Title

Reliability of bioreactance and pulse power analysis in measuring cardiac index in patients undergoing cardiac surgery with cardiopulmonary bypass

Abstract

Objectives

Less invasive and continuous cardiac output monitors have recently been developed to monitor patient hemodynamics. The aim of our study was to compare the accuracy, precision and trending ability of non-invasive bioreactance-based Starling SV and mini-invasive pulse power device LiDCOrapid to bolus thermodilution technique with pulmonary artery catheter (TDCO) when measuring cardiac index in the setting of cardiac surgery with cardiopulmonary bypass.

Design

A prospective method-comparison study.

Setting

Oulu University Hospital, Finland.

Participants

Twenty patients undergoing cardiac surgery with cardiopulmonary bypass.

Interventions

Cardiac index measurements were obtained simultaneously with TDCO intra- and postoperatively resulting in 498 measurements with Starling SV and 444 with LiDCOrapid.

Measurements and Main Results

We used the Bland-Altman method to investigate the agreement between the devices and four-quadrant plots with error grids to assess the trending ability. The agreement between TDCO and Starling SV was qualified with a bias of 0.43 L min^{-1} m^{-2} (95% confidence interval, 95% CI, 0.37 to 0.50), wide limits of agreement (LOA, –1.07 to 1.94 L min^{-1} m^{-2}), and a percentage error (PE) of 66.3%. The agreement between TDCO and LiDCOrapid was qualified with a bias of 0.22 L min^{-1}

m^{-2} (95% CI 0.16–0.27), wide LOA (–0.93 to 1.43), and a PE of 53.2%. With both devices, trending ability was insufficient.

Conclusions

The reliability of bioreactance-based Starling SV and pulse power analyzer LiDCOrapid was not interchangeable with TDCO, thus limiting their usefulness in cardiac surgery with cardiopulmonary bypass.

Key Words

Bioreactance, Cardiac index, Cardiac output, Mini-invasive, Monitoring, Non-invasive, Cardiac surgery, pulse power analysis

Introduction

The measurement of cardiac output (CO) is essential when optimizing hemodynamic management and tissue perfusion in critically ill and unstable patients. [1] The oldest known method of measuring CO is the Fick principle. [2] However, it is a highly invasive and cumbersome technique, and therefore it is not useful in clinical settings. The pulmonary artery catheter (PAC) was first introduced by Swan, Ganz and Forrester in the 1970s [3]. Even after five decades there are conflicting aspects about the usefulness of PAC since its invasiveness can cause severe harm to the patients. [3,4] There are studies reporting that using a PAC can even worsen the patient outcome [5,6], but also one Cochrane review and two large RCTs that do not support these results. [7–9] Two recent retrospective registry-based studies actually suggest an improved outcome in patients with cardiogenic shock, and a review highlighted the usefulness of PAC in these patients. [10,11,12] In clinical settings, PAC has remained as the gold standard for measuring CO by using bolus thermodilution technique (TDCO). [2,3]

The existing severe complications of PAC have induced the development of less invasive CO monitoring techniques. Starling SV is a continuous uncalibrated non-invasive CO monitor, which is based on transthoracic bioreactance technique. [1] It consists of four dual-electrode stickers, which produce an alternating electrical current through the thorax. The phase shift between applied current and measured thoracic voltage is almost entirely due to the aortic blood flow and hence should be closely related to cardiac output. [13,14] LiDCOrapid is a mini-invasive CO monitor, which is based on arterial pressure waveform analysis providing continuous monitoring of CO. LiDCOrapid uses an autocorrelation algorithm, PulseCO, that calculates the stroke volume from the entire pressure waveform using a method called pulse power analysis. [14] The vascular compliance is assessed by a nomogram, thus the device does not need external calibration. LiDCOrapid makes an uncalibrated estimate for stroke volume based on patient variables such as age, height and weight. [14] However, it can be calibrated using a reference method. [15]

Cardiac surgery with cardiopulmonary bypass (CPB) is a high-risk operation necessitating the use of advanced hemodynamic monitoring. Relatively common complications of CPB are severe vasoplegia with low systemic vascular resistance (SVR) and low-cardiac-output syndrome. [16–18] These may affect the reliability of all CO monitoring methods, and especially LiDCOrapid has proved to be unreliable in measuring CI with decreased SVR. [19,20] There are only few studies evaluating the reliability of Starling SV during cardiac surgery with CPB. The reliability of LiDCO during cardiac surgery has been studied more, but with conflicting results. Moreover, the study protocols have not always been ideal due to an insufficient sample size, limited statistical methods, use of an inadequate reference method, or lack of trending analysis. We wanted to study the reliability of the devices in challenging clinical situations with changing hemodynamics.

