiac surgery with cardiopulmonary bypass. The changes of CO determined by the noninvasive esCCO device without external CO calibration were not correlated with $\Delta\text{CO}_{\text{TTE}}$ during PLR and after the fluid challenge. The values of precision and limits of agreement significantly exceeded the boundaries allowing interchangeable use of both devices.

Table 2 Hemodynamic data during passive leg raising ($n = 30$) and after fluid challenge ($n = 14$)

	Baseline	During PLR	P value*	Before FC	After FC	P value [†]
Heart rate ($\text{beats}\cdot\text{min}^{-1}$)	82 (15)	81 (14)	0.216	82 (14)	81 (11)	0.380
SAP (mmHg)	117 (22)	123 (20)	0.002	118 (23)	118 (13)	0.153
DAP (mmHg)	60 (13)	64 (12)	0.001	61 (12)	59 (8)	0.542
MAP (mmHg)	80 (16)	85 (14)	0.001	81 (16)	81 (9)	0.068
CVP (mmHg)	5 (4)	8 (4)	< 0.001	6 (4)	9 (5)	0.006
CO_{TTE} ($\text{L}\cdot\text{min}^{-1}$)	5.6 (1.8)	6.3 (2.3)	0.001	5.8 (2.1)	7.6 (3.0)	0.029
CO_{esCCO} ($\text{L}\cdot\text{min}^{-1}$)	5.9 (1.5)	5.8 (1.5)	0.362	5.9 (1.5)	6.1 (1.4)	0.426
PWTT (msec)	244 (11)	244 (12)	0.417	245 (12)	243 (12)	0.297

Values are mean (SD). *During PLR vs baseline. [†]After fluid challenge vs before fluid challenge. CO_{esCCO} = cardiac output measured with esCCO; CO_{TTE} = cardiac output measured with Doppler transthoracic echocardiography; CVP = central venous pressure; DAP = diastolic arterial pressure; FC = fluid challenge; MAP = mean arterial pressure; PLR = passive leg raising; PWTT = pulse wave transit time; SAP = systolic arterial pressure

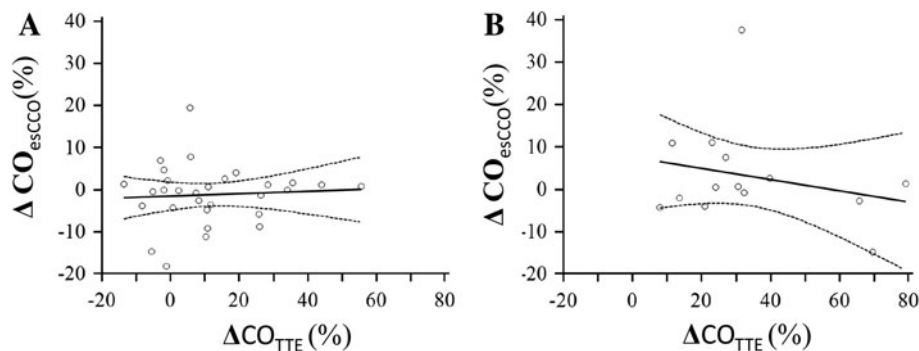


Fig. 3 The relationship between cardiac output changes (%) measured by transthoracic Doppler echocardiography ($\Delta\text{CO}_{\text{TTE}}$) and by estimated continuous cardiac output ($\Delta\text{CO}_{\text{esCCO}}$): (A) during

passive leg raising ($n = 30$) and (B) after fluid challenge ($n = 14$). Dotted line is the 95% confidence interval of linear fit

