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Comparison of noninvasive electrical cardiometry and transpulmonary thermodilution for cardiac output measurement in critically ill patients: a prospective observational study

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Abstract

Background Cardiac output (CO) monitoring is essential for diagnosing and managing critically ill patients. Recently, a non-invasive haemodynamic monitoring technique, electrical cardiometry (EC), has gathered increasing interest among ICU physicians. This study aimed to explore the accuracy of CO estimated by non-invasive EC (CO_{EC}) compared to CO determined by transpulmonary thermodilution (CO_{TPTD}) and to evaluate the ability of CO_{EC} to track CO_{TPTD} changes (ΔCO_{TPTD}).

Methods This prospective, observational, single-center study was conducted from April 2021 to April 2023, involving patients who required haemodynamic monitoring using a transpulmonary thermodilution device (PiCCO). CO_{TPTD} and CO_{EC} were recorded simultaneously, with the investigators obtaining the CO_{EC} measurements were blinded to the CO_{TPTD} results and vice versa. Agreement between the methods was evaluated using Bland–Altman analysis and percentage error (PE). The ability of CO_{EC} to track changes in CO_{TPTD} was examined using four-quadrant and polar plots.

Results Seventy-two patients with PiCCO haemodynamic monitoring were included, yielding 285 paired CO measurements. The bias between CO_{EC} and CO_{TPTD} was 0.47 L/min, with a limit of agreement (LoA) ranging from -2.91 to 3.85 L/min and a PE of 54.0%. Among 212 pairs of ΔCO data, excluding a central zone of 15% in the four-quadrant plot, the concordance rate between ΔCO_{EC} % and ΔCO_{TPTD} % was 70%. In the polar plot, excluding a central zone with a radius of 0.625 L/min (10% of the mean CO_{TPTD}), the mean polar angle for ΔCO_{EC} was 2.2°, with a radial LoA of 56.0°. Exploratory subgroup analysis indicated a PE of 47.0% between CO_{EC} and CO_{TPTD} and a concordance rate of 72% between ΔCO_{EC}% and ΔCO_{TPTD}% in patients with normal CO (CO ≥ 4 L/min). In patients with elevated

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thoracic fluid content (TFC > 35 kΩ), the PE between CO_{EC} and CO_{TPTD} was 45.0%, with a concordance rate of 64% between ΔCO_{EC}% and ΔCO_{TPTD}%. Additionally, in patients receiving low-dose norepinephrine equivalents (NEE ≤ 0.25 μg/kg/min), CO_{EC} and CO_{TPTD} exhibited a PE of 45.0%, while ΔCO_{EC}% and ΔCO_{TPTD}% achieved a concordance rate of 75% and a radial LoA of 44.2°.

Conclusion In critically ill patients, non-invasive EC indicated limited accuracy in measuring CO, along with a restricted ability to reliably track CO changes. These findings suggested that EC may not be interchangeable with TPTD in the general ICU population.

Keywords Noninvasive, Thoracic fluid content, Extravascular lung water, Metrology, stroke volume, Haemodynamic

Background

Monitoring cardiac output (CO) is essential for intensivists in diagnosing and managing critically ill patients [1]. Traditionally, the pulmonary artery catheter (PAC) has long been regarded as the gold standard for CO monitoring. However, its use has declined due to its invasiveness, associated complications, and inability to provide continuous beat-to-beat CO measurements [2]. Consequently, alternative methods like transpulmonary thermodilution (TPTD) has become increasingly favored as the accuracy of TPTD in measuring CO has been repeatedly demonstrated [3–5]. Nevertheless, TPTD requires central venous and arterial catheters, which pose risks of cannulation-related complications [6].

To address these challenges, non-invasive haemodynamic monitoring techniques have been developed as alternatives to invasive methods. Thoracic electrical bioimpedance is one of the widely available non-invasive technologies that allows continuous CO measurement. However, previous studies have reported poor agreement between thoracic bioimpedance and TPTD [7, 8]. Subsequently, electrical cardiometry (EC) was developed as an advancement of the bioimpedance method, utilizing a novel model that interprets the bioimpedance signal. EC attributes changes in impedance following the open of aortic valve to the alignment of erythrocytes, rather than changes in blood volume in the aorta, which is thought to provide a more accurate assessment of CO [9].

Despite these advancements, the accuracy of CO measurements obtained via EC in critically ill patients remains controversial. A recent meta-analysis concluded that the mean percentage error between EC and reference methods was not clinically acceptable in adult patients [10], but it included only a limited number of studies conducted in ICU settings. Furthermore, few studies have assessed the ability of EC to track changes in CO in critically ill patients, although animal studies suggest its potential in monitoring CO trends [11].

