

## Clinical Study

# A Comparison of Third-Generation Semi-Invasive Arterial Waveform Analysis with Thermodilution in Patients Undergoing Coronary Surgery

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Received 25 February 2012; Accepted 12 April 2012

Academic Editors: J. Alvarez, I. Misumi, E. Skalidis, and M. C. Vallejo

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Uncalibrated semi-invasive continuous monitoring of cardiac index (CI) has recently gained increasing interest. The aim of the present study was to compare the accuracy of CI determination based on arterial waveform analysis with transpulmonary thermodilution. Fifty patients scheduled for elective coronary surgery were studied after induction of anaesthesia and before and after cardiopulmonary bypass (CPB), respectively. Each patient was monitored with a central venous line, the PiCCO system, and the FloTrac/Vigileo-system. Measurements included CI derived by transpulmonary thermodilution and uncalibrated semi-invasive pulse contour analysis. Percentage changes of CI were calculated. There was a moderate, but significant correlation between pulse contour CI and thermodilution CI both before ( $r^2 = 0.72$ ,  $P < 0.0001$ ) and after ( $r^2 = 0.62$ ,  $P < 0.0001$ ) CPB, with a percentage error of 31% and 25%, respectively. Changes in pulse contour CI showed a significant correlation with changes in thermodilution CI both before ( $r^2 = 0.52$ ,  $P < 0.0001$ ) and after ( $r^2 = 0.67$ ,  $P < 0.0001$ ) CPB. Our findings demonstrated that uncalibrated semi-invasive monitoring system was able to reliably measure CI compared with transpulmonary thermodilution in patients undergoing elective coronary surgery. Furthermore, the semi-invasive monitoring device was able to track haemodynamic changes and trends.

## 1. Introduction

Estimation of haemodynamic variables such as left ventricular stroke volume and cardiac index in high-risk patients is a prerequisite for performing individual goal-directed therapy. Perioperative haemodynamic optimization and individual tailored therapy have been shown to improve patients' outcome by reducing morbidity and the length of stay on the intensive care unit [1–3]. In clinical practice, determination of cardiac index in the past was mostly related to invasive procedures such as right heart catheterization or femoral access, bearing method-related complications and limitations [4–6]. In this context, less-invasive techniques based on

arterial waveform analysis have gained increasing interest [7–9]. An example for a semi-invasive device for estimation of CI by pulse contour analysis is the FloTrac/Vigileo-system (Edwards Lifesciences LLC, Irvine, CA, USA), which was introduced in 2005 and since then underwent several software upgrades. The underlying method is described in detail elsewhere [10, 11]. This system requires only an arterial line connected to a special transducer (FloTrac) and has been investigated in several studies under various clinical conditions, but its precision to reflect CI is still under debate [12–14].

The aim of the present study was to investigate the precision of CI determination based on arterial waveform analysis

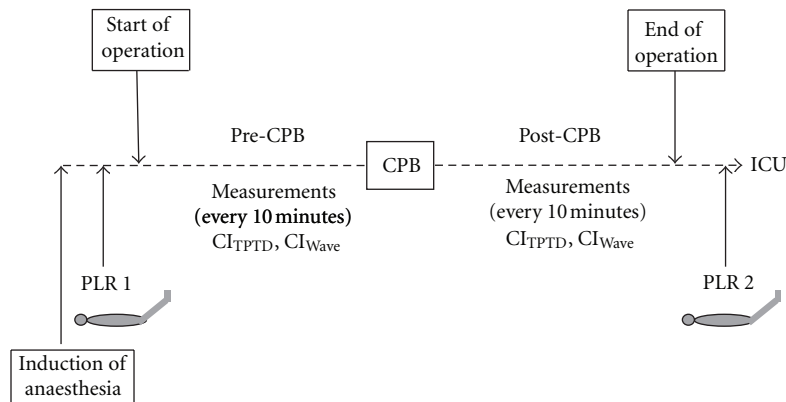


FIGURE 1: Study design. T1: data collection ( $CI_{Wave}$ ,  $CI_{TPTD}$ ) after induction of anaesthesia and passive leg raising (PLR 1) until cardiopulmonary bypass; T2: data collection ( $CI_{Wave}$ ,  $CI_{TPTD}$ ) after cardiopulmonary bypass until the end of surgery and passive leg raising (PLR 2).

by a third-generation device ( $CI_{Wave}$ ) with transpulmonary thermodilution ( $CI_{TPTD}$ ) before and after cardiopulmonary bypass (CPB). Furthermore, we studied the ability of the semi-invasive technique for tracking haemodynamic changes and trends.

