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Original Research Article

Reliability of Bioreactance and Pulse-Power Analysis in Measuring Cardiac Index During Open Abdominal Aortic Surgery

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Objective: To investigate the accuracy, precision, and trending ability of noninvasive bioreactance-based Starling SV and the mini invasive pulse-power device LiDCOrapid as compared to thermodilution cardiac output (TDCO) as measured by pulmonary artery catheter when assessing cardiac index (CIx) in the setting of elective open abdominal aortic (AA) surgery.

Design: A prospective method-comparison study.

Setting: Oulu University Hospital, Finland.

Participants: Forty patients undergoing elective open abdominal aortic surgery.

Interventions: Intraoperative CI measurements were obtained simultaneously with TDCO and the study monitors, resulting in 627 measurement pairs with Starling SV and 497 with LiDCOrapid.

Measurements and Main Results: The Bland-Altman method was used to investigate the agreement among the devices, and four-quadrant plots with error grids were used to assess trending ability. The agreement between TDCO and Starling SV was associated with a bias of 0.18 L/min/m^2 (95% confidence interval [CI] = 0.13 to 0.23), wide limits of agreement (LOA = −1.12 to 1.47 L/min/m^2), and a percentage error (PE) of 63.7 (95% CI = 52.4-71.0). The agreement between TDCO and LiDCOrapid was associated with a bias of −0.15 L/min/m^2 (95% CI = −0.21 to −0.09), wide LOA (−1.56 to 1.37), and a PE of 68.7 (95% CI = 54.9-79.6). The trending ability of neither device was sufficient.

Conclusion: The CI measurements achieved with Starling SV and LiDCOrapid were not interchangeable with TDCO, and the ability to track changes in CI was poor. These results do not support the use of either study device in monitoring CI during open AA surgery.

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DISTURBED ORGAN perfusion may lead to major postoperative complications, such as cognitive dysfunction, acute kidney injury, and myocardial depression.[1] Goal-directed therapy (GDT) with fluids and vasoactive drugs reduces complications and shortens the lengths of both intensive care unit (ICU) and hospital stays after cardiac and major noncardiac surgery.[2-4] The use of GDT requires the reliable monitoring of various hemodynamic parameters, such as cardiac output (CO), arterial pressure, and mixed venous oxygen saturation.[5,6] Arterial pressure itself provides only an estimate of systemic perfusion, and, alone, it is an inadequate measure of tissue perfusion.[7-9] In addition, mean arterial pressure has been proven not to detect changes in CO.[10] On the other hand, other available measurements, such as pulse-pressure variation, only provide data on fluid responsiveness.[11] Therefore, measuring changes in CO and oxygen delivery is essential in the hemodynamic monitoring and management of critically ill patients in ICUs, as well as unstable patients during perioperative care.[12]

Open abdominal aortic (AA) surgery is a major high-risk surgery. Significant changes in cardiac afterload are caused by aortic cross-clamping and clamp release.[13,14] Moreover, the reperfusion of the lower extremities after a period of ischemia may lead to an inflammatory response, decreasing vascular resistance.[14,15] Patients undergoing open AA surgery often are older and have cardiovascular comorbidities, which limit their physiologic reserve and ability to compensate for these hemodynamic effects. Therefore, GDT using advanced hemodynamic monitoring is indicated in this patient group.[16,17]

A pulmonary artery catheter (PAC) used with the thermodilution cardiac output (TDCO) technique is the gold standard for measuring CO.[18-20] The PAC is also the reference standard to which the noninvasive technologies are compared.[19,21] Because a PAC is an invasive CO monitor, it has been associated with rare but potentially severe adverse effects.[18,22] This has led to the development of numerous less-invasive CO monitors.[23] However, their performance and reliability have been shown to be questionable in the presence of hemodynamic instability and cardiac arrhythmias, as well as during high-risk surgeries.[24-26]

Starling SV is a continuous, uncalibrated, noninvasive CO monitor based on a transthoracic bioreactance technique.[23,27] Four dual-electrode stickers are placed on the chest wall: 2 on the left side and 2 on the right side.[27] An alternating electrical current is produced through the thorax, and aortic blood flow creates a phase shift between the applied current and the measured thoracic voltage.[25] This phase shift is related to CO.[28] For further reading concerning Starling SV, the readers are advised to see a detailed review by Marik.[25]

LiDCOrapid is a continuous mini invasive CO monitor based on arterial pressure waveform analysis.[23] It uses an autocorrelation algorithm, PulseCO, that calculates the stroke volume from the entire pressure waveform using a method called "pulse-power analysis".[28] LiDCOrapid uses a nomogram to assess aortic compliance, one that is based on a large database and the patient's demographics, including age, height, and weight.[28] The device does not require external calibration, but it can be calibrated using a reference technique.[29]

In this study, the accuracy, precision, and trending ability of the noninvasive CO monitor Starling SV and the mini invasive CO monitor LiDCOrapid were compared with invasive TDCO in patients undergoing elective open AA surgery. The hypothesis put forward was that all 3 monitoring methods were equally reliable.

