Journal of Cardiothoracic and Vascular Anesthesia 000 (2026) 1−10

Contents lists available at ScienceDirect

Journal of Cardiothoracic and Vascular Anesthesia

journal homepage: www.jcvaonline.com

Original Article

Comparative Study of Hemodynamic Indices of Fluid Responsiveness by Electrical Cardiometry and Thermodilution Methods After Passive Leg Raise Test in Patients After Coronary Artery Bypass Graft Surgery

Ravina Mukati, MD, DrNB[*], Ajmer Singh, MD[*,1], Prajeesh M. Nambiar, MD, DNB[*], Bhanu Prakash Zawar, MD[*], Yatin Mehta, MD, MNAMS, FRCA[*], Naresh Trehan, MD[†]

[*]*Department of Cardiac Anesthesia, Institute of Critical Care and Anesthesiology, Medanta-The Medicity, Gurugram, Haryana, India*

[†]*Department of Cardiac Surgery, Institute of Critical Care and Anesthesiology, Medanta-The Medicity, Gurugram, Haryana, India*

Objectives: Assessing fluid responsiveness using the passive leg raise test is crucial for optimizing cardiac preload and maintaining cardiac output. Patients recovering from coronary artery bypass graft surgery (CABG) are at risk of hemodynamic instability. Electrical Cardiometry has been compared with the pulmonary artery thermodilution method for measuring cardiac output and other hemodynamic parameters in various clinical settings. This study was designed to compare the accuracy of Electrical Cardiometry with the thermodilution method in measuring hemodynamic changes in patients after off-pump CABG surgery. Additionally, the effect of the passive leg raise test on fluid responsiveness was assessed.

Design: Prospective, observational, comparative study.

Setting: Tertiary care cardiac center.

Participants: Thirty patients who underwent off-pump CABG surgery were evaluated in the cardiac surgical intensive care unit.

Interventions: Simultaneous measurements of cardiac output and other hemodynamic indices were taken using both pulmonary artery thermodilution and Electrical Cardiometry methods at three predefined time points.

Measurements and Main Results: Moderate correlations (r = 0.413 and 0.523) were found between the two methods, both before and after the passive leg raise test. Bland-Altman analysis revealed a bias of 1.68 L/min, a precision of 0.533 L/min, and wide limits of agreement (−2.55 to −0.8 L/min). The percentage errors between the methods were 38.62% and 34.24% before and after the passive leg raise test, respectively. The passive leg raise did not significantly predict fluid responsiveness in either intubated or extubated patients. Moreover, Electrical Cardiometry consistently reported higher values.

Conclusions: The agreement between thermodilution-derived parameters and Electrical Cardiometry-derived hemodynamic indices was clinically unacceptable; therefore, these two techniques cannot be used interchangeably in cardiac surgical patients.

Keywords: Pulmonary artery thermodilution; Electrical Cardiometry; passive leg raise test; coronary artery bypass graft surgery

AN OFF-PUMP coronary artery bypass graft (CABG) surgery can induce hemodynamic instability due to heart manipulation, myocardial ischemia, and blood loss. Hemodynamic instability in the form of low cardiac output (CO) can also

[1]*Address correspondence to:* Ajmer Singh, MD, Senior Director, Department of Cardiac Anesthesia, Institute of Critical Care and Anesthesiology, Medanta-The Medicity, Sector-38, Gurugram, 122001, India; Tel.: + 91 9818797549.

E-mail address: ajmersingh@yahoo.com (A. Singh).

https://doi.org/10.1053/j.jvca.2026.01.006

manifest in the postoperative period. Therefore, it becomes essential to assess CO and other hemodynamic parameters in the immediate postoperative period after off-pump CABG surgery. The management of fluid therapy becomes more complex after CABG surgery due to underlying cardiac disease, cardiopulmonary dysfunction, prolonged durations of anesthesia and surgery, surgical stress, and tissue trauma.[1] The concept of fluid responsiveness has relevance because fluid loading is the first step in the resuscitation of hemodynamically unstable patients.[2] A reversible endogenous fluid challenge, performed by passive leg raise (PLR), is a simple, safer, and widely applied method to augment stroke volume and thereby CO. The PLR test is a bedside assessment to determine fluid responsiveness and involves raising a patient's lower limbs to induce a gravitational transfer of approximately 150 to 300 mL of venous blood from the lower extremities into central circulation. If a patient is fluid-responsive, there will be increases in right ventricular preload, stroke volume, and thereby CO. On the contrary, these changes will not be significant if the patient is fluid nonresponsive.

The thermodilution-derived CO (TD-CO) method using a pulmonary artery catheter (PAC) has often been questioned for risk−benefit ratio, cost-effectiveness, invasiveness, inability to provide continuous beat-to-beat measurements, and the effect on outcome consequent to its use.[3] This has led to an increased interest in noninvasive methods to measure CO. Measurement of CO by noninvasive thoracic electrical bioimpedance (TEB) method is based on the principle that cyclical increases in blood volume in the great vessels, as well as alignment of red blood cells in the thoracic aorta resulting from increased velocity, cause concomitant decreases in the electrical impedance in the chest. TEB technology has shown satisfactory-to-poor agreement with TD-CO in previous reports.[4,5] A meta-analysis conducted by Raaijmakers et al. concerning the validation of TEB technology in animals, healthy human subjects, and patients with different clinical conditions demonstrated an overall correlation coefficient of 0.67 between CO measured by TEB and that measured by other methods.[6]

Subsequently, Electrical Cardiometry (EC) was developed as an advancement of the bioimpedance method, using a novel model that interprets the bioimpedance signal. EC-derived CO (EC-CO) is a new, noninvasive method for measuring hemodynamic indices. EC attributes changes in impedance following the opening of the 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.[4] EC interprets the sharp decrease in impedance (or increase in conductivity) due to the pulsatile flow in the aorta.[7]

The current authors hypothesized that a new-generation EC-CO hemodynamic monitor would show clinically acceptable precision and agreement with TD-CO in post-cardiac surgical patients. Hemodynamic indices of fluid responsiveness before and after PLR testing were also compared using the TD and EC techniques for CO measurement.