This study aims to compare the CO estimated by non-invasive EC (CO_{EC}) with the CO determined by TPTD (CO_{TPTD}) and to evaluate whether CO_{EC} can reliably track changes in CO_{TPTD} in a general ICU population.

Methods

Study population

This prospective, observational, single-center study was conducted between April 2021 and April 2023 in an 18-bed ICU at the First Affiliated Hospital of Sun Yat-sen University, Guangzhou, China. The study protocol was approved by the local ethics committee (2019–172) and registered with the China Clinical Trial Registry (ChiCTR2100045861). Informed consent was obtained from each patient or from the patient's legally authorized representative if the patient was unable to provide consent. Alternatively, deferred informed consent was obtained from patients.

Patients who underwent advanced haemodynamic monitoring by the TPTD technique (PiCCO, Pulsion Medical Systems, Getinge, Feldkirchen, Germany) was included. The decision to insert a PiCCO device was made by the attending physician. Exclusion criteria included: (1) presence of cardiac arrhythmias; (2) known severe valvulopathies (e.g., tricuspid regurgitation, aortic regurgitation, aortic stenosis); (3) use of circulatory support devices such as intra-aortic balloon pump (IABP) or extracorporeal membrane oxygenation (ECMO); (4) conditions preventing electrode placement (e.g., severe burn injury); (5) pregnancy; and (6) age ≤ 18 years.

Data collection

Demographic, clinical, and physiological data were collected, including age, sex, heart rate (HR), central venous pressure (CVP), mean arterial pressure (MAP), sequential organ failure assessment (SOFA) score, primary indication for haemodynamic monitoring, and use of mechanical ventilation (MV). Vasopressor exposure was quantified using norepinephrine equivalence (NEE) [12]. A threshold value of 0.25 μg /kg/min was chosen to define a high dose of vasopressors [13].

PiCCO monitoring

Patients were equipped with a jugular venous catheter and a thermistor-tipped femoral arterial catheter (Pulsion Medical Systems, Getinge, Feldkirchen, Germany). CO measurements via TPTD were obtained from three

bolus injections of 15 ml of cold saline (< 4℃) through the venous catheter. The mean of the three measurements was used to determine CO_{TPTD} [14]. TPTD-derived CO measurements with a coefficient of variation (CV) exceeding 10% were excluded, as this threshold has been established to enhance measurement reliability. All patients were monitored in the supine position, with pressure transducer connected to the arterial and central venous catheters fixed at the mid-axillary line on the upper arm.

Electrical cardiometry

CO_{EC} was measured using an ICON haemodynamic monitor (Osypka Medical GmbH, Berlin, Germany). The mechanism of EC is based on the variation in thoracic blood conductivity with changes in blood volume and flow during each heartbeat. Cardiac contraction causes red blood cells to align in parallel within the aorta, increasing conductivity. The EC system detects these impedance changes to estimate aortic blood flow, thus enabling real-time calculation of stroke volume and CO. Four electrodes were placed in predefined positions to detect the bioimpedance signal: two at the base of the left side of the neck, and two at the inferior aspect of the thorax at the level of the xiphoid process along the left mid-axillary line [15]. The EC device employed in this study was a non-calibrated method, and the average values over a 60-s period were used for analysis.

Study design

For each patient, a series of CO measurements along with corresponding haemodynamic variables were obtained at random intervals. Each pair of CO measurements was recorded simultaneously using EC and TPTD. The EC measurements were averaged over a 60-s period, initiated immediately after each TPTD bolus. This procedure yielded three EC-CO values following three TPTD injections, with their mean calculated to represent CO_{EC} for comparison. This approach was intended to minimize any time discrepancy between the two methods. The researchers collecting CO_{EC} data were blinded to the CO_{TPTD} results and vice versa. To assess the trending ability of EC for ΔCO, subsequent sets of CO measurements were recorded.