Methods

This prospective single-center observational method-comparison study (reference number 30/2019) was approved by the Ethical Committee of Oulu University Hospital, Oulu, Finland (Chairperson Prof J Mäkelä) and conducted according to the principles of the Helsinki Declaration. Forty consecutive patients undergoing elective open AA surgery between May 2018 and May 2021 were enrolled. Written informed consent to participate in the study was obtained from all patients. Patients who declined to participate in the study, those aged under 18 years, and those who required emergency surgery were excluded. The first 7 patients were monitored only with Starling SV and TDCO. The rest of the patients were equipped with both study monitors.

Before the induction of general anesthesia, a thoracic epidural catheter was inserted. The 4 Starling SV dual-electrode stickers (CMM-ST5, 2017-12-01, Version 5.2, Cheetah Medical, Newton, MA) were placed on the patient's back.[27] An arterial line was placed in the radial or brachial artery (BD Arterial Cannula 20G, Becton Dickinson and Company, Franklin Lakes, NJ). LiDCOrapid (LiDCOrapid V2.03-318, LiDCO, London, UK) was connected to the patient monitor (Carescape B850 Monitor, GE Healthcare, Chicago, IL). A 7.5-Fr PAC (Criticath SP5507U TD Catheter, Merit Medical, South Jordan, UT) was inserted via an 8.5-Fr sheath placed in the right internal jugular vein and advanced into the pulmonary artery.

General anesthesia was induced with intravenous propofol and remifentanil or alfentanil, depending on the preferences of the attending anesthesiologist. Anesthesia was maintained with a combination of sevoflurane and propofol. Remifentanil or alfentanil was given to provide intraoperative analgesia, and rocuronium was used as a neuromuscular blocker. Therapeutic decisions were based on TDCO measurements and

according to local clinical practice. Epidural analgesia was maintained with boluses of fentanyl and 0.9% saline or with an infusion consisting of fentanyl, levobupivacaine, and 0.9% saline. Postoperatively, the patients were transferred to the ICU.

TDCO was measured approximately once in 30 minutes during the surgery when hemodynamic parameters were stable. Each TDCO measurement was a mean of at least 3, 10-mL 0.9% saline bolus injections at room temperature. Unreliable thermodilution curves (as defined by their morphology and lack of coherence with the other measurements) were deleted. The TDCO measurements were not synchronized with the respiratory cycle because the reliability of TDCO improves when measurements are performed independently of the respiratory phase.[30-32] The authors used the cardiac index (CI) instead of CO, according to the local clinical practice.

Starling SV calibrates itself automatically at the beginning of the monitoring session. The Starling SV data were stored in its database. A CI value obtained with Starling SV is the mean of the CIs measured during 1 minute. As the time settings were synchronized with the electronic patient monitoring system, measurements performed at the same time as TDCO could be analyzed. To eliminate potential errors, a value was rejected if it was significantly different from the values before and after it. LiDCOrapid was not calibrated. The arterial line was zeroed initially, and, each time, the signal became unreliable. The data derived from LiDCOrapid were recorded manually in the electronic anesthesia record simultaneously with each TDCO measurement. The data were divided into 3 phases: no aortic occlusion, partial occlusion (other iliac artery clamped), and total occlusion. The study protocol was completed when the patient was transferred to the ICU for postoperative care.

Statistics

The sample size was calculated as recommended in the literature[33] based on a data structure with multiple dependent measurements within the subject. The mean CI and the standard deviation of TDCO were calculated, and it was assumed that there was a 10% difference as compared with the other 2 monitors. A noninferiority margin of 0.42, an alpha of 0.05, and a beta of 0.20 were used, resulting in 428 measurement points.

All analyses were performed using SPSS for Windows (IBM SPSS, Inc, Version 25.0, Armonk, NY) and SAS for Windows (version 9.4 SAS Institute Inc, Cary, NC). Summary statistics are presented as medians with the 25th-to-75th percentiles unless stated otherwise, and two-tailed p values are given.