Methods

Study Design

This prospective observational study was designed to compare hemodynamic indices of fluid responsiveness to the PLR test using TD-CO and EC-CO methods. Patients with significant coronary artery disease undergoing elective off-pump CABG surgery, in whom hemodynamic monitoring with a PAC was planned, were included. The study was conducted in the cardiac surgical intensive care unit (ICU) of a tertiary care cardiac center. Thirty patients admitted to the ICU after CABG surgery performed between August 2022 and January 2024 were included. Approval from the institutional review board and ethics committee was obtained before initiating the study. The study was registered with the Clinical Trial Registry of India (CTRI/2022/11/047766).

Preanesthetic evaluation included measurement of vital signs and review of chest radiograph, electrocardiogram, and echocardiogram to rule out valvular or congenital heart defects, impaired left ventricular function, or arrhythmias. Written informed consent was obtained from all participants. All participants were monitored with standard cardiac monitors, including a TD PAC (Edwards Lifesciences, Irvine, CA, USA), and transesophageal echocardiography (TEE) whenever indicated. Exclusion criteria included emergency surgery, hemodynamic instability (heart rate >120 beats/min, systolic blood pressure <90 mmHg, and/or mean arterial pressure <60 mmHg), severe left ventricular dysfunction (ejection fraction <35%), re-exploration, intra-aortic balloon pump support, presence of congestive heart failure, valvular heart disease, intracardiac shunts, chronic obstructive pulmonary disease, obesity (body mass index >30 kg/m^2), deep vein thrombosis, and hip and /knee joint arthritis restricting performance of the PLR test. In the ICU, all patients were mechanically ventilated using pressure-regulated volume control mode (Datex-Ohmeda, Inc., Madison, WI, USA) with a square wave constant inspiratory flow, a tidal volume of 6 to 8 mL/kg, a respiratory rate of 14/min, an inspiratory:expiratory ratio of 1:2, and a positive end-expiratory pressure of 4 cm of water. A balanced salt solution was used for maintenance fluid therapy at a rate of 1 mL/kg/h. Hemodynamic management, use of vasopressors, control of bleeding, weaning from mechanical ventilation, and the decision on tracheal extubation were at the discretion of the intensivist.

Interventions

The study interventions were started 15 minutes after arrival in the ICU, once a hemodynamically steady state condition was achieved (absence of bradycardia and/or tachycardia, systolic blood pressure >90 mmHg, and core temperature ≥36° C). Based on results from previous studies, fluid responsiveness was defined as a 15% increase in stroke volume and/or a ≥10% increase in CO from baseline.[8-11] The investigator obtaining the TD-CO measurements was blinded to the EC-CO results and vice versa. TD-CO was measured by injecting

10 mL of cold saline into the PAC's proximal injectate port. The average of three readings per measurement was used for all hemodynamic recordings. For EC-derived parameters, four electrodes were placed on the neck and thorax as recommended by the manufacturer. An ICON (Osypka Medical, Inc., Cardiotronic, La Jolla, CA, USA) monitoring system, a simple, portable device, was used to simultaneously measure CO and other hemodynamic indices. The ICON monitor incorporates an algorithm that transforms the ohmic equivalent of mean aortic blood flow acceleration into mean aortic blood flow velocity. The device emits a high-frequency (50 kHz) and low-voltage (2 mA) alternating electrical current of constant amplitude via a pair of surface electrodes across the left side of the thorax. The voltage drop is sensed by a second pair of electrodes located inside the current electrodes.

Hemodynamic parameters were recorded at three predefined time points: (1) T_1: 15 minutes after arrival in the ICU; (2) T_2: after 4 hours, while on ventilator; and (3) T_3: 15 minutes after tracheal extubation. At each time point, the parameters were noted twice, once with the patient in the semirecumbent position with the trunk at 45°, and once 5 minutes after the trunk was lowered to achieve a horizontal position and the lower extremities raised to 45° (PLR test) using automated adjustment of the ICU bed. During the PLR test, the crepe bandage wrapped around the lower limbs during surgery was released.

Sample Size Calculation

The parameter of interest for sample size calculation was Pearson's correlation coefficient (r). For the clinical significance of the two methods of CO measurement, a correlation coefficient of more than 0.7 was considered a strong positive correlation, whereas an r between 0.4 and 0.7 indicated moderate correlation, and an r of less than 0.4 was considered a weak correlation. The assumptions in the calculation of sample size were as follows: (1) $r = 0.7$, (2) confidence level = 99% (2.576 corresponding to a 99% confidence level), and (3) power of study = 90% (1.282 corresponding to 90% power). With these assumptions, the calculated sample size (n) was 53. In the study, a minimum of two paired observations was proposed for each patient. Given this, a sample size of 30 patients (ie, 60 paired observations) was considered adequate for the study.

Measurements

Real-time, simultaneous measurements of the following parameters were done: heart rate, systolic blood pressure, CO, cardiac index, stroke volume, and systemic vascular resistance. Hemodynamic parameters were recorded at three predefined time points in two patient positions (semirecumbent and PLR) and with both CO measurement methods. Vasoactive infusion rates and ventilatory settings remained unchanged for at least 10 minutes before and during the measurement. Rapid fluid boluses were avoided during the measurement period.

Statistical Analysis

The analysis included patient profiling across different demographic and clinical parameters. All descriptive values are presented as mean and standard deviation (SD), and categorical data are expressed as absolute numbers and percentages. Pearson's correlation coefficient (r) was determined for paired CO values. Mean CO with SD, bias (mean difference between the CO from the paired values), and precision (±2 SD of the average of biases) were compared for each pair as recommended by Bland and Altman.[12] The percentage error (ratio of precision to mean CO of the two methods) to determine acceptable limits of agreement between the techniques of CO measurement was calculated using the formula given by Critchley and Critchley.[13] In addition to presenting the global Bland-Altman plot, individual Bland-Altman analyses were also plotted at three predefined time points. To measure the trending ability of EC for CO and stroke volume, four-quadrant concordance plots were created with an exclusion zone. For CO values, a predefined exclusion zone of ±0.5 L/min was used to eliminate clinically insignificant variations. For stroke volume, a predefined exclusion zone of ±10% of the baseline stroke volume was applied. A p-value of less than 0.05 was considered statistically significant. All analyses were done using SPSS software, Version 24.0 (Chicago, IL, USA).

Results

Thirty-two patients admitted to the cardiac surgical ICU after undergoing off-pump CABG surgery were enrolled in the study. Two patients who required re-exploration for mediastinal bleeding were excluded from the study, and data from 30 patients were used for the final analysis. The demographic characteristics of the patients are shown in Table 1. The mean age was 62 ± 7.8 years, with a male preponderance. The mean left ventricular ejection fraction was 45% ± 8.6% with an equal distribution of mild and moderate left ventricular dysfunction. Twelve patients required noradrenaline infusion (0.05-0.1 μg/kg/min) during the study period.