Statistical analysis

The normality of data distribution was assessed using Q-Q plots. Normally distributed continuous variables were presented as mean ± standard deviation ($\bar{x} \pm s$), while non-normally distributed data were reported as median (interquartile range). Categorical variables were expressed as counts and percentages. The least significant change (LSC) was calculated for both TPTD and EC measurements to identify the minimum detectable change in CO that can be distinguished from random measurement error [16]. The correlation between CO_{EC} and CO_{TPTD} was evaluated using Pearson's correlation coefficient (r), with $|r| < 0.4$ indicating weak correlation, $|r|$ between 0.4 and 0.7 indicating moderate correlation, and $|r| > 0.7$ indicating strong correlation. Agreement between CO_{EC} and CO_{TPTD} was assessed using Bland–Altman plots. Bias, representing the measurement error between CO_{EC} and CO_{TPTD}, was calculated as the mean difference between the two methods. Limits of agreement (LoA) were determined as the mean bias ± 1.96 standard deviations. Percentage error (PE) was calculated as the LoA divided by the mean CO of the two methods, with a PE lower than 30% indicating clinically acceptable agreement [17]. Changes in CO_{EC} (ΔCO_{EC}) and CO_{TPTD} (ΔCO_{TPTD}) were calculated as the difference between two consecutive measurements. The ability of EC to track changes in CO_{TPTD} was evaluated using four-quadrant plots, excluding a central zone of 15%, with concordance rates > 90% indicating good tracking ability. Additionally, polar plot analysis with a radius exclusion zone of 0.625 L/min (10% of the mean CO_{TPTD} in this study) was used to assess tracking ability, with a mean polar angle < ± 5° and radial LoA < ± 30° considered indicative of good tracking [18]. Given that factors like thoracic fluid content (TFC) [19, 20] and peripheral vascular resistance [21] might influence the accuracy of CO measurements obtained via EC, an exploratory subgroup analysis was conducted. Patients were stratified based on CO (CO < 4 L/min and CO ≥ 4 L/min) and the presence or absence of vasoplegia (SVR < 800 dyn·s·cm^{-5} and SVR ≥ 800 dyn·s·cm^{-5}), as well as other factors, including thoracic fluid content (TFC ≤ 35kΩ and TFC > 35kΩ), norepinephrine equivalence (NEE ≤ 0.25 μg/kg/min and NEE > 0.25 μg/kg/min), body mass index (BMI ≥ 25 kg/m^2 and BMI < 25 kg/m^2), cumulative fluid balance(≥ 0 ml and < 0 ml), and extravascular lung water (EVLWI ≥ 10 ml/kg and EVLWI < 10 ml/kg), to identify potential factors impacting the accuracy of CO_{EC}.

All statistical analyses were performed using MedCalc software (version 20.218; MedCalc Software, Mariakerke, Belgium) and R (version 4.3.1; R Studio, version 1.0.136). A p-value < 0.05 was considered statistically significant.

Results

Patient characteristics

The study included 72 patients who underwent PiCCO haemodynamic monitoring, comprising 46 males and 26 females, with a median age of 64 years (range 55–77). The primary indication for PiCCO monitoring was shock, accounting for 87.5% of cases, with septic shock present in 62.5% of the patients (Table 1). A total

Table 1 Characteristics of the study population

Characteristic	Overall, N = 72[a]
Sex	
Female	26 (36.1%)
Male	46 (63.9%)
Age	64 [55, 77]
APACHE II	20 [14, 26]
SOFA at admission	8.00 [5.00, 11.00]
Reasons for hemodynamic monitoring	
Septic shock	46 (63.9%)
Hypovolemic shock	8 (11.1%)
Obstructive shock	2 (2.8%)
Cardiogenic shock	7 (9.7%)
Others	9 (12.5%)
ICU length of stay	6 [3, 11]
ICU mortality	17 (23.6%)

APACHE II Acute Physiology and Chronic Health Evaluation, *SOFA* Sequential Organ Failure Assessment, *ICU* Intensive Care Unit

[a] n (%); Median (IQR)

Table 2 Patients status at the time of CO measurement

Characteristic	Overall CO measurements N = 285
CO_{TPTD}, L/min	6.05 [4.86, 7.30]
CO_{EC}, L/min	5.70 [4.70, 7.00]
HR, bpm	92 [81, 101]
MAP, mmHg	80 [70, 89]
CVP, mmHg	8 [5, 11]
PaO2/FiO2	318 [254, 398]
Blood lactate, mmol/L	1.6 [1.1, 2.3]
NEE, ug/kg.min	0.06 [0.00, 0.28]
Mechanical ventilation	209 (73.3%)
Sedation	187 (65.6%)

CO_{TPTD} Cardiac output measured by transpulmonary thermodilution, *HR* Heart rate, *MAP* Mean artery pressure, *PaO_2* Arterial oxygen partial pressure, *FiO_2* Fractional inspired oxygen, *NEE* Norepinephrine equivalent dose

of 285 paired CO measurements were obtained using both EC and TPTD, with an average interval between measurements of 6.8 ± 2.9 h. The median CO_{EC} was 5.70 L/min (4.70, 7.00), and the median CO_{TPTD} was 6.05 L/min (4.86, 7.30). Detailed patient status at the time of CO measurement was summarized in Table 2. Among the total paired measurements, 168 (58.9%) were obtained while patients were receiving vasoactive drugs, and 209 (73.3%) during invasive mechanical ventilation.