A Bland-Altman plot was used to evaluate the mean bias for accuracy, with the limits of agreement (LOA) for precision, between each test monitor and TDCO.[19,34-36] Proportional bias was evaluated by calculating regression coefficients.[19] The 95% CIs were calculated for bias, LOA, and the regression coefficients.[37] To assess LOA and bias (both average and proportional bias), multiple dependent measurements within the subject were used.[35,36] Percentage errors (PEs) with 95% CIs are reported to describe precision.[19,21] Predefined targets were set for acceptable bias, LOA, and PE according to the literature at 0.25 L/min/m^2, 0.5 L/min/m^2, and 30%, respectively.[19,21]

To evaluate trending ability, a four-quadrant (4Q) plot was used, which consists of the changes in 2 consecutive CI measurements (delta CI) obtained with the reference method and the study monitor.[19,38] An exclusion zone of 0.25 L/min/m^2 was used, as recommended in the literature. Based on the 4Q plots, error grids with 4 zones were created to describe the clinical significance and level of trending ability. In zone 1, the change in CI measured with the study device and TDCO was either positive or negative, and the extent of the change was equal. These results led to similar treatment interventions. In zone 2, both devices detected the direction of the change similarly, but the extent of the change measured was not comparable. In zone 3, only one device detected a change in CI, and, in zone 4, the changes were opposite one another, which may have resulted in divergent treatment decisions.[19,38]

Results

The patient characteristics are presented in Table 1. The median age of the patients was 70 years, and 83% of them were male. All surgeries were elective. There was no hospital mortality. There was one readmission to the ICU. CI measurements obtained simultaneously with TDCO resulted in 627 pairs with Starling SV and 497 pairs with LiDCOrapid. The median number of CI measurements per patient was 15. In total, 587 and 452 delta CI measurements were taken with Starling SV and LiDCOrapid, respectively, which were compared with the delta CI measurements obtained with TDCO and used for the 4Q plot.

Starling SV, as compared with TDCO, was associated with a bias of 0.18 L/min/m^2 (95% CI = 0.13 to 0.23) at all measurement points. When all measurement points were observed, the LOA was −1.12 to 1.47 L/min/m^2, and PE was 63.7% (Fig 1, A). The changes in CI, as measured by Starling SV and TDCO, were plotted against one another in the 4Q plot (Fig 1, B). The level of agreement in trending was assessed with error grids, resulting in 33.6% of the measurement points being in zone 1. Considering all measurement points, the regression coefficient was 0.48 L/min/m^2, but when the aorta was partially occluded, it was 1.00 L/min/m^2. The results for Starling SV and TDCO are presented in Tables 2 and 3.

LiDCOrapid, as compared with TDCO, was associated with a bias of −0.15 L/min/m^2 (95% CI = −0.21 to −0.09) at all measurement points. When all measurement points were considered, the LOA was −1.56 to 1.37 L/min/m^2, and PE was 68.7% (Fig 2, A). The changes in CI measured by LiDCOrapid and TDCO were plotted against each other in the 4Q plot (Fig 2, B). The level of agreement in trending was assessed with error grids, resulting in 41.2% of the measurement points being in zone 1. The regression coefficient was −0.04 L/min/m^2 when all measurement points were considered. When the aorta was partially occluded, the regression indicated a nonlinear effect, with a quadratic term of 0.68 L/min/m^2. The results for LiDCOrapid and TDCO are presented in Tables 4 and 5.

Table 1
Patient Characteristics (N = 40)

Age, y	70 (66-74)
Male sex	33 (83)
BMI, kg/m^2	27 (24-30)
BSA, m^2	1.93 (1.80-2.10)
ASA class	
ASA 2	6 (15)
ASA 3	23 (57.5)
ASA 4	11 (27.5)
Prior comorbidities	
Hypertension	31 (78)
Diabetes	14 (35)
Coronary artery disease	10 (25)
COPD	13 (33)
ASO	8 (20)
Reason for surgery	
AAA	35 (87.5)
ASO	1 (2.5)
Redo-AAA	4 (10)
Norepinephrine max dose, μg/kg/min	0.19 (0.13-0.25)
Dobutamine used	28 (70)
Levosimendan used	2 (5)
Milrinone used	1 (3)
IV nitrate used	18 (45)
Cross-clamp time, min	122 (98-145)
Partial occlusion time, min	93 (71-107)
Suprarenal cross-clamp	10 (25)
Duration of surgery, min	344 (295-403)
ICU length of stay, d	1 (1-3)
Readmission	1 (3)
Hospital length of stay, d	8 (7-11)

NOTE. The values given are medians with 25th and 75th percentiles or numbers of patients (n) with percentages (%).
Abbreviations: AAA, abdominal aortic aneurysm; ASA, American Society of Anesthesiologists; ASO, arteriosclerosis obliterans; BMI, body mass index; BSA, body surface area; COPD, chronic obstructive pulmonary disease; IV, intravenous; ICU, intensive care unit; Redo, reoperative surgery.