Intragroup comparisons of fluid responsiveness data before and after the PLR test are shown in Table 2. None of the

Table 1
Demographic Data

Variable	Mean ± SD	Range
Number of patients (n)	30	–
Age (y)	62 ± 7.8	41-77
Sex (male:female)	21:9	–
Height (cm)	163 ± 8.7	148-182
Weight (kg)	69 ± 12.5	51-97
Body surface area (m^2)	1.75 ± 8.6	1.48-2.03
Body mass index (kg/m^2)	23 ± 3.9	21.4 ± 28.6
LVEF (%)	45 ± 8.6	35-55
LVEF 35%-45%	14	–
LVEF 46%-55%	16	–

Abbreviations: LVEF, left ventricular ejection fraction; SD, standard deviation.

Table 2
Fluid-responsiveness After Passive Leg Raise Test

Clinical Parameter	Baseline/After PLR	Mean ± SD		TD method		EC method	
		TD	EC	Percentage Change	p-Value	Percentage Change	p-Value
Heart rate (beats/m)	Baseline	67.5 ± 14.1	59.4 ± 7.5	−2.2	0.073	−1.7	0.287
	After PLR T_1	66.1±13.5	58.3±7.8	−2.9	0.029	−2.1	0.185
	T_2	65.5±13.5	57.9±7.9	−0.7	0.245	−0.6	0.452
	T_3	72.5 ± 15.6	73.6 ± 11.2	4.5	0.664	5.7	0.775
Systolic blood pressure (mmHg)	Baseline	112.8±18.8	109.9±16.5	3.5	0.176	8.7	0.129
	After PLR T_1	116.4±18.9	128.7±17.8	2.0	0.459	5.6	0.203
	T_2	114.7±19.1	124.4±11.7	−1.8	0.325	−3.5	0.195
	T_3	118.6 ± 21.2	129.2 ± 22.1	3.7	0.564	4.1	0.701
Stroke volume (ml/beat)	Baseline	47.8 ± 12.8	64.7 ± 21.8	3.6	0.616	3.9	0.713
	After PLR T_1	51.1 ± 13.3	68.6 ± 20.5	3.9	0.605	4.2	0.729
	T_2	58.6 ± 16.0	76.0 ± 20.9	3.6	0.285	3.0	0.278
	T_3	54.7 ± 9.5	62.7 ± 18.5	−2.2	0.330	−2.1	0.342
Cardiac OUTPUT (L/m)	Baseline	4.4 ± 1.2	6.0 ± 2.1	3.8	0.415	3.7	0.478
	After PLR T_1	4.8 ± 1.2	6.4 ± 2.1	3.5	0.485	2.9	0.678
	T_2	5.2 ± 1.4	6.9 ± 1.8	3.9	0.239	3.7	0.286
	T_3	5.2 ± 1.1	6.2 ± 2.0	−1.1	0.063	−2.5	0.254

NOTE. Intragroup, paired comparison of clinical parameters between thermodilution and Electrical Cardiometry methods.
Abbreviations: EC, Electrical Cardiometry; PLR, passive leg raise test; SD, standard deviation; T1, at 15 minutes; T2, at 4 hours; T_3, after extubation; TD, thermodilution.

patients at any time point showed a significant change in heart rate, systolic blood pressure, stroke volume, or CO following the PLR test compared with baseline. The percentage change was less than 10% for all measured parameters at all time points (baseline, T_1, T_3), and the p-values were greater than 0.05. The EC-derived values for systolic blood pressure, stroke volume, and CO were consistently higher than the TD-derived values.

Bland-Altman analysis of the CO data, before and after performing the PLR test, is shown in Table 3A and Figs 1 and 2. The EC-derived hemodynamic data overestimated CO measurement values, showed large percentage errors (38.62% and 34.24%), significant bias (−1.68 L/m and −1.63 L/m), wider limits of agreement (−2.55 to −0.8), and moderate correlations (r = 0.413 and 0.523) compared with TD-derived values both before and after the PLR test. Figures 1 and 2 (Bland-Altman plots) represented wide scattering of CO data, in both the semirecumbent and PLR positions, indicating a lack of agreement between the two methods of measurement of CO. Individual Bland-Altman analysis data for CO and stroke volume also showed poor-to-moderate correlations, significant bias, and wide limits of agreement at all time points (Table 3B). The percentage errors were above the clinically acceptable threshold of 30% (72.3%, 66.2%, and 61.2%, respectively) for CO, indicating poor agreement despite moderate correlations. The percentage errors for stroke volume were also more than 50% at all time points. Bland-Altman plots are depicted in Figs 3-5 for CO, and in Figs 6-8 for stroke volume.

Table 4 presents intergroup comparisons of mean values for CO, cardiac index, stroke volume, and systemic vascular resistance before and after the PLR test at three predefined time points. The mean difference with standard error, 95% confidence interval of difference, p-value, and correlation (r) at 15 minutes, 4 hours, and after extubation are shown. The EC-derived values for CO, cardiac index, and stroke volume were significantly higher ($p < 0.05$) than those derived from the TD method. Systemic vascular resistance values measured with the EC method were lower compared with the TD method. The large mean differences in hemodynamic indices were also evident in their wider 95% confidence interval differences, p-values less than 0.05, and poor correlation (r = 0.260 to 0.609) at all time points, indicating a large difference between the two methods of measurement.

Trending analyses of both CO and stroke volume were performed using four-quadrant concordance plots to compare values measured by TD and EC technologies (Figs 9 and 10). The concordance rates were 68.2% for CO and 76.1% for stroke volume, indicating suboptimal agreement in the direction of changes in CO and stroke volume.