Correlation and agreement between CO_{EC} and CO_{TPTD}

The LSC was determined to be 5.9% for CO_{TPTD} and 2.6% for CO_{EC}, reflecting the intrinsic measurement variability of each method. The correlation analysis of all hemodynamic variables between non-invasive EC and TPTD was presented in Fig. 1.

Pearson's correlation analysis revealed a moderate correlation between CO_{EC} and CO_{TPTD} ($r = 0.55$, $p < 0.001$, Fig. 2a). The Bland–Altman plot indicated a bias of 0.47 L/min, with LoA ranging from −2.91 to 3.85 L/min and a PE of 54.0% (Fig. 2b).

Ability of EC to track CO changes

A total of 212 paired ΔCO% measurements were analyzed. There was a significant correlation between ΔCO_{EC}% and ΔCO_{TPTD}% ($r = 0.56$, $p < 0.001$, Fig. 3a). The four-quadrant plot, excluding a central region of 15%, showed a concordance rate of 70%, indicating barely acceptable agreement for tracking CO_{TPTD} changes with EC (Fig. 3b). The polar plot, with a radius exclusion zone of 0.625 L/min (10% of the mean CO_{TPTD} in our study), indicated a mean polar angle of 2.2° and a radial LoA of 56.0°, suggesting that EC has acceptable tracking accuracy but limited tracing precision for ΔCO_{TPTD} (Fig. 3c).

*E*xploratory post-hoc analysis

An exploratory post-hoc analysis was conducted to assess potential factors influencing EC performance. In patients with high dose of vasopressors (NEE > 0.25 μg/kg/min), CO_{EC} showed compromised accuracy and reduced ability to track changes in CO_{TPTD}. Conversely, patients receiving low doses of vasopressors (NEE ≤ 0.25 μg/kg/min) exhibited significantly better EC performance, with a higher correlation between CO_{EC} and CO_{TPTD} (0.65 *vs.* 0.29, $p < 0.001$), a reduced PE (47% *vs.* 68%), and improved tracking of ΔCO (correlation: 0.67 vs. 0.07, concordance rate: 75% vs. 45%, mean polar angle: −3° vs. 17.1°, radial LoA: 44.2° vs. 69.2°) (Table 3).

Among patients with normal CO ($CO_{TPTD} \geq 4$ L/min), there was a significantly higher correlation between CO_{EC} and CO_{TPTD} (0.56 vs. 0.13, $p = 0.021$) and a reduced PE (47% vs. 100%) compared to those with low CO ($CO_{TPTD} < 4$ L/min). Furthermore, in patients with normal cardiac output (CO), the effectiveness of EC tended to be better in the subgroup with a SVR of 800 or higher compared to the subgroup with an SVR of less than 800 (0.59 vs. 0.33, $p = 0.04$) (Table 3). In contrast, in patients with low CO, EC exhibited a poor correlation, with a correlation coefficient of $r = 0.18$ for the SVR ≥ 800 group and $r = 0.16$ for the SVR < 800 group, along with a wide bias relative to the TPTD (Table 3).