Discussion

This prospective method-comparison study was designed to evaluate the reliability of the less-invasive CO monitors Starling SV and LiDCOrapid as compared with TDCO during elective open AA surgery. Both monitors showed acceptable accuracy, as the mean bias was low. Both study devices were imprecise due to wide LOA and high PE. The trending ability of both devices was insufficient, as less than 50% of the changes in CI were comparable with TDCO. The results suggested that CI measurements with Starling SV and LiDCOrapid are not interchangeable with TDCO and that their ability to track changes in CI is poor. These results do not support their use in monitoring CI during open AA surgery.

There was a significant proportional bias associated with the study findings. Especially with Starling SV, the regression coefficient was significant at all measurement points. In a subgroup analysis of separate phases, the bias varied. When the aorta was partially occluded, regression coefficients increased with both study monitors, indicating that the bias was proportional to changes in CI. These findings suggested that mini invasive and noninvasive monitors cannot track the sudden and marked hemodynamic changes that occur when an aortic cross-clamp is applied and released.

To the authors' knowledge, there are no previous studies comparing the bioreactance technique with TDCO during open AA surgery or any other major vascular surgeries. Regarding other major noncardiac surgeries, Ylikauma et al. investigated the accuracy, precision, and trending abilities of Starling SV and LiDCOrapid during cytoreductive surgery (CRS) with hyperthermic intraperitoneal chemotherapy (HIPEC), with results comparable to those reported here.[26] Kober et al. studied patients with ovarian carcinoma undergoing CRS. CIs measured with bioreactance were compared with

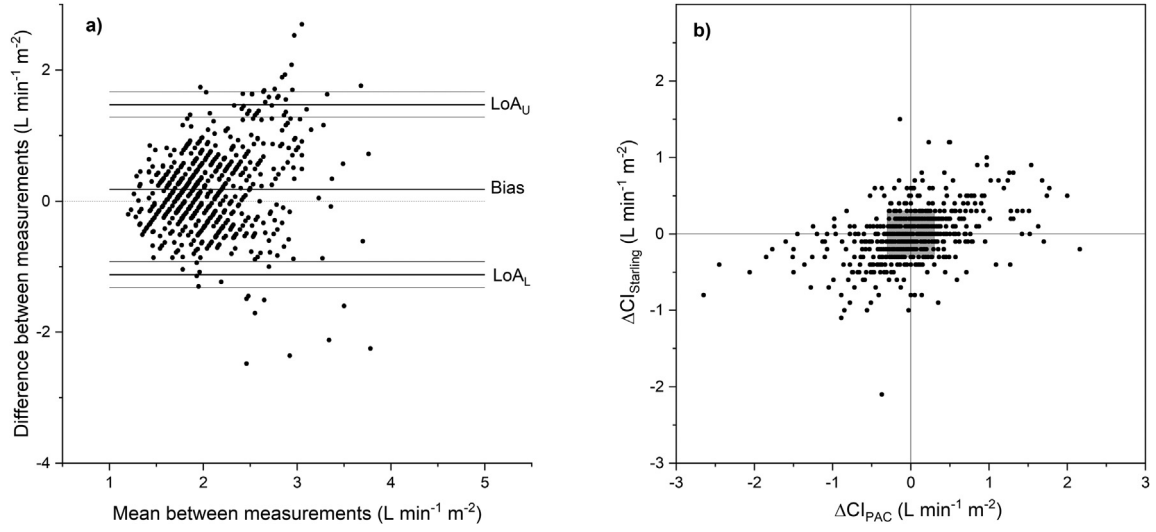

Fig 1. (A) The Bland-Altman plot for cardiac index measured with the bolus thermodilution technique with a pulmonary artery catheter and bioreactance-based Starling SV at all measurement points. The lines for bias, the limits of agreement, and the 95% CIs of the LOA are shown. See Table 2 for exact numbers. (B) The four-quadrant plot showing the trending ability of Starling SV by plotting the change in consecutive CI measured with Starling SV ($\Delta CI_{Starling}$) and the authors' reference method of thermodilution (ΔCI_{PAC}) at all measurement points. See Table 3 for exact numbers. LOA, limits of agreement.