Discussion

With advances in technology, there is a strong urge to develop minimally invasive or noninvasive methods for measuring CO and other hemodynamic indices. The ideal technology for measuring CO is cost-effective, reproducible, and reliable across various physiological states, and it provides a fast response time. Therefore, the current authors conducted a comparative study of CO measurement using the TD and EC methods in patients after off-pump CABG surgery and determined the accuracy and precision of the newer method of CO monitoring—the EC technique by the ICON monitoring system. Hemodynamic indices of fluid responsiveness were also evaluated by both technologies before and after performing the PLR test. The key findings of this study are that the PLR test failed to predict fluid responsiveness in post-CABG patients and that the EC method consistently overestimated

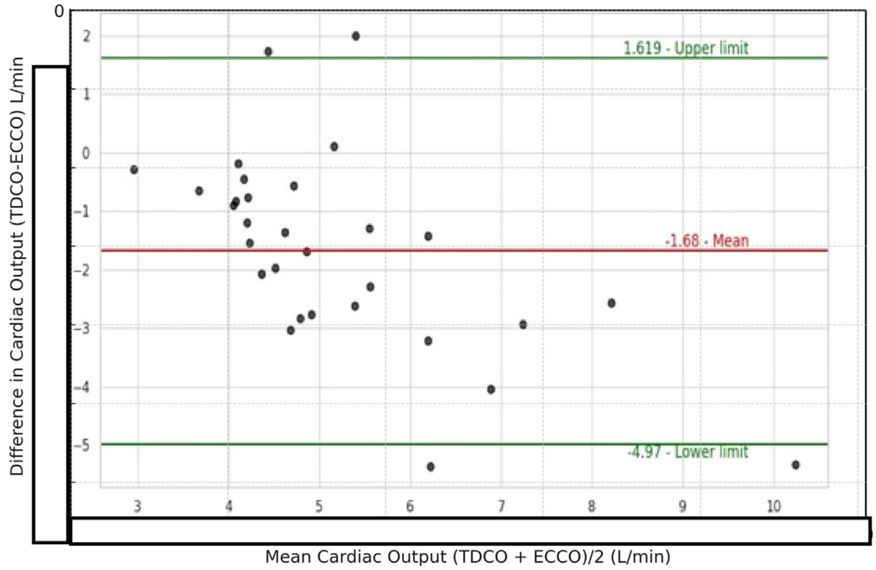

Fig 1. Bland-Altman plot of cardiac output measurements in semirecumbent position. The X-axis shows mean cardiac output (TDCO + ECCO)/2 (L/m) for each data pair. The Y-axis shows the difference in cardiac output (TDCO-ECCO) in L/m. ECCO, Electrical Cardiometry-derived cardiac output; TDCO, thermodilution-derived cardiac output.

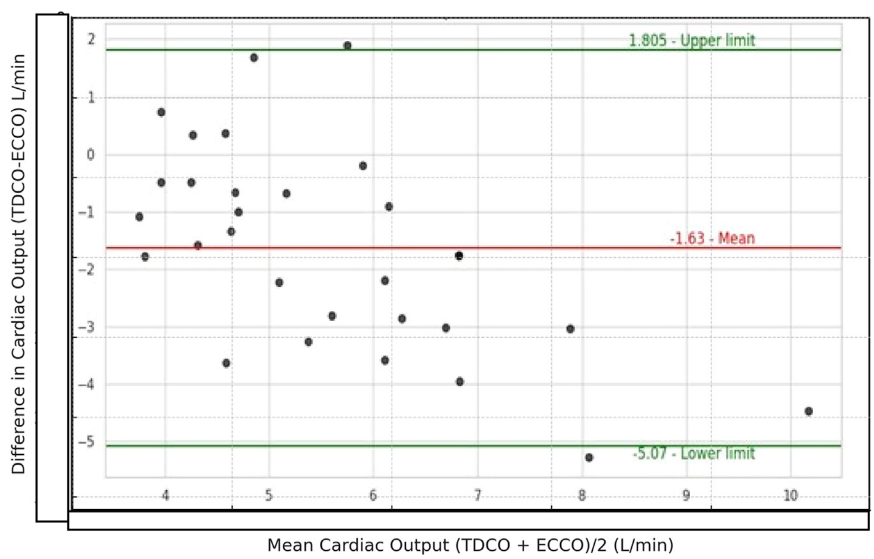

Fig 2. Bland-Altman plot of cardiac output measurements after the passive leg raise test. The X-axis shows mean cardiac output (TDCO + ECCO)/2 (L/m) for each data pair. The Y-axis shows the difference in cardiac output (TDCO-ECCO) in L/m. ECCO, Electrical Cardiometry-derived cardiac output; TDCO, thermodilution-derived cardiac output.

CO, cardiac index, and stroke volume, likely due to differences in algorithms for interpreting thoracic bioimpedance. The weak-to-moderate correlation aligns with prior studies questioning EC's accuracy in cardiac surgical patients.[14,15]

Failure to predict fluid responsiveness may have been due to preload and CO optimization through intensive perioperative monitoring, including PAC and TEE. Optimization of preload, stroke volume, and therefore CO by these two modalities has been shown to reduce perioperative morbidity and hospital length of stay in both cardiac and noncardiac surgery patients.[1] In the postoperative period after cardiac surgery, fluid therapy becomes more complex due to the presence of underlying cardiac disease, cardiopulmonary dysfunction, other organ dysfunctions, surgical stress, prolonged durations of anesthesia and surgery, and tissue trauma. Venoconstriction caused by sternotomy pain can also adversely affect the utility of PLR in cardiac surgical patients. In anesthetized canines, greater agreement between the two methods and better EC performance were observed during hemorrhage, indicating its ability to detect sudden hemodynamic changes induced by hypovolemia.[16] In a recent trial, Sharma et al. reported poor agreement between EC and echocardiography for the assessment of fluid responsiveness in adult patients with acute circulatory failure.[17] The diagnostic value of an increase in stroke volume after fluid challenge for the prediction of fluid responsiveness in the preoperative period of CABG was reported by Zou et al.[8] None of the current patients were hemodynamically unstable or hypovolemic at the time of study. This avoided the most

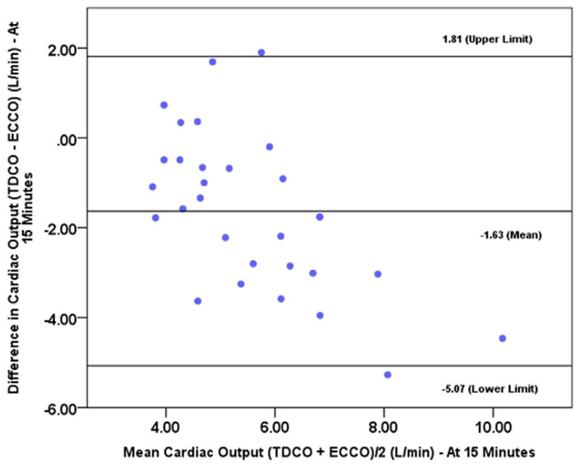

Fig 3. Bland-Altman plot comparing cardiac output (CO) measured by thermodilution (TD) and Electrical Cardiometry (EC) at 15 minutes. The X-axis shows the mean CO. The Y-axis shows the difference in CO.