In this study we compared the accuracy, precision and trending ability of the non-invasive CO monitor Starling SV and the mini-invasive CO monitor LiDCOrapid to invasive TDCO in patients undergoing cardiac surgery with CPB. Our hypothesis was that all the monitors are equally reliable.

Methods

This prospective single-center observational method comparison study was approved by the Ethics Committee of Oulu University Hospital (56/2018, 15/08/2018) and conducted according to the principles of the Helsinki declaration. We included 20 consecutive patients undergoing elective or urgent cardiac surgery with CPB between March and June 2019. The patients were properly informed both orally and in writing before obtaining the study consent, and our exclusion criteria were the refusal of the patient to attend the study and the need of an emergency operation. Therapeutic decisions were based on TDCO measurements according to local clinical practice.

Prior to induction of anesthesia, an arterial line was placed into the radial or brachial artery (BD Arterial Cannula 20G, Becton Dickinson and Company, Franklin Lakes, New Jersey, USA). LiDCOrapid (LiDCOrapid V2.03-318, LiDCO, London, UK) was connected to the patient monitor (Carescape B850 Monitor, GE Healthcare, Chicago, Illinois, USA). A 7.5F PAC (Criticath SP5507U TD Catheter, Merit Medical, South Jordan, Utah, USA) was inserted via an 8.5F sheath placed in the right internal jugular vein and advanced into the pulmonary artery. Four dual-electrode stickers of Starling SV (CMM-ST5, 2017-12-01, version 5.2, Cheetah Medical, Newton, Massachusetts, USA) were placed on the back of the patients, two of them on the right and two of them on the left side of the chest wall according to the instructions. [21]

General anesthesia was induced with intravenous infusions of propofol and remifentanil. Anesthesia was maintained with a combination of sevoflurane and propofol. Remifentanil was given to provide

intraoperative analgesia, and rocuronium was used as the neuromuscular blocker. Postoperatively, the patients were transferred to the intensive care unit (ICU). In the ICU remifentanil was replaced with intravenous oxycodone, and propofol infusion was continued until awakening. Extubation was performed according to local fast-track principles.

TDCO measurements were taken as a mean of at least three 10 ml 0.9% saline bolus injections at room temperature. [22] The thermodilution curve was carefully checked each time and unreliable curves were discarded. The measurements were not synchronized with the respiratory cycle. [23] We used cardiac index (CI) instead of CO according to the clinical practice in our hospital. The data from Starling SV was recorded continuously into its own database. Starling SV calibrates itself automatically at the start of the monitoring session. It was recalibrated manually during the operation every time the position of the patient or the heart was significantly altered or if the signal became unreliable. The CI values of LiDCOrapid were written down every time CI was measured with TDCO. LiDCOrapid was calibrated with our reference method TDCO prior to anesthesia induction and upon arrival in the ICU.

We calculated our sample size for an equivalence study as recommended in the literature and considered the data structure with multiple independent measurements within the subject.[24] We used the data from a previous study of our group, in which the mean CI of TDCO was 2.4 and the mean CI of Starling SV was 2.2.[25] We got the following results: standard deviation of differences (SD) 0.7, non-inferiority margin 0.36, alpha 0.05, beta 0.10 (power 0.9), giving a sample size of 414 measurements. We included 20 patients in our study.

The measurements were performed in the OR at least every 30 minutes prior to and after CPB. Postoperatively in the ICU the measurements were taken at least once in an hour before extubation

and at least every 3 hours after extubation until the first postoperative morning. The data was divided into four essential phases. First phase was before CPB and second phase after CPB in the OR. Third phase was before extubation in the ICU and fourth phase after extubation.

Statistics

Our summary statistics are given as medians with 25^{th}–75^{th} percentiles [25–75 PCT] unless stated otherwise. Two-tailed p-values are presented. All analyses were performed using SPSS for Windows (IBM Corp. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.) and SAS for Windows (version 9.4 SAS Institute Inc., Cary, NC, USA).