Table 2
Cardiac Index Measurements Made by Starling SV as Compared to the Bolus Thermodilution Technique with a Pulmonary Artery Catheter

Starling SV	Bias, L/min/m^2	Bias, 95% CI	LOA Lower, L/min/m^2	LOA Lower, 95% CI	LOA pper, L/min/m^2	LOA Upper, 95% CI	Percentage Error, %	Percentage Error, 95% CI	Regression Coefficient, L/min/m^2	Regression Coefficient, 95% CI
All n = 627	0.18	0.13-0.23	−1.12	−1.32 to −0.92	1.47	1.28-1.67	63.7	52.4-71.0	0.48	0.39-0.58
No occlusion n = 417	0.23	0.17-0.29	−1.02	−1.21 to −0.83	1.49	1.31-1.68	61.1	50.5-67.8	0.36	0.25-0.48
Partial occlusion n = 49	0.20	0.00-0.40	−1.21	−1.60 to −0.81	1.63	1.23-2.03	62.2	46.2-82.1	1.00	0.74-1.25
Total occlusion n = 161	0.04	−0.07 to 0.15	−1.29	−1.60 to −0.98	1.36	1.05-1.67	71.2	51.5-83.2	0.42	0.23-0.62

Abbreviations: LOA, limits of agreement.

Table 3
The Error Grid with 4 Zones Demonstrating the Trending Ability of Starling SV

Starling SV	Error Grid, Zone 1, %	Error Grid, Zone 2, %	Error Grid, Zone 3, %	Error Grid, Zone 4, %
All n = 587	33.6	17.4	33.0	16.0
No occlusion n = 377	34.2	15.9	33.2	16.7
Partial occlusion n = 49	44.9	24.5	20.4	10.2
Total occlusion n = 161	28.6	18.6	36.6	16.1

those measured using transpulmonary thermodilution. Accuracy and good trending ability were detected, but precision was insufficient (bias = 0.26 l/min/m^2, LOA = −1.39 to 1.92 l/min/m^2, PE = 50.7%). Trending ability was evaluated via polar plot analysis.[39] This finding differed from the results reported here, possibly because open AA surgery and CRS with HIPEC are associated with more significant hemodynamic changes than CRS without HIPEC. Therefore, mini invasive and noninvasive monitors may not track changes in CO as accurately.

No previous studies were found comparing LiDCOrapid with TDCO in patients undergoing elective open AA surgery. Beattie et al. studied the performance of LiDCOplus, a CO monitor that uses the pulse-power technique but requires calibration with lithium indicator dilution to determine vascular compliance, in the setting of open AA surgery.[13] They found that LiDCOplus was affected markedly by anesthesia and aortic cross-clamping, and required recalibration to obtain absolute values of CO accurately during open AA surgery.[13] However, 2 studies investigating other pulse-pressure devices during open AA surgery were found. Montenij et al. studied the accuracy, precision, and trending ability of the FloTrac/Vigileo pulse-pressure analysis device versus TDCO. They reached a similar conclusion, with acceptable bias but poor precision and trending ability. The sample size of only 86 measurements was small compared with that of

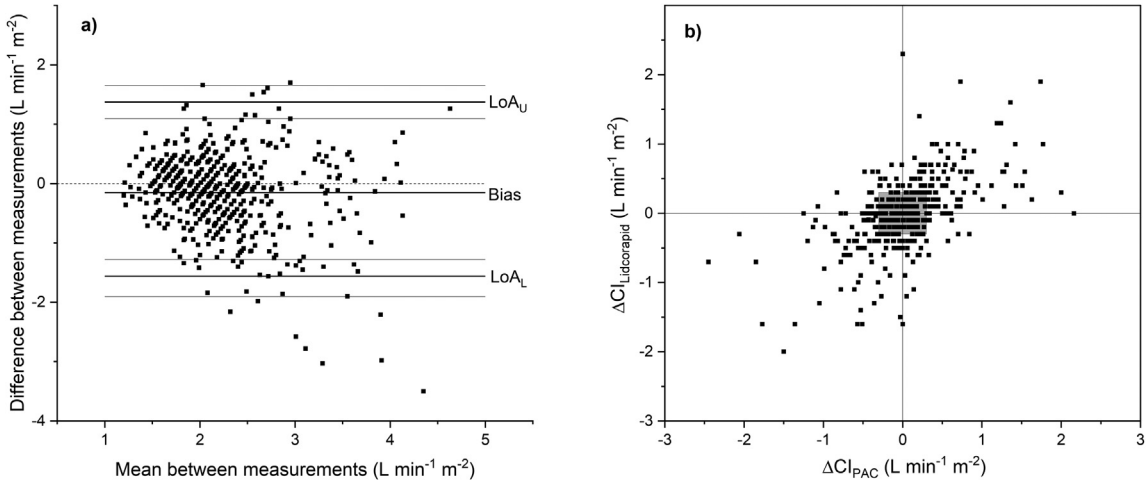

Fig 2. (A) The Bland-Altman plot for cardiac index measured with the bolus thermodilution technique with a pulmonary artery catheter and pulse-power device LiDCOrapid at all measurement points. The lines for bias, the limits of agreement, and the 95% CIs for the limits of agreement are shown. See Table 4 for exact numbers. (B) The four-quadrant plot showing the trending ability of LiDCOrapid by plotting the change in consecutive CI measured with LiDCOrapid ($\Delta CI_{Lidcorapid}$) and the author's reference method of thermodilution (ΔCI_{PAC}) at all measurement points. See Table 5 for exact numbers. LOA, limits of agreement.