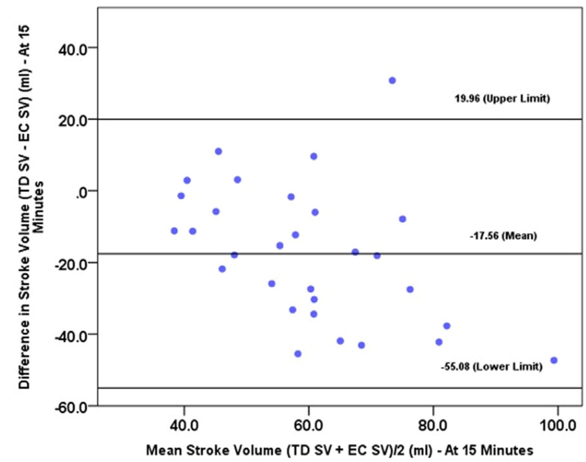

Fig 6. Bland-Altman plot comparing stroke volume (SV) measured by thermodilution (TD) and Electrical Cardiometry (EC) technology at 15 minutes. The X-axis shows the mean SV, and the Y-axis shows the difference in SV.

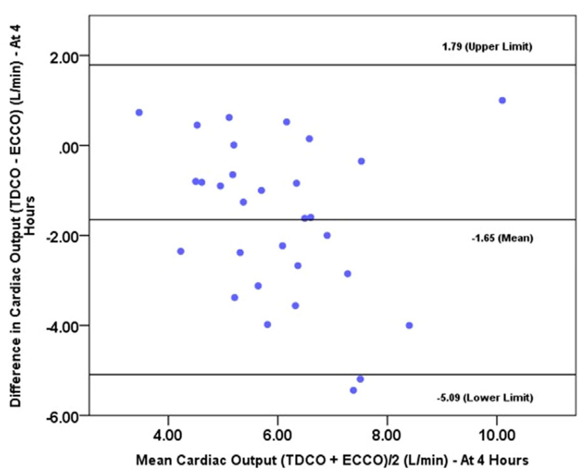

Fig 4. Bland-Altman plot comparing cardiac output (CO) measured by thermodilution (TD) and Electrical Cardiometry (EC) at 4 hours. The X-axis shows the mean CO. The Y-axis shows the difference in CO.

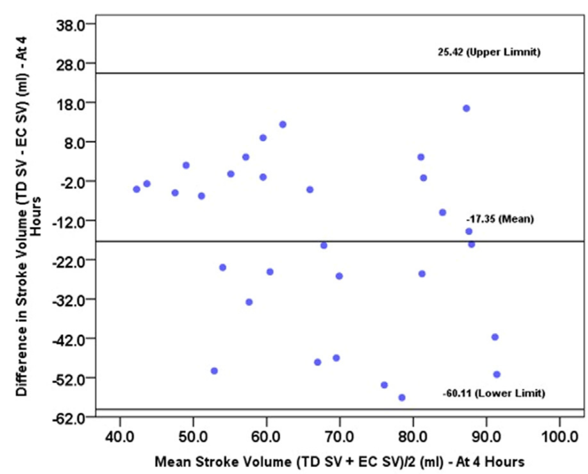

Fig 7. Bland−Altman plot comparing stroke volume (SV) measured by thermodilution (TD) and Electrical Cardiometry (EC) technology at 4 hours. The X-axis shows the mean SV, and the Y-axis shows the difference in SV.

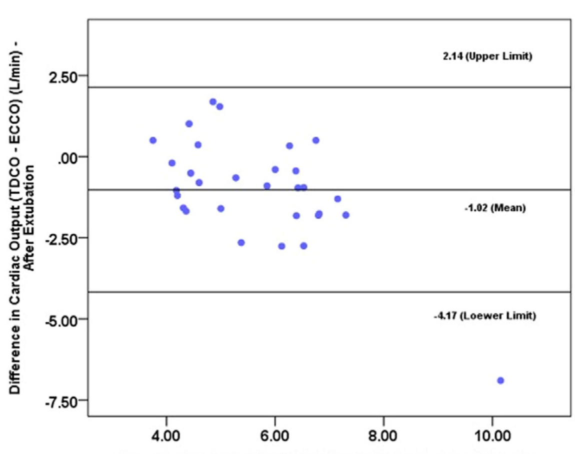

Fig 5. Bland-Altman plot comparing cardiac output (CO) measured by thermodilution (TD) and Electrical Cardiometry (EC) after extubation. The X-axis shows the mean CO. The Y-axis shows the difference in CO.

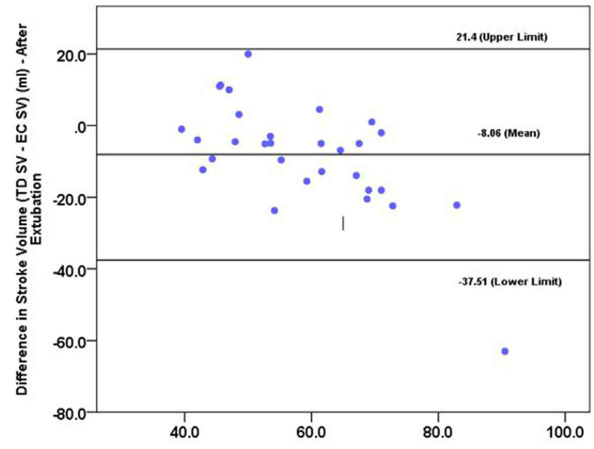

Fig 8. Bland-Altman plot comparing stroke volume (SV) measured by thermodilution (TD) and Electrical Cardiometry (EC) technology after extubation. The X-axis shows the mean SV, and the Y-axis shows the difference in SV.