To evaluate the accuracy and precision between test devices and TDCO, we calculated the mean bias between measurements and the limits of agreement (LOA) with 95% confidence intervals (95% CI) according to Bland and Altman. [26–32] When calculating the LOA, we used the method where the true value varies as our data consists of multiple independent measurements within the subject. [27,29] Regression coefficients with 95% CI were calculated to evaluate proportional bias. Since the bias and LOA were uniform in our study, we reported the regression coefficients as absolute values. [26] Percentage errors (PE) with 95% CI were calculated to further describe the precision of the devices. [26] We set predefined targets for acceptable bias and LOA according to the literature. [26] As we used CI instead of CO, we divided CO by an average body surface area (2 m^2) resulting in acceptable bias of 0.25 L/min/m^2 and LOA of 0.5 L/min/m^2. As an acceptable PE value we used 30% [33].

The trending ability of the study monitors compared to TDCO was evaluated with four-quadrant (4Q) plots, which consisted of the changes of two consecutive CI measurements. Exclusion zones were included as recommended in the literature. [26,34] Based on the 4Q plot, error grids were created

from the perspective of therapeutic consequences. Four zones of the error grid define the level of agreement between changes in CI measured by the study device and TDCO. In zone 1 the change in CI measured with two devices has either been positive or negative and the extent has been comparable. This means that both have changed less than 5%, between 5–15%, or over 15%, leading to similar treatment interventions. In zone 2 the CI has changed in the same direction but unequal extent, which can generate insufficient or exaggerated treatment. In zone 3 only one of the devices has detected a change in CI, which can lead either to unnecessary treatment interventions or omitted necessary interventions. In zone 4 the changes have been opposite leading to incorrect treatment decisions. [26]

Results

The median age of the patients was 66 years and 75% of them were male. 70% of the surgeries were elective while the rest were urgent procedures. There was no hospital mortality. The characteristics of the study patients are presented in Table 1. Cardiac index measurements obtained simultaneously with TDCO resulted in 498 measurements with Starling SV and 444 with LiDCOrapid. The median number of measurements per patient was 25. There were 470 and 396 delta CI measurement pairs used in the 4Q plot when comparing TDCO with Starling SV and LiDCOrapid, respectively.

Considering all measurement points over the study protocol, Starling SV was associated with a bias of 0.43 L min^{-1} m^{-2} (95% CI 0.37 to 0.50) and LOA of –1.07 to 1.94 L min^{-1} m^{-2} when compared with TDCO (Figure 1a). The PE was 66.3%. The changes in CI measured by Starling SV and TDCO were plotted against each other in the 4Q plot (Figure 1b). The error grids based on the 4Q plot demonstrate that the level of agreement in trending was 26% in zone 1. The regression coefficient was 0.14 L min^{-1} m^{-2} considering all measurement points, but in phase 2 it was 0.95 L min^{-1} m^{-2}. The results between Starling SV and TDCO are presented in Tables 2 and 3.

Considering all measurement points over the study protocol, LiDCOrapid was associated with a bias of 0.22 L min^{-1} m^{-2} (95% CI 0.16–0.27) and LOA of –0.93 to 1.43 L min^{-1} m^{-2} when compared with TDCO (Figure 2a). The PE was 53.2%. The changes in CI measured by LiDCOrapid and TDCO were plotted against each other in the 4Q plot (Figure 2b). The error grids based on the 4Q plot demonstrate that the level of agreement in trending was 39% in zone 1. The regression coefficient was 0.00 L min^{-1} m^{-2} considering all measurement points, but in phase 3 it was –1.30 L min^{-1} m^{-2}. The results between LiDCOrapid and TDCO are presented in Tables 4 and 5.

Discussion

In this investigation less invasive monitors were not interchangeable with TDCO when assessing cardiac index in patients undergoing cardiac surgery with CPB. Compared with TDCO, Starling SV utilizing bioreactance showed inaccuracy with a high mean bias, whereas the mean bias of mini-invasive continuous pulse power analysis LiDCOrapid was lower suggesting sufficient accuracy. Although the proportional bias was absent over all phases, it was present in phases 1–3 with Starling SV and in phase 3 with LiDCOrapid, indicating increasing bias when CI increases. The wide LOA and high PE of both devices indicate that neither of the devices was precise enough. Furthermore, the trending ability of both devices was poor. These results challenge the usefulness of Starling SV and LiDCOrapid in the setting of cardiac surgery with CPB.