Table 4
Cardiac Index Measurements by LiDCOrapid as Compared to the Bolus Thermodilution Technique with a Pulmonary Artery Catheter

LiDCOrapid	Bias, L/min/m^2	Bias, 95% CI	LOA Lower, L/min/m^2	LOA Lower, 95% CI	LOA Upper, L/min/m^2	LOA Upper, 95% CI	Percentage Error, %	Percentage Error, 95% CI	Regression Coefficient, L/min/m^2	Regression Coefficient, 95% CI
All n = 497	−0.15	−0.21 to −0.09	−1.56	−1.84 to −1.28	1.37	1.09-1.65	68.7	54.9-79.6	−0.04*	−0.13 to 0.06
No occlusion n = 325	0.01	−0.06 to 0.07	−1.30	−1.56 to −1.03	1.36	1.09-1.62	61.4	47.8-71.2	−0.07*	−0.18 to 0.04
Partial occlusion n = 40	−0.34	−0.58 to −0.10	−1.90	−2.39 to −1.40	1.36	0.86-1.85	67.2	48.4-88.3	−3.79*	−6.22 to −1.36
									0.68†	0.26 to 1.10
Total occlusion n = 132	−0.50	−0.62 to −0.37	−1.81	−2.18 to −1.45	1.12	0.76-1.48	75.0	57.3-90.0	−0.22†	−0.41 to −0.04

Abbreviations: LOA, limits of agreement.
* Linear regression.
† Quadratic term.

Table 5
The Error Grid with 4 Zones Demonstrating the Trending Ability of LiDCOrapid

LiDCOrapid	Error Grid, Zone 1, %	Error Grid, Zone 2, %	Error Grid, Zone 3, %	Error Grid, Zone 4, %
All n = 452	41.2	15.7	30.3	12.8
No occlusion n = 283	40.3	15.9	32.2	11.7
Partial occlusion n = 39	46.2	20.5	23.1	10.3
Total occlusion n = 130	41.5	13.8	28.5	16.2

the present study.[40] Kusaka et al. investigated the performance of uncalibrated Flotrac/Vigileo during open AA surgery. In this study, transesophageal echocardiography was used as the reference technique instead of TDCO, which is against recommendations.[19] The CO values obtained with Flotrac/Vigileo were not acceptable because of wide variations during aortic cross-clamping and unclamping.[41]

One strength of the present study was the use of highly recommended statistical methods. A Bland-Altman plot was used to evaluate the reliability of the monitors.[19] Because there are no specific reference values for acceptable bias or the LOA, the targets were set according to the literature and clinical judgment.[19] In addition, CIs for bias and the LOA were declared. Regarding PE, an acceptable value of 30% was set, according to Critchley and Critchley.[21] There are no preset ideal target values to interpret the results of the 4Q plot or error grid. Thus, there were no reference values for trending ability, which can be seen as a weakness. However, the best clinical knowledge was used to interpret the results. Another strength of the present study was that TDCO was used as a reference technique, as recommended in the literature.[19] Because TDCO is used widely at the hospital where this study was performed, the use and interpretation of its data are convenient for the staff. TDCO precision was not calculated as part of the present study. However, the precision of TDCO has been shown to be 5% to 13% when 3 consecutive reliable measurements are used to calculate the average value.[19,21,42] LiDCOrapid was not calibrated because the study sought to investigate its performance as an uncalibrated monitor.

One potential benefit of Starling SV and LiDCOrapid is that they are continuous monitors, which could offer insights into trending due to fast response times. However, neither of the study monitors was reliable in terms of trending ability in patients undergoing open AA surgery or a HIPEC procedure because less than 50% of the changes in CI were comparable with TDCO.[26] Continuous CO (CCO) monitoring can also be achieved by continuous thermodilution with a PAC (PAC-CCO). PAC-CCO has been compared to TDCO, with conflicting results. One study concluded a lack of interchangeability of PAC-CCO compared with TDCO in cardiac surgical patients 6 hours after cardiopulmonary bypass, with an acceptable bias and LOA (0.33 L/min and ±0.6 L/min) but with a PE of 34%, which is above recommendations.[21,43] In a systematic review and meta-analysis of perioperative and critically ill patients, the accuracy of PAC-CCO was sufficient, but the LOA was wide, and the PE barely reached the target of 29.7% (95% CI 20.5 to 38.9).[21,44] The conclusion was that TDCO remains the gold standard for measuring CO.[44] Because the reference method used in this study was intermittent, the study design could be considered suboptimal. This was a limitation that must be considered when interpreting the results. Another limitation of the investigation was that the results applied only to patients undergoing elective open AA surgery.