Table 3A
Comparison of TD-CO and EC-CO Before and After PLR Test

Patient Position	TD-CO (L/m) Mean ± SD	EC-CO (L/m) Mean ± SD	Percentage Error (%)	Bias (L/m)	Precision (L/m)	Limits of Agreement Lower to Upper	Pearson's Correlation Coefficient (*r*)
Before PLR	4.35 ± 1.16	6.03 ± 2.10	38.62	−1.68	0.533	−2.55 to −0.8	0.413
After PLR	4.76 ± 1.16	6.39 ± 2.11	34.24	−1.63	0.487	−2.51 to −0.75	0.523

NOTE. Percentage error, bias, precision, LOA, and correlation.
Abbreviations: EC-CO: Electrical Cardiometry cardiac output; LOA, limits of agreement; PLR, passive leg raise test; SD, standard deviation; TD-CO, thermodilution-derived cardiac output.

common confounding factor, hypovolemia, in the study. However, central venous pressure, pulmonary artery wedge pres-

Table 3B
Agreement Analysis Between Thermodilution and Electrical Cardiometry for Cardiac Output and Stroke Volume at Three Time Points

Time Point→	At 15 min	At 4 h	After Extubation
Cardiac output (L/min)			
Correlation coefficient (*r*)	0.559	0.423	0.577
Bias (L/min)	−1.63	−1.65	−1.02
Limits of agreement	−5.07 to 1.81	−5.09 to 1.79	−4.17 to 2.14
Precision (L/min)	1.75	1.76	1.61
Percentage error (%)	72.3%	66.2%	61.2%
Stroke volume (mL/beat)			
Correlation coefficient (*r*)	0.424	0.322	0.589
Bias (mL/beat)	−17.56	−17.35	−8.06
Limits of agreement	−55.08 to 19.96	−60.11 to 25.42	−37.51 to 21.4
Precision (mL/beat)	19.14	21.82	15.03
Percentage error (%)	73.4%	72.9%	53.9%

Table 4
Intergroup Comparison of Mean Values of Hemodynamic Parameters at Different Time Points

Hemodynamic Parameter		TD (n = 30) Mean ± SD	EC (n=30) Mean ± SD	Mean Difference ± SE	95% CI of Difference		p-Value	Correlation Coefficient (r)
					Lower	Upper		
				After 15 min				
CO	Before PLR	4.4 ± 1.2	6.0 ± 2.1	−1.7 ± 0.4	−2.6	0.8	<0.001	0.601
	After PLR	4.8 ± 1.2	6.4 ± 2.1	−1.6 ± 0.4	−2.5	0.8	0.001	0.413
CI	Before PLR	2.5 ± 0.8	3.4 ± 1.3	−0.9 ± 0.3	−1.5	0.4	0.003	0.609
	After PLR	2.7 ± 0.8	3.7 ± 1.2	−0.9 ± 0.3	−1.5	0.4	0.002	0.408
SV	Before PLR	47.8 ± 12.8	64.7 ± 21.8	−16.9 ± 4.6	−26.2	−7.7	0.002	0.567
	After PLR	51.1 ± 13.3	68.6 ± 20.5	−17.6 ± 4.5	−26.5	−8.6	0.001	0.394
SVR	Before PLR	1448.7 ± 365.6	1107.2 ± 363	341.5 ± 94.1	153.2	−529.8	0.001	0.446
	After PLR	1393 ± 408.9	1066.5 ± 350.1	326.5 ± 98.3	129.7	−523.2	0.002	0.285
				After 4 h				
CO	Before PLR	4.6 ± 1.1	6.2 ± 2.0	−1.6 ± 0.4	−2.4	−0.7	<0.001	0.559
	After PLR	5.2 ± 1.4	6.9 ± 1.8	−1.7 ± 0.4	−2.5	−0.8	0.001	0.423
CI	Before PLR	2.6 ± 0.6	3.5 ± 1.2	−0.9 ± 0.2	−1.4	−0.4	<0.001	0.557
	After PLR	3.0 ± 0.8	3.9 ± 1.0	−0.9 ± 0.2	−1.4	−0.4	0.002	0.383
SV	Before PLR	53.2 ± 12.6	68.5 ± 20.8	−15.2 ± 4.4	−24.1	−6.4	0.002	0.424
	After PLR	58.6 ± 16	76.0 ± 20.9	−17.3 ± 4.8	−27.0	−7.7	0.021	0.322
SVR	Before PLR	1389.3 ± 502.4	1114.2 ± 422.2	275.1 ± 119.8	35.3	515	0.025	0.583
	After PLR	1257.9 ± 415.2	947.1 ± 296.2	310.8 ± 93.1	124.2	497.2	0.015	0.260
				After extubation				
CO	Before PLR	4.6 ± 1.0	5.4 ± 1.8	−0.8 ± 0.4	−1.6	−0.1	0.033	0.552
	After PLR	5.2 ± 1.1	6.2 ± 2.0	−1.0 ± 0.4	−1.8	−0.2	0.025	0.577
CI	Before PLR	2.7 ± 0.6	3.2 ± 1.0	−0.5 ± 0.2	−0.9	−0.1	0.019	0.553
	After PLR	3.0 ± 0.6	3.6 ± 1.1	−0.6 ± 0.2	−1.0	−0.1	0.009	0.446
SV	Before PLR	48.5 ± 9.8	56.7 ± 17.4	−8.2 ± 3.6	−15.5	−0.9	0.029	0.537
	After PLR	54.7 ± 9.5	62.7 ± 18.5	−8.1 ± 3.8	−15.7	−0.5	0.038	0.589
SVR	Before PLR	1351.3 ± 390	1229.6 ± 463.4	121.7 ± 110.6	−99.6	343.1	0.018	0.398
	After PLR	1163.9 ± 316.8	1058.6 ± 349.9	105.3 ± 86.2	−67.2	277.8	0.031	0.455

Note. Thermodilution versus Electrical Cardiometry method.
Abbreviations: CI, confidence interval; CO, cardiac output; EC, Electrical Cardiometry; PLR, passive leg raise test; SD, standard deviation; SE, standard error; SV, stroke volume; SVR, systemic vascular resistance; TD, thermodilution.