There are only few studies comparing Starling SV to TDCO in cardiac surgery. We compared Starling SV to TDCO in our previous study in patients undergoing off-pump coronary artery bypass surgery, resulting in insufficient accuracy, precision and trending ability. [25] The earlier version of bioreactance, NICOM, was compared to TDCO in cardiac surgery patients during the first 2 hours

after surgery. [35] The results showed inaccuracy and imprecision with a bias of –0.71 L/min, the LOA of ±2.70 L/min and a PE of 47%. Another study [36] compared NICOM to continuous thermodilution with PAC (PAC-CCO) after cardiac surgery resulting in acceptable accuracy. However, the results are not comparable to ours, since PAC-CCO is not considered as a valid reference technique for measuring CO. [26] Studies comparing Starling SV to TDCO or to another accepted reference method, intermittent transpulmonary thermodilution (TPTD), in non-surgical settings, have shown unreliability. [21,26,37]

There are multiple studies comparing LiDCO devices to TDCO in patients undergoing cardiac surgery with CPB. Two studies comparing LiDCOrapid to TDCO in the setting of cardiac surgery with CPB reached a similar conclusion to ours with acceptable bias and poor precision, but the sample size was small in both studies. [38,39] Two studies compared LiDCOplus to TDCO in postcardiac surgery patients resulting in acceptable bias but wide LOA. The PEs in the studies were 35% and 29%, respectively, showing better precision than of our study. However, the measurements were done only during the first two and four postoperative hours, respectively. [35,40] One study compared LiDCOplus to TDCO in patients having impaired left ventricular function after cardiac surgery. The measurements were performed during the first four postoperative hours resulting in adequate accuracy and PE of 27%, but wide LOA. However, the sample size was small. [41] Studies comparing LiDCOrapid to TPTD have shown similar results to ours suggesting insufficient reliability, even though calibration of LiDCOrapid seemed to improve its accuracy. [15,42]

An ideal CO monitor is reliable, non-invasive, continuous, operator-independent, cost-effective and it should have a fast response time. [43] When assessing the reliability of new technologies, the reference method needs to be accurate and precise. Choosing an inaccurate or imprecise reference technique can lead to rejecting the new device despite its qualities. [44,45] TDCO is still considered as

the gold standard for measuring cardiac output and therefore it is a strength of our study that we used TDCO as our reference method. However, it needs to be considered that in the setting of cardiac surgery with CPB, the systemic cooling and rewarming performed during CPB causes a temperature decrease in pulmonary artery after CPB. This leads to changes in the baseline temperature during TDCO measurements, and hence can underestimate the true cardiac output. However, in a previous study the underestimation was detected only during the first 10 minutes after cardiopulmonary bypass. [46]

Using the Bland-Altman method is widely recommended when evaluating the agreement of two CO monitors. [26,28] It is a clinical decision when the bias and LOA are acceptable since there are no specific reference values. We defined acceptable boundaries in advance for LOA and bias according to the literature. [26] Our patients underwent a high-risk cardiac surgery, where even small hemodynamic changes can be relevant and thus require fast interventions. Thus, the requirements for monitoring devices are also high. The acceptable value of PE has been debated. Critchley and Critchley defined that the PE should not exceed 30% when using thermodilution as a reference method. [33]

Evaluating the trending ability of a new CO monitor is important when considering its clinical usefulness. The 4Q plot gives an intuitive picture of the agreement of the methods, but it does not provide clearly defined cutoff values for evaluating the trending. [34] We used the error grid with four zones to demonstrate the ability to track changes in CO. [26] We did not have specific boundaries to evaluate our results, which can be seen as a weakness. Still, there are no exact values how to interpret the results of 4Q plot and error grid, which highlights the importance of clinical judgement.

This study has some limitations. We did not calculate the precision of TDCO in our study, which would have been ideal. However, the precision of TDCO is proved in the literature to be 20%, while calculating the average of three consecutive reliable measurements further increases precision.[22,26,33,44,47] Also, we did not use the LiDCO device-specific calibration, i.e. lithium, when calibrating LiDCOrapid. A potential advantage of continuous monitors is their ability to detect the changes in CO and to offer an insight into trending. Since our reference method is intermittent and the experimental devices are continuous, the study design was not ideal to investigate this feature. This is a major limitation of our study. However, none of the continuous monitors has been proved to be reliable enough to be used as a reference technique.[26] As another limitation, the majority (75%) of the patients were male. The median body mass index of the patients was not higher than 27 kg m^{-2}, and one should extrapolate our results to more obese patients only with caution.