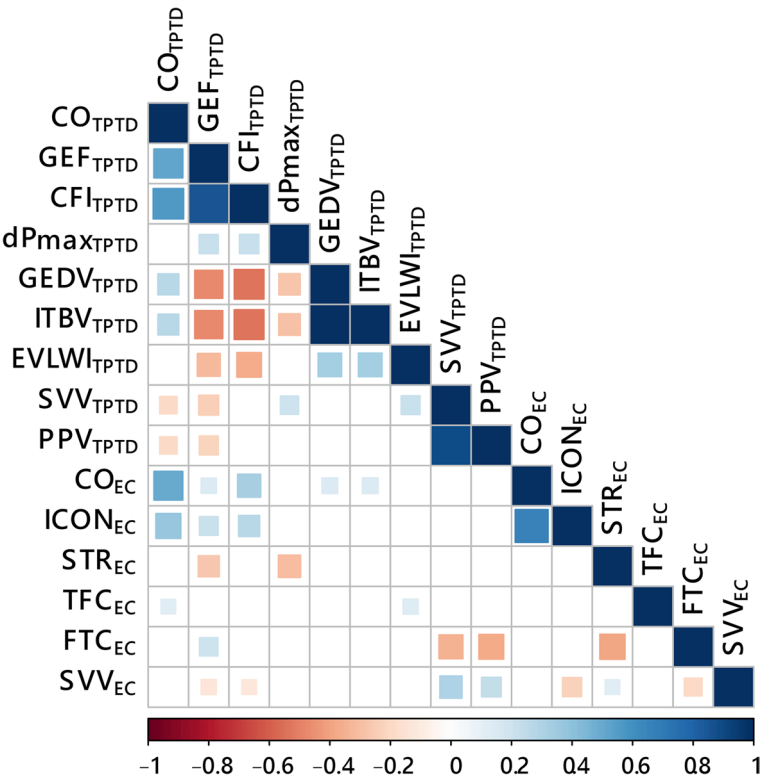

Fig. 1 Correlation between haemodynamic variables monitored by non-invasive electrical cardiometry and transpulmonary thermodilution. The blue color represents a positive correlation, while the red color signifies a negative correlation. The color saturation reflects the strength of the correlation, with deeper shades indicating stronger positive or negative associations. *CO* cardiac output, *GEF* global ejection fraction, *CFI* cardiac function index, *dPmax* maximum left ventricular contractility, *GEDV* global end-diastolic volume, *ITBV* intrathoracic blood volume, *EVLWI* extravascular lung water index, *SVV* stroke volume variation, *PPV* pulse pressure variation, *ICON* index of contractility, *STR* systolic time ratio, *TFC* thoracic fluid content, *FTC* corrected flow time

In patients with elevated TFC (TFC > 35kΩ), a strong correlation was observed between CO_{EC} and CO_{TPTD}, as well as between ΔCO_{EC}% and ΔCO_{TPTD}% (both r = 0.73), significantly outperforming the TFC ≤ 35 kΩ group (CO correlation: 0.73 vs. 0.40, $p < 0.001$; ΔCO correlation: 0.73 *vs.* 0.48, p = 0.013). The TFC > 35 kΩ group also showed a reduced PE (45% vs. 57%) (Table 3). Moreover, we observed that a high body mass index (BMI ≥ 25 kg/m^2) ($r = -0.03$), a positive cumulative fluid balance ($r = 0.49$), and an elevated extravascular lung water index (EVLWI ≥ 10 mL/kg) ($r = 0.37$) contributed to impaired EC accuracy. This was in contrast to individuals with a low BMI ($r = 0.66$, $p < 0.001$), a negative fluid balance ($r = 0.60$, $p = 0.19$), and normal EVLWI ($r = 0.60$, $p = 0.04$). These trends were reflected by reduced correlation coefficients and increased PE, as shown in Table 3.

Discussion

The present study evaluated the performance of non-invasive EC for estimating CO compared with TPTD in critically ill patients. Our findings indicated the agreement between CO_{EC} and CO_{TPTD} was limited, with a PE of 54%. Furthermore, EC displayed a restricted ability to reliably track changes in CO, with a concordance rate of 70%, reasonable tracking accuracy (mean polar angle = 2.2°), but limited precision (LoA = 56°). Nevertheless, in patients with less severe illness, EC exhibited a trend towards a better performance with a reduced PE and higher concordance rate to track ΔCO_{TPTD}. These results suggested that EC may not be interchangeable with TPTD for CO monitoring in the general ICU population.

Thoracic bioimpedance methods have been utilized clinically for many years [22], though earlier studies have highlighted concerns regarding the accuracy of traditional bioimpedance-based devices in measuring CO [23, 24]. Despite these concerns, the non-invasiveness and easy use of bioimpedance methods have driven ongoing efforts to refine their algorithms and expand their clinical utility. EC, as employed in this study, represents an advanced improvement in bioimpedance technology [9]. However, the accuracy of EC in ICU patients remains contentious. Raue et al. [25]