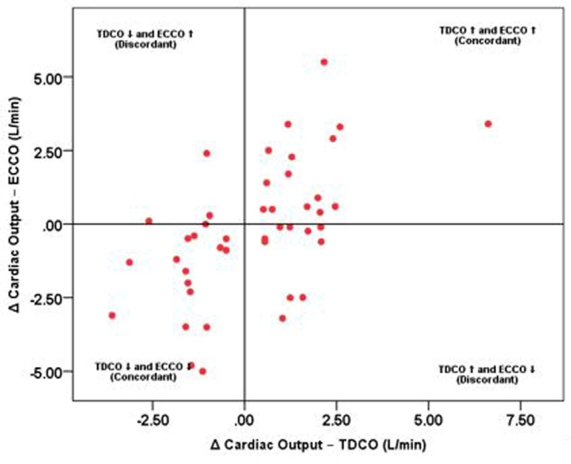

Fig 9. Four-quadrant concordance plot of cardiac output (CO) showing directional agreement between thermodilution (TD) and Electrical Cardiometry (EC) technology. Δ CO, delta CO.

sure, and dynamic indices of fluid responsiveness (stroke volume variation and pulse pressure variation) were not part of the current study protocol. Perioperative use of afterload-reducing agents, antihypertensive agents, and diuretics can affect fluid responsiveness after PLR, which could be studied in future trials. Based on the currently available evidence, fluid responsiveness after PLR is predominantly limited to the ICU setting, where many comorbid conditions, such as sepsis, acute kidney injury, cardiac dysfunction, and inotropic therapy, can confound fluid dynamics.[2]

Many published studies have shown poor correlation and lack of agreement between CO measured by TEB and a reference technique (most often TD) across various patient subgroups.[14,15] The results of the current study align with those of Sharma et al., who found a moderate correlation (r = 0.548) between TD-CO and TEB-CO measurements in post-CABG patients during controlled ventilation.[18] They also reported an even weaker correlation ($r = 0.469$) in spontaneously breathing patients. The presence of an endotracheal

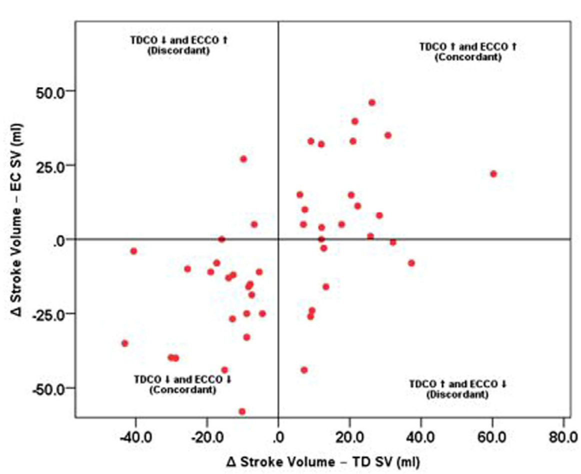

Fig 10. Four-quadrant concordance plot of stroke volume (SV) showing directional agreement between thermodilution (TD) and Electrical Cardiometry (EC) technology. Δ SV, delta SV.

tube, mediastinal tubes, pleural tubes, sternal wires, and alterations in physiology caused by mechanical ventilation and positive end-expiratory pressure have all been shown to affect CO measurements derived from TEB and EC technology.[18]

Critchley and colleagues demonstrated that a mean percentage error of approximately 30% between two different methods is clinically acceptable if the inherent errors in both techniques are similar to the expected error in TD-CO measurements.[13] Thus, according to objective criteria, the percentage errors of 38.62% and 34.24% between TD-CO and EC-CO, which were observed in the present study, cannot be accepted, and these two techniques cannot be used interchangeably in post-cardiac surgical patients. The trending analysis of both CO and stroke volume values, using four-quadrant concordance plots, indicated suboptimal agreement between TD and EC technologies. These findings suggest that while EC shows moderate correlations with TD-derived measurements, it is unable to reliably track CO and stroke volume trends or directional changes. A recent prospective, observational study conducted in 72 critically ill medical patients has also shown wide limits of agreement, ranging from −2.91 to 3.85 L/min, and a percent error of 54.0% between TD-CO and EC-CO monitoring.[19] Greiwe et al. reported clinically unacceptable agreement and a large percentage error (47%) between TD-CO and EC-CO in patients after CABG surgery.[20] A weak correlation in extubated patients can also result from occasional, small bodily movements or diaphoresis, leading to suboptimal contact of chest and neck electrodes. Although sensing electrodes were placed according to the manufacturer's recommendations, a small alteration in their position can produce changes in CO of 5% to 10%; decreased distance leads to overestimation, whereas increasing distance produces underestimation of CO.[21]

Only a few studies have demonstrated clinically acceptable agreement between TD-CO and EC-CO, and have suggested that these techniques can be used interchangeably. Malik et al. reported a bias of 0.08 L/min, a precision of 0.15 L/min, a percentage error of 3.59%, and a narrow limit of agreement (−0.13 to 0.28 L/min) between continuous CO derived from the TD method and EC-CO in patients undergoing CABG with cardiopulmonary bypass.[22] Their observations were similar to Spiess et al., who reported that mediastinal opening and cardiopulmonary bypass had minimal effect on the correlation between the two technologies.[23] The major limitation of Malik et al.'s study is the reference method used, continuous CO, which is not the gold standard for the measurement of CO. Second, they could not measure CO values more frequently because of interference caused by hemodynamic disturbances during surgical manipulations and the use of diathermy, which affected the impedance of the sensors. Rajput et al. also found a fair agreement with a mean bias of 0.18 L/m and narrow limits of agreement (−1.25 to 0.89 L/m) between the EC-CO measurement method and TD-CO method during on-pump CABG surgery.[24] They have suggested that EC can be used to evaluate hemodynamic variables when invasive methods are to be avoided or not available.

Sanders et al. performed a systematic review and meta-analysis comparing the accuracy and precision of CO measurement by EC with a reference method.[25] A total of 13 studies in adults (620 patients) and 11 studies in pediatrics (603 patients) were included. For adults, the pooled bias was 0.03 L/min (95% confidence interval: 0.23; 0.29), the limits of agreement were −2.78 to 2.84 L/min, and the mean percentage error was 48.0%. For pediatrics, pooled bias was −0.02 L/min (95% confidence interval: 0.09; 0.05), limits of agreement were −1.22 to 1.18 L/min, and mean percentage error was 42.0%. They concluded that despite low bias in both adults and pediatrics, the mean percentage error was not clinically acceptable, and EC cannot replace TD and transthoracic echocardiography for the measurement of CO.

The possible limitations of this study include its single-center, observational design, lack of randomization, and a relatively small sample size. A larger cohort could not be included because the ICON monitoring system was available for only a limited time due to logistical constraints. A relatively smaller number of female patients (9 *v* 21 male patients) was another limitation, considering the fact that sex is an important patient characteristic that factors into the computation of CO. Therapeutic interventions based on CO values and derived hemodynamic indices in patients with severe left ventricular dysfunction are considered one of the indications for the use of PAC. It would be interesting to evaluate newer technology and compare it with TD-CO in this patient population. The finding that none of the patients were fluid-responsive to the PLR test, including those who clearly were fluid-responsive, underscores the need for further study of this technology. It also highlights the need for alternative methods to assess fluid responsiveness. The effects of cardiac medications on fluid responsiveness and hemodynamic variables are another area needing further research.