The median Euroscore II of our patients was 1.40%. This may limit the applicability of our results to more high-risk patients. Moreover, high-risk cardiac surgery does not provide an ideal setting for testing the reliability of new CI monitors. However, as the reference method PAC is invasive, its use during low-risk surgeries due to a study setting would be ethically questionable. Also, new monitors should have the ability to detect hemodynamic changes reliably, and this can only be investigated during high-risk surgeries with anticipated hemodynamic changes. Still, in general, it needs to be considered that our results consider patients undergoing cardiac surgery with CPB and may not be directly applied to other settings.

Conclusion

Despite the potential benefits that these two less invasive and easily usable CO devices offer, our study shows that their results are probably not interchangeable with TDCO, thus limiting their

usefulness in cardiac surgery with CPB. Accordingly, our hypothesis was not supported by the results.

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Table 1. Patient characteristics (n = 20).

Age, years	66 (58–68)
Sex male	15 (75)
BSA, m^2	1.97 (1.74–2.08)
BMI, kg m^{-2}	27 (24–29)
Prior co-morbidities	
Hypertension	12 (60)
Type 1 diabetes mellitus	1 (5)
Type 2 diabetes mellitus	4 (20)
Asthma	4 (20)
Left ventricular hypertrophy	5 (25)
Atrial fibrillation	6 (30)
Medication prior to surgery	
Acetylsalicylic acid	7 (35)
Clopidogrel	1 (5)
Low molecular weight heparin, or other anticoagulant	7 (35)
Beta blocker	15 (75)
Statin	11 (55)
ACE inhibitor or AT II receptor inhibitor	10 (50)
Long-acting nitrate	4 (20)
Medical state prior to surgery	
Ejection fraction	
> 50%	18 (90)
31–50%	1 (5)
21–30%	1 (5)
Coronary artery stenoses	
RCA	6 (30)
CX	5 (25)
LAD	6 (30)
LM	2 (10)
NYHA class	2 (1–3)
Euroscore II, %	1.40 (0.89–2.50)
Hemoglobin, g L^{-1}	147 (129–153)
Thrombocytes, E9 L^{-1}	200 (165–243)
INR	1.0 (1.0–1.1)
Surgery	
Urgency	
Urgent	6 (30)
Elective	14 (70)
Single coronary bypass surgery	4 (20)
Single aortic valve surgery	5 (25)
Single mitral valve surgery	5 (25)

Single descending aortic surgery	1 (5)
Combined procedures	5 (25)
Levosimendan used	6 (30)
Norepinephrine max dose, microg kg^{-1} min^{-1}	0.25 (0.13–0.50)
Dobutamine max dose, microg kg^{-1} min^{-1}	2.40 (0.39–3.48)
I.v. nitrate used	9 (45)
OR stay, min	410 (353–445)
Time in ventilator, OR and ICU combined, h	9.5 (7.5–11.0)
ICU length of stay, days	2 (1–2)
Time at tertiary care hospital, days	7 (6–9)
Hospital mortality	0 (0)

The values given are medians with 25th and 75th percentiles, or number of patients (n) with percentages (%). BSA, body surface area; BMI, body mass index; ACE, angiotensin-converting enzyme; RCA, right coronary artery; CX, circumflex artery; LAD, left anterior descending artery; LM, left main artery; NYHA Class, New York Heart Association Classification; INR, international normalized ratio; OR, operating theatre; ICU, intensive care unit.

Table 2. Cardiac index measurements by Starling SV compared to bolus thermodilution technique with a pulmonary artery catheter.