## 2. Materials and Methods

After approval from our institutional ethics committee (Christian Albrecht University Kiel, Schwanenweg 20, D-24105 Kiel), written informed consent for participation in the study was obtained from all patients.

Fifty patients undergoing elective coronary artery bypass grafting (CABG) were studied after induction of general anaesthesia until discharge to the intensive care unit. Exclusion criteria were patients <18 years of age, a left ventricular ejection fraction  $\leq 0.5$ , emergency procedures, and patients with haemodynamic instability requiring continuous pharmacologic support. Patients with intracardiac shunts, severe aortic, tricuspid or mitral stenosis or insufficiency and mechanical circulatory support were also excluded.

**2.1. Instrumentation and Protocol.** All patients were pre-medicated with midazolam 0.1 mg/kg orally 30 min before induction of anaesthesia. Routine monitoring was established including peripheral oxygen saturation ( $SpO_2$ ) and heart rate (HR) (S/5 monitor, GE Healthcare, Helsinki, Finland). Subsequently patients received a peripheral venous access and a radial arterial line. A FloTrac/Vigileo-system was connected to the arterial line, followed by adjustment of the transducer and input of required individual demographic data according to the manufacturer's instructions (Software version 1.07, "third generation"). Variables were automatically indexed to body surface area. After induction of anaesthesia with sufentanil (0.5  $\mu\text{g}/\text{kg}$ ) and propofol (1.5 mg/kg), orotracheal intubation was facilitated with rocuronium (0.6 mg/kg). Anaesthesia was maintained with sufentanil (1  $\mu\text{g}/\text{kg}/\text{h}$ ), and propofol (3 mg/kg/h) and patients were ventilated with an oxygen/air mixture using a

tidal volume of 8 mL/kg ideal body weight and positive end-expiratory pressure was set at 5 cm  $H_2O$ . After placement of a central venous catheter in the right internal jugular vein, a transpulmonary thermodilution catheter (Pulsion Medical Systems; Munich, Germany) was introduced in the femoral artery. The thermodilution catheter was connected to the PiCCO<sub>2</sub> monitor (Software version 1.3.0.8).

**2.2. Data Collection.** After induction of anaesthesia,  $CI_{TPTD}$  and  $CI_{Wave}$  were recorded every 10 minutes both before and after CPB. Stable haemodynamic conditions and an undamped arterial signal were prerequisites for the measurements.  $CI_{TPTD}$  was determined by injecting 15 mL ice cold saline ( $\leq 8^\circ\text{C}$ ) through the central venous line at least three times randomly assigned to the respiratory cycle. In case of a difference of  $\geq 15\%$ , the value obtained was discarded and the measurement repeated. Simultaneously, measurement of  $CI_{Wave}$  was performed by plotting 5 numerical values over a period of three minutes and determining the mean value. Systolic, diastolic, and mean arterial pressures as well as CVP were also recorded every 10 minutes. After induction of anaesthesia, a passive leg raising manoeuvre (PLR 1) was performed, and haemodynamic variables including CI ( $CI_{TPTD}$ ,  $CI_{Wave}$ ) and stroke volume index (SVI) were recorded before, during and after PLR. Subsequently, measurements of  $CI_{TPTD}$  and  $CI_{Wave}$  were carried out every 10 minutes until the beginning of CPB (T1), which differed from patient to patient yielding different numbers of measurements in this time period. Measurements of  $CI_{TPTD}$  and  $CI_{Wave}$  were restarted 15 minutes after weaning from CPB and were obtained up to the end of the surgical intervention (T2), again yielding a different number of measurement pairs in individual patients. Immediately before discharge to the intensive care unit, a second PLR manoeuvre (PLR 2) was performed. Study design is displayed in Figure 1.