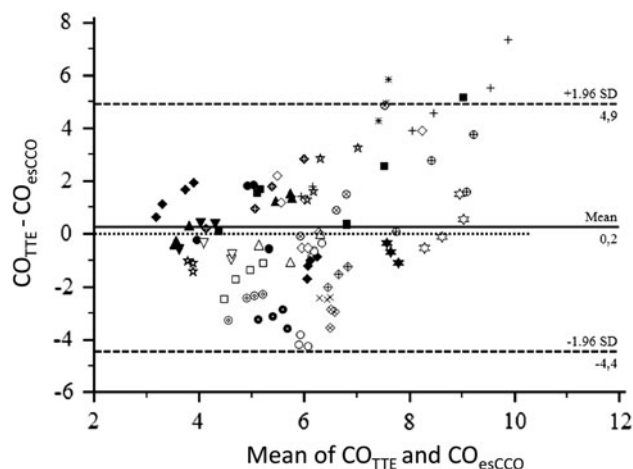


Fig. 4 Bland-Altman analysis for repeated measurements of absolute values of cardiac output measured by transthoracic Doppler echocardiography (CO_{TTE}) and estimated continuous cardiac output (CO_{esCCO}) ($n = 104$)

In the present study, we used TTE as the reference method for CO assessment. An excellent correlation with use of a bolus pulmonary artery catheter has been previously reported in ICU patients.^{4,5} Our intra-observer variability for CO_{TTE} measurement was low (much lower than the changes in CO we observed during PLR and after fluid loading) and similar to previous reports.²⁰ Moreover, we required high-quality TTE criteria, which explains the high rate of exclusion and strengthens the internal validity of our results. It is noteworthy that TTE offered a continuous beat-to-beat and noninvasive CO measurement while esCCO averaged 64 consecutive heart beats. Subsequently, we recorded the highest values of CO_{esCCO} within the two minutes following the highest values of CO_{TTE} , as previously described. In accordance with the manufacturer guidelines, a single calibration was performed at the start of the study period using measurement of noninvasive brachial pressure. Thus, the esCCO device was used in an entirely

noninvasive manner in full accordance with a modern concept of CO monitoring, i.e., to encourage a noninvasive, beat-to-beat, plug and play, easy to use device.⁶ As no CO monitoring tool can currently replace thermodilution,²¹ the ability of new mini- and noninvasive CO monitors to assess trends could be more important at the bedside than their accuracy in measuring absolute values of CO under stable hemodynamic conditions.¹⁸ The esCCO device fulfills these specifications and thereby justifies the main objective of the present study.

We found that esCCO was convenient and easy to use in almost all cardiac surgical patients when compared with TTE, which is both operator- and patient-dependent and of limited clinical usefulness. This result highlights the need for simple plug-and-play CO monitors, such as esCCO, for use in critically ill patients. Nevertheless, the esCCO device was unable to track the direction of rapid changes in CO induced by PLR and the fluid challenge, as shown by both the absence of correlation between $\Delta\text{CO}_{\text{TTE}}$ and $\Delta\text{CO}_{\text{esCCO}}$ and the polar plot analysis. A previous study reported a significant correlation between spontaneous changes in CO_{TTE} and CO_{esCCO} over time in critically ill patients.⁹ The same study also showed a poor concordance rate and finally concluded that esCCO failed to trend CO reliably. Recently, Kim *et al.* suggested that the variations of PWTT were correlated with invasive systolic blood pressure during induction of anesthesia and could represent a valuable alternative to invasive systolic blood pressure in high-risk hypertensive patients.²² The indirect arterial pressure approach derived from CO is misleading, however, and could be notoriously insufficient at the bedside.²³ In our study, neither systolic arterial pressure nor pulse pressure were correlated with PWTT (data not shown). To date, the esCCO device uses an undisclosed built-in proprietary algorithm that incorporates patient characteristics and PWTT to estimate arterial compliance. The CO calculation is based on the assumption that the SV is proportional to pulse pressure and arterial compliance.