Starling SV	Bias ($L\ min^{-1}\ m^{-2}$)	Bias 95% CI	LOA lower ($L\ min^{-1}\ m^{-2}$)	LOA lower 95% CI	LOA upper ($L\ min^{-1}\ m^{-2}$)	LOA upper 95% CI	Percentage error	Percentage error 95% CI	Regression coefficient ($L\ min^{-1}\ m^{-2}$)	Regression coefficient 95% CI
All n=498	0.43	0.37 to 0.50	–1.07	–1.34 to –0.8	1.94	1.66–2.21	66.3%	52.3–80.2%	0.14	–0.01 to 0.29
Phase 1 n=98	–0.05	–0.17 to 0.08	–1.25	–1.55 to –0.95	1.23	0.94–1.53	56.3%	41.1–71.5%	0.57	0.31 to 0.84
Phase 2 n=129	0.48	0.37 to 0.59	–0.75	–1.09 to –0.42	1.73	1.4–2.06	59.6%	41.8–77.4%	0.95	0.65 to 1.26
Phase 3 n=118	0.41	0.29 to 0.52	–0.9	–1.26 to –0.53	1.67	1.3–2.03	57.2%	36.9–77.4%	0.49	0.14 to 0.84
Phase 4 n=153	0.69	0.56 to 0.82	–0.94	–1.46 to –0.42	2.35	1.83–2.87	69.8%	51.0–88.6%	0.20	–0.06 to 0.46

Phase 1 was before cardiopulmonary bypass and phase 2 after it in the OR. Phase 3 was before extubation in the ICU and phase 4 after extubation. LOA, limits of agreement.

Table 3. The error grid with four zones demonstrating the trending ability of Starling SV. The level of agreement between changes in cardiac index measured by the Starling SV and bolus thermodilution technique with a pulmonary artery catheter is ideal in zone 1, whereas in zone 4 the level of agreement is poor.

Starling SV	Error grid Zone 1	Error grid Zone 2	Error grid Zone 3	Error grid Zone 4
All n=470	26%	13%	40%	21%
Phase 1 n=78	35%	18%	32%	15%
Phase 2 n=127	26%	12%	39%	23%
Phase 3 n=113	26%	11%	41%	22%
Phase 4 n=152	21%	13%	44%	22%

Phase 1 was before cardiopulmonary bypass and phase 2 after it in the OR. Phase 3 was before extubation in the ICU and phase 4 after extubation.

Table 4. Cardiac index measurements by LiDCOrapid compared to bolus thermodilution technique with a pulmonary artery catheter.

LiDCOrapid	Bias ($L\ min^{-1}\ m^{-2}$)	Bias 95% CI	LOA lower ($L\ min^{-1}\ m^{-2}$)	LOA lower 95% CI	LOA upper ($L\ min^{-1}\ m^{-2}$)	LOA upper 95% CI	Percentage error	Percentage error 95% CI	Regression coefficient ($L\ min^{-1}\ m^{-2}$)	Regression coefficient 95% CI
All n=444	0.22	0.16 to 0.27	–0.93	–1.14 to –0.71	1.43	1.21–1.65	53.2%	44.9–61.4%	0.00	–0.11 to 0.11
Phase 1 n=91	0.25	0.16 to 0.35	–0.59	–0.77 to –0.41	1.17	0.99–1.35	44.6%	36.0–53.2%	0.13	–0.07 to 0.33
Phase 2 n=113	0.27	0.18 to 0.35	–0.65	–0.91 to –0.4	1.32	1.06–1.57	44.2%	28.1–60.4%	0.04	–0.18 to 0.26
Phase 3 n=107	–0.11	–0.23 to 0.01	–1.25	–1.64 to –0.85	1.28	0.89–1.67	53.8%	31.9–75.6%	–1.30	–2.52 to –0.09
Phase 4 n=133	0.38	0.27 to 0.50	–1.2	–1.7 to –0.71	1.83	1.34–2.33	55.0%	35.9–74.1%	–0.04	–0.31 to 0.23