Conclusion

Bioreactance-based Starling SV and pulse-power-analysis-based LiDCOrapid were not interchangeable with TDCO in measuring CI during open AA surgery. The results indicated that the precision and trending ability of both Starling SV and LiDCOrapid are insufficient and do not support their use in

monitoring hemodynamics and guiding fluid therapy during elective open AA surgery.

Declaration of competing interest

None.

CRediT authorship contribution statement

Heikki Pekka Oskari Ronkainen: Writing – review & editing. **Laura Anneli Ylikauma:** Writing – review & editing. **Mari Johanna Pohjola:** Writing – review & editing. **Pasi Petteri Ohtonen:** Writing – review & editing, Formal analysis. **Tiina Maria Erkinaro:** Writing – review & editing. **Merja Annika Vakkala:** Writing – review & editing. **Janne Henrik Liisanantti:** Writing – review & editing. **Tatu Sakari Juvonen:** Writing – review & editing. **Timo Ilari Kaakinen:** Writing – review & editing, Supervision, Project administration, Methodology.

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References

1 Lobo SM, Rezende E, Knibel MF, et al. Early determinants of death due to multiple organ failure after noncardiac surgery in high-risk patients. Anesth Analg 2011;112:877–83.
2 Chong MA, Wang Y, Berbenetz NM, et al. Does goal-directed haemodynamic and fluid therapy improve peri-operative outcomes?: A systematic review and meta-analysis. Eur J Anaesthesiol 2018;35:469–83.
3 Pölönen P, Ruokonen E, Hippeläinen M, et al. A prospective, randomized study of goal-oriented hemodynamic therapy in cardiac surgical patients. Anesth Analg 2000;90:1052–9.
4 Gan TJ, Soppitt A, Maroof M, et al. Goal-directed intraoperative fluid administration reduces length of hospital stay after major surgery. Anesthesiology 2002;97:820–6.
5 Kaakinen TI, Ikäläinen T, Erkinaro TM, et al. Association of low mixed venous oxygen saturations during early ICU stay with increased 30-day and 1-year mortality after cardiac surgery: A single-center retrospective study. BMC Anesthesiol 2022;22:322.
6 Waldron NH, Miller TE, Gan TJ. Perioperative goal-directed therapy. J Cardiothorac Vasc Anesth 2014;28:1635–41.
7 Asfar P, Meziani F, Hamel J-F, et al. High versus low blood-pressure target in patients with septic shock. N Engl J Med 2014;370:1583–93.
8 Lamontagne F, Richards-Belle A, Thomas K, et al. Effect of reduced exposure to vasopressors on 90-day mortality in older critically ill patients with vasodilatory hypotension. JAMA 2020;323:938.
9 Kjaergaard J, Møller JE, Schmidt H, et al. Blood-pressure targets in comatose survivors of cardiac arrest. 2020 2022;387:1456-66.
10 Pierrakos C, Velissaris D, Scolletta S, et al. Can changes in arterial pressure be used to detect changes in cardiac index during fluid challenge in patients with septic shock? Intensive Care Med 2012;38:422–8.
11 Messina A, Pelaia C, Bruni A, et al. Fluid challenge during anesthesia: A systematic review and meta-analysis. Anesth Analg 2018;127:1353–64.
12 Cove ME, Pinsky MR. Perioperative hemodynamic monitoring. Best Pract Res Clin Anaesthesiol 2012;26:453–62.
13 Beattie C, Moores C, Thomson AJ, et al. The effect of anaesthesia and aortic clamping on cardiac output measurement using arterial pulse power analysis during aortic aneurysm repair. Anaesthesia 2010;65:1194–9.
14 Gelman S. The pathophysiology of aortic cross-clamping and unclamping. Anesthesiology 1995;82:1026–60.
15 Norwood MGA, Bown MJ, Sayers RD. Ischaemia-reperfusion injury and regional inflammatory responses in abdominal aortic aneurysm repair. Eur J Vasc Endovasc Surg 2004;28:234–45.
16 Aronow WS. Peripheral arterial disease and abdominal aortic aneurysm in elderly people. Minerva Med 2011;102:483–500.
17 Hamilton MA, Cecconi M, Rhodes A. A systematic review and meta-analysis on the use of preemptive hemodynamic intervention to improve postoperative outcomes in moderate and high-risk surgical patients. Anesth Analg 2011;112:1392–402.
18 Swan HJ, Ganz W, Forrester J, et al. Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. N Engl J Med 1970;283:447–51.
19 Montenij LJ, Buhre WF, Jansen JR, et al. Methodology of method comparison studies evaluating the validity of cardiac output monitors: A stepwise approach and checklist. Br J Anaesth 2016;116:750–8.
20 Peeters Y, Bernards J, Mekeirele M, et al. Hemodynamic monitoring: To calibrate or not to calibrate? Part 1 – Calibrated techniques. Anaesthesiol Intensive Ther 2015;47:487–500.
21 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.
22 Evans DC, Doraiswamy VA, Prosciak MP, et al. Complications associated with pulmonary artery catheters: a comprehensive clinical review. Scand J Surg 2009;98:199–208.
23 Arya VK, Al-Moustadi W, Dutta V. Cardiac output monitoring - invasive and noninvasive. Curr Opin Crit Care 2022;28:340–7.
24 Kobe J, Mishra N, Arya VK, et al. Cardiac output monitoring: Technology and choice. Ann Card Anaesth 2019;22:6–17.
25 Marik PE. Noninvasive cardiac output monitors: A state-of the-art review. J Cardiothorac Vasc Anesth 2013;27:121–34.
26 Ylikauma LA, Tuovila MJ, Ohtonen PP, et al. Reliability of bioreactance and pulse power analysis in measuring cardiac index during cytoreductive abdominal surgery with hyperthermic intraperitoneal chemotherapy (HIPEC). BMC Anesthesiol 2023;23:38.
27 Raval NY, Squara P, Cleman M, et al. Multicenter evaluation of noninvasive cardiac output measurement by bioreactance technique. J Clin Monit Comput 2008;22:113–9.
28 Bernards J, Mekeirele M, Hoffmann B, et al. Hemodynamic monitoring: To calibrate or not to calibrate? Part 2 — Non-calibrated techniques. Anaesthesiol Intensive Ther 2015;47:501–16.
29 Broch O, Renner J, Höcker J, et al. Uncalibrated pulse power analysis fails to reliably measure cardiac output in patients undergoing coronary artery bypass surgery. Crit Care 2011;15:R76.
30 McMillan RW, Morris DM. Effect of respiratory cycle on measurements of cardiac output by thermodilution. Surg Gynecol Obstet 1988;167:420–2.
31 Moise SF, Sinclair CJ, Scott DHT. Pulmonary artery blood temperature and the measurement of cardiac output by thermodilution. Anaesthesia 2002;57:562–6.
32 Thrush DN, Varlotta D. Thermodilution cardiac output: Comparison between automated and manual injection of indicator. J Cardiothorac Vasc Anesth 1992;6:17–9.
33 Julious SA. Sample sizes for clinical trials. Boca Raton, FL: Chapman and Hall/CRC; 2009.
34 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–10.
35 Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res 1999;8:135–60.
36 Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. J Biopharm Stat 2007;17:571–82.
37 Zou GY. Confidence interval estimation for the Bland-Altman limits of agreement with multiple observations per individual. Stat Methods Med Res 2013;22:630–42.