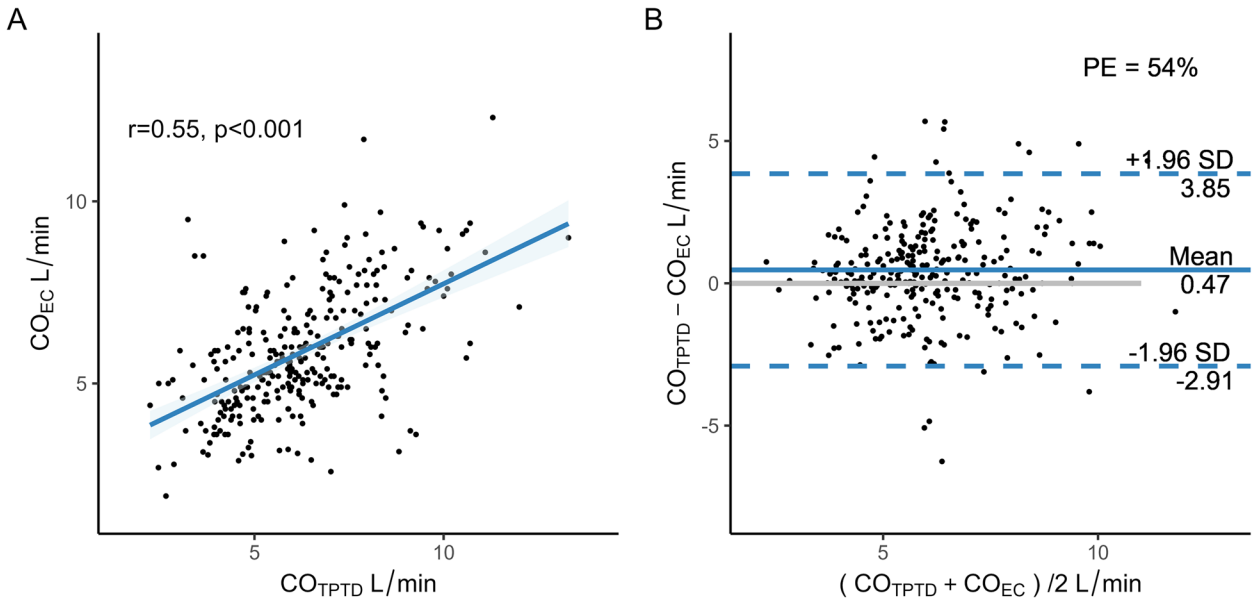

Fig. 2 Correlation and agreement analysis between CO estimated by non-invasive electrical cardiometry (CO_{EC}) and CO determined by transpulmonary thermodilution (CO_{TPTD}). **A** Correlation between CO_{TPTD} and CO_{EC} ($n = 285$, $r = 0.55$, $p < 0.001$). **B** Bland–Altman plot for CO_{TPTD} and CO_{EC}. *Solid line*: bias; *dashed line*: LOA. CO_{TPTD} cardiac output measured by transpulmonary thermodilution, CO_{EC} cardiac output estimated by electrical cardiometry

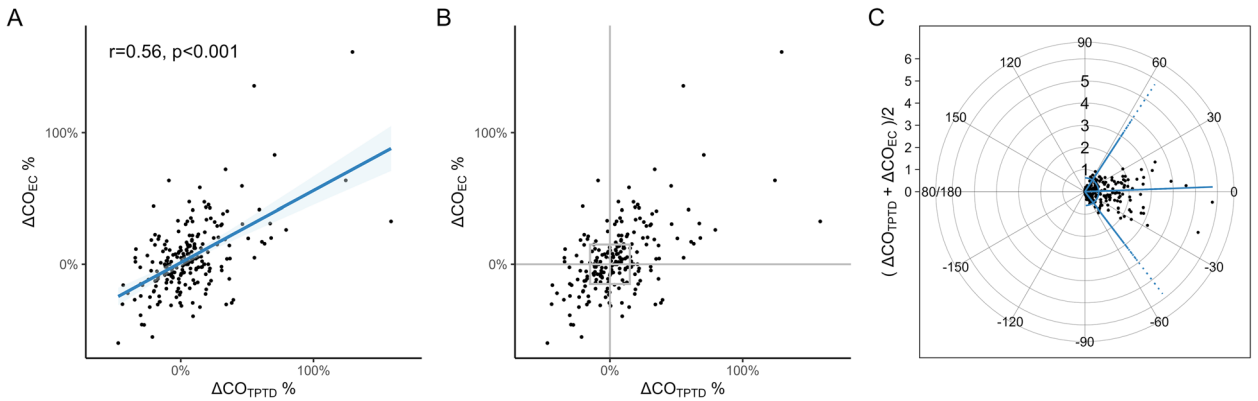

Fig. 3 Assessment of the ability of electrical cardiometry to track changes in CO. **A** Correlation between ΔCO_{EC}% and ΔCO_{TPTD}% ($n = 212$, $r = 0.56$, $p < 0.001$). **B** Four-quadrant plot comparing ΔCO_{EC}% with ΔCO_{TPTD}%, showing a concordance rate of 70%. C Polar plot illustrating ΔCO_{EC} in comparison with ΔCO_{TPTD} with a mean polar angle of 2.2° and a radial LoA of 56.0°. *Square*: A central exclusion zone of 15%. *Half circle*: A central exclusion zone of 10% (0.625 L/min). *Blue solid line*: angular bias. *Blue dashed line*: radal LOA. CO_{TPTD} cardiac output measured by transpulmonary thermodilution, CO_{EC} cardiac output estimated by Electrical Cardiometry