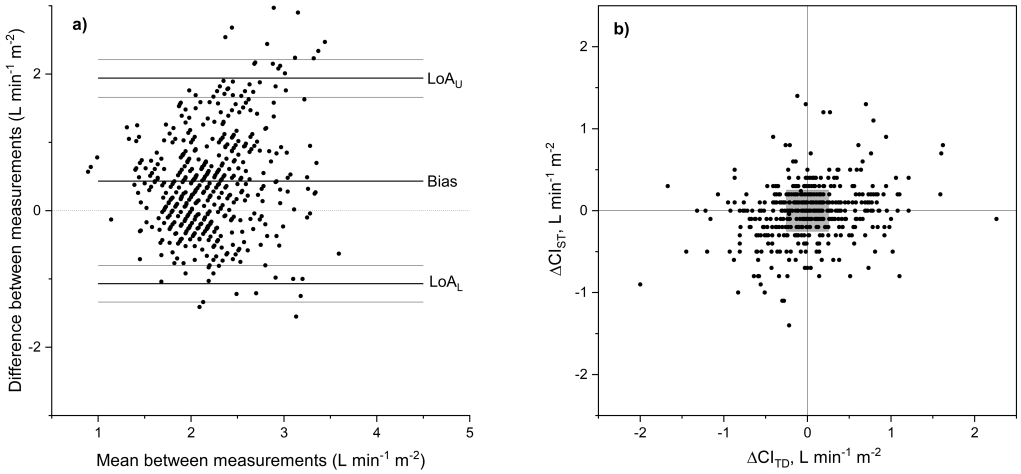
Phase 1 was before cardiopulmonary bypass and phase 2 after it in the OR. Phase 3 was before extubation in the ICU and phase 4 after extubation. LOA, limits of agreement.

Table 5. The error grid with four zones demonstrating the trending ability of LiDCOrapid. The level of agreement between changes in cardiac index measured by the LiDCOrapid and bolus thermodilution technique with a pulmonary artery catheter is ideal in zone 1, whereas in zone 4 the level of agreement is poor.

LiDCOrapid	Error grid Zone 1	Error grid Zone 2	Error grid Zone 3	Error grid Zone 4
All n=396	39%	16%	33%	12%
Phase 1 n=66	49%	21%	13%	17%
Phase 2 n=99	33%	19%	35%	13%
Phase 3 n=101	39%	12%	38%	11%
Phase 4 n=130	39%	14%	36%	11%

Phase 1 was before cardiopulmonary bypass and phase 2 after it in the OR. Phase 3 was before extubation in the ICU and phase 4 after extubation.

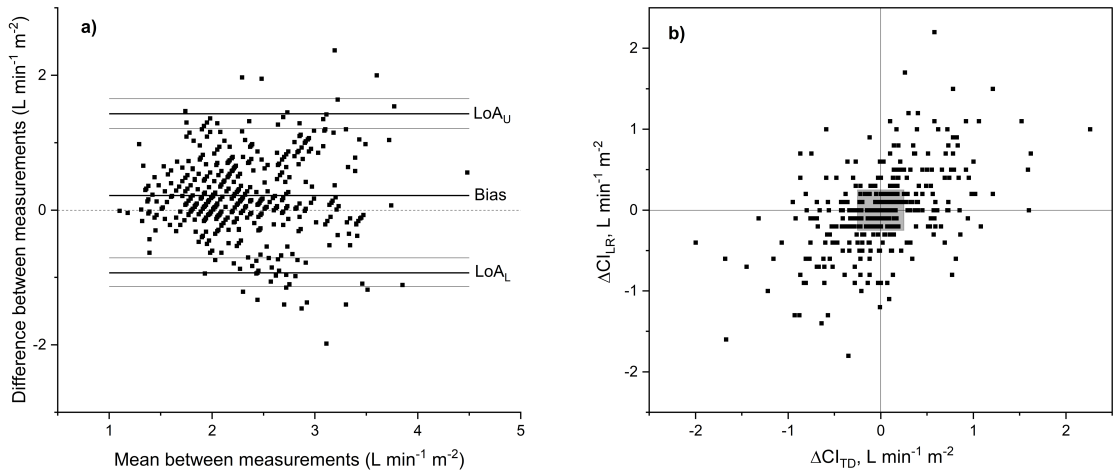
Figure 1.



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, LOA and 95% CIs of LOA are shown. See also Table 2 for exact numbers.

b) The 4-quadrant plot showing the trending ability of Starling SV by plotting the change of consecutive CI measured with Starling SV (ΔCI_{ST}) and our reference method thermodilution (ΔCI_{TD}) at all measurement points. See also Table 3 for exact numbers.

Figure 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, LOA and 95% CIs of LOA are shown. See also Table 4 for exact numbers.

b) The 4-quadrant plot showing the trending ability of LiDCOrapid by plotting the change of consecutive CI measured with LiDCOrapid (ΔCI_{LR}) and our reference method thermodilution (ΔCI_{TD}) at all measurement points. See also Table 5 for exact numbers.