38 Saugel B, Grothe O, Wagner JY. Tracking changes in cardiac output: Statistical considerations on the 4-quadrant plot and the polar plot methodology. Anesth Analg Lippincott 2015;121:514–24.
39 Kober D, Trepte C, Petzoldt M, et al. Cardiac index assessment using bioreactance in patients undergoing cytoreductive surgery in ovarian carcinoma. J Clin Monit Comput 2013;27:621–7.
40 Montenij LJ, Buhre WF, De Jong SA, et al. Arterial pressure waveform analysis versus thermodilution cardiac output measurement during open abdominal aortic aneurysm repair: A prospective observational study. Eur J Anaesthesiol 2015;32:13–9.
41 Kusaka Y, Yoshitani K, Irie T, et al. Clinical comparison of an echocardiograph-derived versus pulse counterderived cardiac output measurement in abdominal aortic aneurysm surgery. J Cardiothorac Vasc Anesth 2012;26:223–6.
42 Yang X-X, Critchley LA, Joynt GM. Determination of the precision error of the pulmonary artery thermodilution catheter using an in vitro continuous flow test rig. Anesth Analg 2011;112:70–7.
43 Bendjelid K, Schütz N, Suter PM, et al. Continuous cardiac output monitoring after cardiopulmonary bypass: A comparison with bolus thermodilution measurement. Intensive Care Med 2006;32:919–22.
44 Kouz K, Michard F, Bergholz A, et al. Agreement between continuous and intermittent pulmonary artery thermodilution for cardiac output measurement in perioperative and intensive care medicine: A systematic review and meta-analysis. Crit Care 2021;25:125.