Conclusion

The TD and EC methods of CO measurement showed poor agreement in measuring hemodynamic indices after off-pump CABG surgery. PLR did not reliably predict fluid responsiveness, highlighting the need for alternative assessment methods, such as echocardiography, in cardiac surgery. The clinical implication of whether EC can be used for trend monitoring needs further evaluation, but this technology lacks precision for absolute measurements. While EC offers the advantages of noninvasiveness and easy portability, future studies should explore larger cohorts and newer monitoring approaches.

Declaration of competing interest

None.

CRediT authorship contribution statement

Ravina Mukati: Methodology, Formal analysis, Data curation. **Ajmer Singh:** Writing − review & editing, Writing − original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Prajeesh M. Nambiar:** Investigation, Data curation, Conceptualization. **Bhanu Prakash Zawar:** Investigation, Data curation, Conceptualization. **Yatin Mehta:** Writing − review & editing, Supervision, Project administration, Conceptualization. **Naresh Trehan:** Validation, Supervision, Project administration.

References

1 Andre AS, DelRossi AL. Hemodynamic management of patients in the first 24 hours after cardiac surgery. Crit Care Med 2005;33:2082–93.
2 Suresh V, Sethuraman M, Karunakaran J, et al. Fluid responsiveness to passive leg raising in patients with and without coronary artery disease: A prospective observational study. Ann Card Anaesth 2020;23:439–46.
3 Sandham JD, Hull RD, Brant RF, et al. A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients. New Engl J Med 2003;348:5–14.
4 Bernstein DP, Lemmens HJ. Stroke volume equation for impedance cardiography. Med Biol Eng Comput 2005;43:443–50.
5 Peyton PJ, Chong SW. Minimally invasive measurement of cardiac output during surgery and critical care: A meta-analysis of accuracy and precision. Anesthesiology 2010;113:1220–35.
6 Raaijmakers E, Faes TJ, Scholten RJ, et al. A meta-analysis of three decades of validating thoracic impedance cardiography. Crit Care Med 1999;27:1203–13.
7 Bernstein DP and Osypka MJ. Apparatus and method for determining an approximation of the stroke volume and the cardiac output of the heart. United States Patent, 2003;US006511438B2.
8 Zou Y, Chen M, Liu Y. Passive leg raising tests under a monitoring device to predict fluid responsiveness in off-pump coronary artery bypass grafting patients. Int J Clin Exp Med 2020;13:4346–53 www.ijcem.com/ISSN:1940-5901/IJCEM0109604.
9 Cavallaro F, Sandroni C, Marano C, et al. Diagnostic accuracy of passive leg raising for prediction of fluid responsiveness in adults: Systematic review and meta-analysis of clinical studies. Intensive Care Med 2010;36:1475–83.
10 Monnet X, Marik P, Teboul J-L. Passive leg raising for predicting fluid responsiveness: A systematic review and meta-analysis. Intensive Care Med 2016;42:1935–47.
11 Chaves RC, Corrêa TD, Neto AS, et al. Assessment of fluid responsiveness in spontaneously breathing patients: A systematic review of literature. Ann Intensive Care 2018;8:21.
12 Bland JM, Altman DG. Comparing methods of measurement: Why plotting difference against standard method is misleading? Lancet 1995;346:1085–7.
13 Critchley LA, Critchley JA. A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. J Clin Monit Comput 1999;15:85–91.
14 Doering L, Lum E, Dracup K, et al. Predictors of between-method differences in cardiac output measurement using thoracic electrical bioimpedance and thermodilution. Crit Care Med 1995;23:1667–73.
15 de Waal EE, Konings MK, Kalkman CJ, et al. Assessment of stroke volume index with three different bioimpedance algorithms: Lack of agreement compared to thermodilution. Intensive Care Med 2008;34:735–9.
16 Paranjape VV, Henao-Guerrero N, Menciotti G, et al. Agreement between Electrical Cardiometry and pulmonary artery thermodilution for measuring cardiac output in isoflurane-anesthetized dogs. Animals 2023;13:1420.
17 Sharma S, Ramachandran R, Rewari V, et al. Evaluation of Electrical Cardiometry to assess fluid responsiveness in patients with acute circulatory failure: A comparative study with transthoracic echocardiography. Indian J Crit Care Med 2024;28:650–6.
18 Sharma V, Singh A, Kansara B, et al. Comparison of transthoracic electrical bioimpedance cardiac output measurement with thermodilution method

in post coronary artery bypass graft patients. Ann Card Anaesth 2011; 14:104–10.

19 Song W, Guo J, Cao D, et al. Comparison of noninvasive electrical cardiometry and transpulmonary thermodilution for cardiac output measurement in critically ill patients: A prospective observational study. BMC Anesthesiol 2025;25:123.

20 Greiwe G, Saad R, Hapfelmeier A, et al. Electrical cardiometry for noninvasive cardiac output monitoring: A method comparison study in patients after coronary artery bypass graft surgery. J Clin Monit Comput 2025; 39:371–6.

21 Guha A, Arora D, Mehta Y. Comparative study of cardiac output measurement by regional impedance cardiography and thermodilution method in patients undergoing off pump coronary artery bypass graft surgery. Ann Card Anaesth 2022;25:335–42.

22 Malik V, Subramanian A, Chauhan S, et al. Correlation of Electric Cardiometry and continuous thermodilution cardiac output monitoring systems. World J Cardiovasc Surg 2014;4:101–8.

23 Spiess BD, Patel MA, Soltow LO, et al. Comparison of bioimpedance versus thermodilution cardiac output during cardiac surgery: Evaluation of a second-generation bioimpedance device. J Cardiothorac Vasc Anesth 2011;15:567–73.

24 Rajput RS, Das S, Chauhan S, et al. Comparison of cardiac output measurement by noninvasive method with Electrical Cardiometry and invasive method with thermodilution technique in patients undergoing coronary artery bypass grafting. World J Cardiovasc Surg 2014;4:123–30.

25 Sanders M, Servaas S, Slagt C. Accuracy and precision of non-invasive cardiac output monitoring by electrical cardiometry: A systematic review and meta-analysis. J Clin Monit Comput 2020;34:433–60.