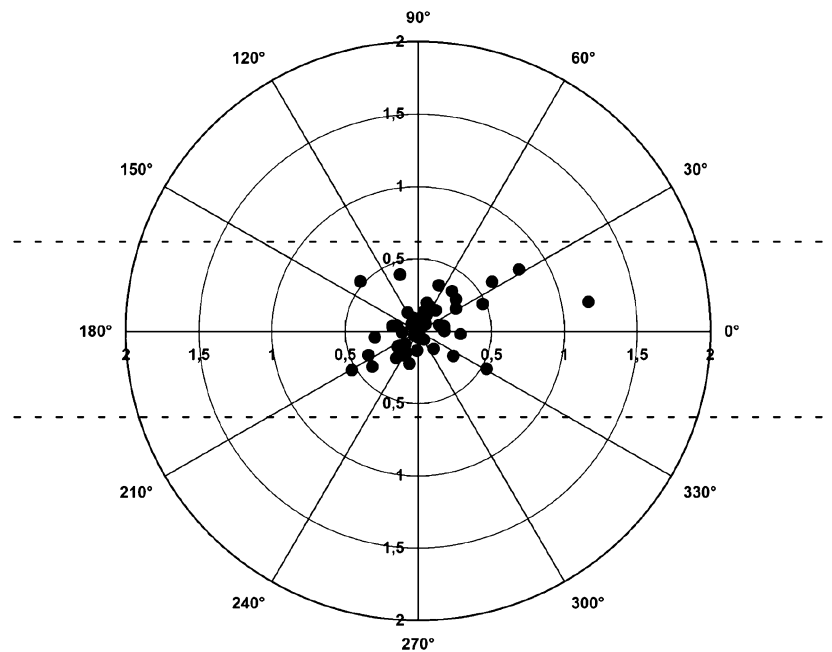


Fig. 5 Polar plot comparing changes in cardiac output during each step of the study: baseline to PLR ($n = 30$), PLR to return to baseline ($n = 30$), and baseline to after fluid challenge ($n = 14$) using transthoracic Doppler echocardiography and estimated continuous

cardiac output (esCCO). The first circle of $0.5 \text{ L}\cdot\text{min}^{-1}$ represents the central exclusion zone ($n = 50$), while remaining points showed the significant variations of cardiac output ($n = 24$). Twenty-one points (87%) were above the 30° radial sector lines

Unfortunately, acute changes in arterial compliance are not taken into account, even when serial noninvasive brachial pressure measurements are performed.⁹ The use of vasopressors could strongly modify the CO measurement taken with the esCCO device. Nevertheless, our results were similar when patients receiving norepinephrine were excluded from the analysis (data not shown). Passive leg raising and the fluid challenge were expected to modify blood volume and density and subsequently impact the velocity of arterial blood flow. Surprisingly, PWTT remained unchanged throughout the current study. Cardiac failure could also influence SV and PWTT. Postoperative inotropic support was used in 20% of our patients, leading to a quite normal left ventricular ejection fraction. In accordance with manufacturer recommendations, we measured noninvasive brachial pressure only at the beginning of the study. A systematic calibration of noninvasive brachial pressure before each measurement of CO_{esCCO} could improve the reliability of the device; however, a recent study found that this approach failed to improve agreement between TTE and esCCO.⁹ These last results emphasize the lack of interchangeability between esCCO and TTE. In contrast, studies using both a pulmonary artery catheter and invasive continuous arterial pressure for external calibration showed a good correlation between absolute values of CO measurements.^{7,8} Even so, the need for external invasive calibration significantly limits the applicability of esCCO

as a complete noninvasive monitoring tool. Unfortunately, implementing an automated exclusion algorithm with the esCCO device seems unable to improve its reliability.²⁴

Some comments are necessary concerning the limitations of the present study. First, the assessment of CO with TTE was unreliable in nearly 40% of our study population, mainly because of the absence of both predefined quality criteria required to reach intra-observer variability below 5%. This limitation clearly highlights the need for a simple plug-and-play CO monitor. Second, despite many attempts to reposition the pulse oximeter, two patients were excluded from esCCO analysis due to the absence of a signal. This could be another limitation of the device in routine practice. Third, the PWTT was calculated by averaging data of 64 consecutive heart beats, while TTE provided a beat-to-beat CO measurement. We tried to solve this problem by recording the highest value of CO_{esCCO} within the two minutes following the highest value of CO_{TTE} . Fourth, this phase II validation study was conducted in a subgroup of postoperative cardiac surgical patients. Further studies are required to assess the usefulness of esCCO as a trend CO monitor in other patient populations and to evaluate the influence of external invasive calibration at the bedside on the accuracy and reliability of esCCO.

In conclusion, the use of the noninvasive esCCO device without external CO calibration seemed unable to assess rapid changes in CO induced by PLR and a fluid challenge,

and the device was not interchangeable with TTE following elective cardiac surgery.

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Competing interest None declared.

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