analyzed 30 septic shock patients and found a bias of −0.3 L/min with a PE of 54% when comparing EC with TPTD. More recently, Paranjape et al. [11] examined an animal model of hemorrhagic shock and reported a bias of 0.55 L/min and a PE of 49.4% for EC, using PAC thermodilution as the gold standard. In contrast, Zoremba et al. [26] reported a bias of 0.22 L/min and a PE of 26.4% in 25 postoperative ICU patients. Our study, which included a critically ill cohort with 87.5% in shock and 62.5% in septic shock, found a bias of 0.47 L/min and a PE of 53% for EC, aligning with the findings of Raue et al. and Paranjape et al. Moreover, our exploratory subgroup analysis indicated that the severity of illness influenced the accuracy of EC. In patients with NEE ≤ 0.25 µg/kg/min, CO_{EC} was observed a trend towards better performance with a higher correlation (0.65 vs. 0.29, $p < 0.001$) with CO_{TPTD} and a reduced PE (47% vs. 68%).

Table 3 Exploratory subgroup analysis of potential factors influencing EC accuracy and its tracking ability

Subgroup		CO_{EC} vs. CO_{TPTD}			ΔCO_{EC} (%) vs. ΔCO_{TPTD} (%)			
	Sample size	Pearson's correlation	Bland–Altman plots		Pearson's correlation	Four-quadrant plots	Polar plot	
	n	r	Bias (L/min)	Percentage error, PE (%)	*r*	Concordance rates (%)	Polar angle (°)	Radial LoA (°)
Total paired	285	0.55	0.47	53%	0.55	70%	2.2°	56.0°
CO								
< 4L/min	26	0.13	−1.3	100%	/	/	/	/
SVR < 800	4	0.16	/	/	/	/	/	/
SVR ≥ 800	21	0.18	−1.6	53%	/	/	/	/
≥ 4L/min	259	0.56	0.6	47%	0.63	72%	0.6°	52.1°
SVR < 800	50	0.33	−0.1	43%	0.13	70%	6.0°	61.7°
SVR ≥ 800	201	0.59	0.8	46%	0.67	76%	−3.7°	49.4°
TFC								
> 35 kΩ	99	0.73	0.08	45%	0.73	64%	4.1°	52.2°
≤ 35 kΩ	186	0.40	0.55	57%	0.48	69%	−2.6°	56.9°
NEE								
> 0.25 ug/kg/min	72	0.29	0.08	68%	0.07	45%	17.1°	69.2°
≤ 0.25 ug/kg/min	213	0.65	0.60	47%	0.67	75%	−0.3°	44.2°
BMI								
BMI ≥ 25 kg/m^2	39	−0.03	1.3	73%	/	/	/	/
BMI < 25 kg/m^2	246	0.66	0.3	46%	0.57	69%	−2.8°	50.3°
Fluid balance								
≥ 0 ml	131	0.49	0.6	58%	0.45	64%	−0.8°	60.6°
< 0 ml	154	0.60	0.5	49%	0.67	77%	1.8°	44.5°
EVLWI								
EVLWI < 10 ml/kg	178	0.60	0.5	47%	0.49	69%	3.3°	52.1°
EVLWI ≥ 10 ml/kg	68	0.37	0.6	65%	0.76	61%	−1.6°	52.9°
PVPI ≥ 3	8	−0.54	/	/	/	/	/	/
PVPI < 3	60	0.50	0.6	61%	0.30	58%	−3.5°	57.9°

EC Electrical cardiometry, *TPTD* Transpulmonary thermodilution, *CO* Cardiac output, *ΔCO* Changes in CO, *TFC* Thoracic fluid content, *NEE* Norepinephrine equivalents, *BMI* Body mass index, *EVLWI* Extravascular lung water index, *PVPI* Pulmonary vascular permeability index, *PE* Percentage error, *LoA* Limits of agreement

A meta-analysis by Sanders et al. [10] reported an overall bias of 0.03 L/min and a PE of 48% for EC across various clinical settings, including the operating room and ICU. Subgroup analysis suggested better performance of EC in cardiac surgery patients, with a bias of 0.01 L/min and a PE of 33.3%, which the authors attributed to lower CO and higher peripheral resistance in these patients. However, in our study, EC correlated poorly with TPTD in patients with low CO (CO < 4 L/min) ($r = 0.13$). It is important to note that our sample size for low CO patients was small, with only 26 paired CO measurements, underscoring the need for further research to validate EC accuracy in this subgroup. Additionally, factors such as TFC [19, 20], patient height and weight [27, 28], sedation status, and electrode placement [15] may affect accuracy of EC. Our exploratory subgroup analysis also indicated that in patients with TFC > 35, EC exhibited a reduced PE (45% vs. 57%). This may be attributed to TFC reflecting the patient's fluid status [29], given that previous studies suggested that low fluid levels may compromise the accuracy of bioimpedance methods [20, 30]. Furthermore, our findings suggested that high BMI, positive cumulative fluid balance, and pulmonary edema were associated with impaired accuracy of EC in CO measurement, highlighting the need for clinicians to exercise caution when using EC for CO assessment in patients with these conditions.

Few studies have assessed the ability of EC to track changes in CO, yielding inconsistent results across various patient populations. Magliocca et al. [31] reported a concordance rate of over 93% for EC in tracking CO changes during orthotopic liver transplantation. Similarly, Servaas et al. [32] found a concordance rate of 79% for EC in tracking CO changes during abdominal surgery,

along with a mean polar angle of 8.5° and radial LoA of 52°. However, these studies were conducted in operating room, where patients are generally more stable than those in ICUs. Critically ill patients in the ICU often necessitate recalibration by TPTD every 6–8 h to ensure accurate and responsive hemodynamic monitoring.

In our study of critically ill patients, EC showed a concordance rate of 70% for tracking ΔCO_{TPTD}% in the four-quadrant plot, and a mean polar angle of 2.2° with radial LoA of 56° in the polar plot. These findings suggested that EC has limited accuracy in tracking ΔCO_{TPTD}% in critically ill patients.

We acknowledge several limitations in our study. Firstly, as a single-center observational study, the sample size was limited, and the generalizability of our findings requires validation through larger, multicenter studies. Secondly, we evaluated the trending ability of EC by tracking CO changes at approximately 6-h intervals. However, our results should not be extrapolated to hemodynamic interventions, such as fluid challenges, or vasoconstrictor introduction. Further studies are warranted to assess the performance of EC specifically during these shorter, intervention-driven scenarios. Thirdly, the accuracy of CO_{EC} and its ability to track changes in CO_{TPTD} were compromised in severe shock patients, though shock severity in our cohort was milder than anticipated, potentially underpowering subgroup analysis. Future studies specifically addressing shock populations are needed to confirm these findings. Fourthly, the included patients had a median of 4 measurements (IQR: 2–5). It is important to note that these measurements were not obtained in rapid succession, with a mean interval of 6 h between assessments. The intraclass correlation coefficient (ICC = 0.24) indicates low within-subject correlation, suggesting that patients may exhibit varying hemodynamic profiles during those periods. Nevertheless, caution should be exercised when interpreting the results due to the issue of repeated measurements on the same subjects. Lastly, although TPTD was used as the reference method for CO measurement rather than the classical PAC thermodilution, it is important to recognize that the accuracy of TPTD in measuring CO has been well-established in numerous studies [33–37].

Conclusion

In critically ill patients, non-invasive EC indicated limited accuracy in measuring CO, and tracking changes in CO. Additionally, in less critically ill patients, particularly those with CO ≥ 4 L/min, TFC ≥ 35kΩ, or NEE < 0.25 μg/kg/min, EC exhibited a trend towards a better performance. Nevertheless, these findings indicate that EC may not be interchangeable with TPTD in the general ICU population. In clinical practice, it is essential to select appropriate patients and interpret EC results in the context of various clinical scenarios.

Abbreviations

AUROC	Area under the receiver operating characteristic curve
BMI	Body mass index
CO	Cardiac output
CVP	Central venous pressure
CV	Coefficient of variation
EC	Electrical cardiometry
EVLWI	Extravascular lung water index
ECMO	Extracorporeal membrane oxygenation
HR	Heart rate
IABP	Intra-aortic balloon pump
LoA	Limit of agreement
LSC	Least significant change
MAP	Mean arterial pressure
MV	Mechanical ventilation
NEE	Norepinephrine equivalents
PAC	Pulmonary artery catheter
PE	Percentage error
SOFA	Sequential organ failure assessment
TPTD	Transpulmonary thermodilution
TFC	Thoracic fluid content

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None

Authors' contributions

XS and XG had the idea of the study and conceptualized the research aims; XS and WS designed the study and take responsibility for the integrity of the data and the accuracy of the data analysis. WS and JG implemented the study and collected the data; WS, JG and DC did the statistical analysis and wrote the first version of the paper; JJ, TY and XM contributed substantially to the acquisition of data. XS, JW and XG revised the first draft. All the authors approved the final manuscript.

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Data availability

The datasets used in the present study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of the First Affiliated Hospital of Sun Yat-sen University (protocol number: 2019–172). The study was registered in China Clinical Trial Registry (ChiCTR2100045861, registered 2021–4-25, https://www.chictr.org.cn/showproj.html?proj=125013). Informed consent was obtained from each patient or from the patient's legally authorized representative if the patient was unable to provide consent. Alternatively, deferred informed consent was obtained from patients. The current study was performed in accordance with Chinese law and the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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