**2.3. Statistical Analysis.** All data are given as mean  $\pm$  SD. Statistical comparisons were performed using commercially available statistics software (GraphPad Prism 5, GraphPad

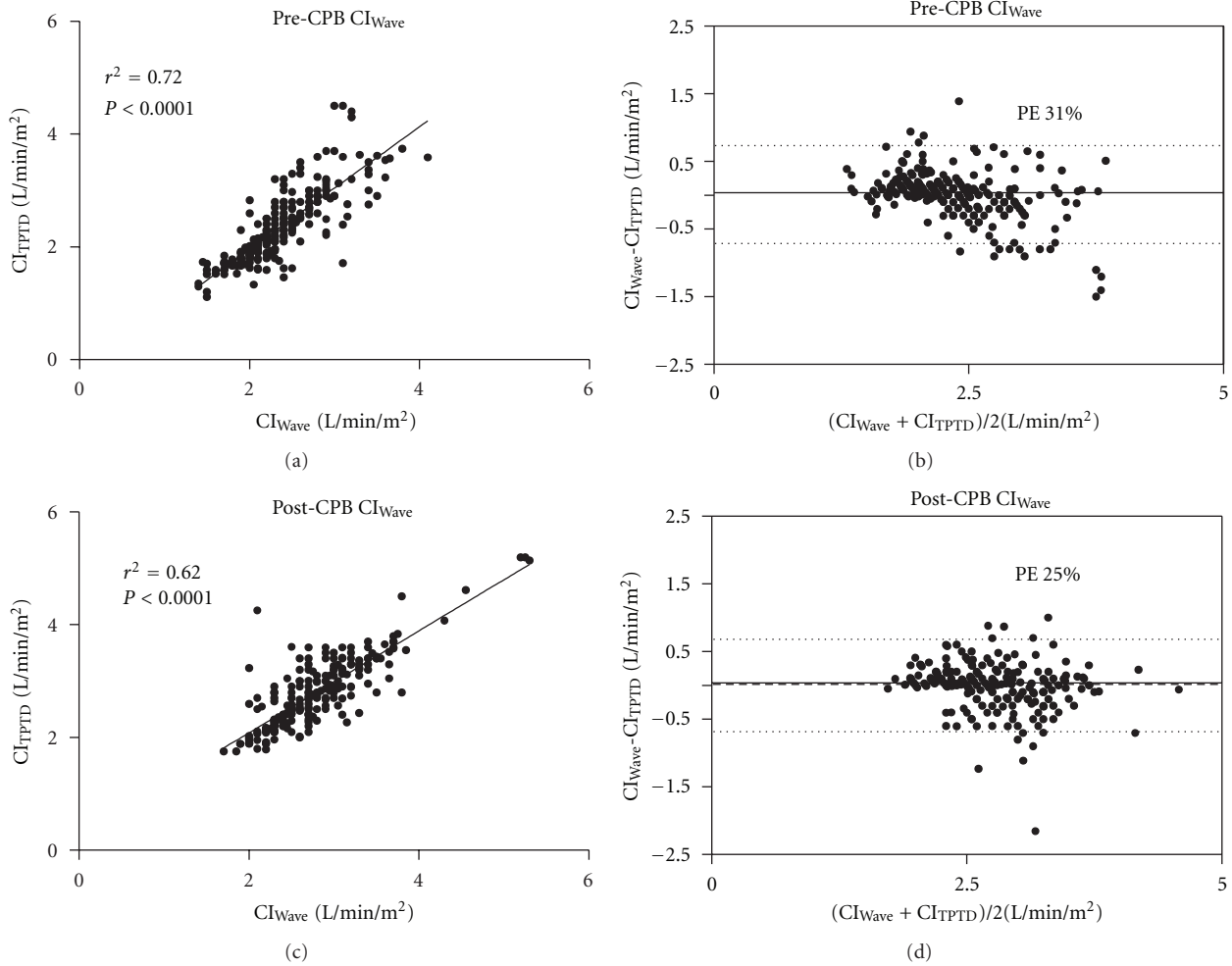


FIGURE 2: Correlation and Bland-Altman analysis of cardiac index measured by transpulmonary thermodilution ( $CI_{TPTD}$ ) and cardiac index measured by uncalibrated semi-invasive pulse contour analysis ( $CI_{Wave}$ ) before (T1) and after (T2) cardiopulmonary bypass.

TABLE 1: Haemodynamic variables before (T1) and after (T2) cardiopulmonary bypass.

Variables	Pre-CPB		P
	T1 (n = 245)	T2 (n = 223)	
HR ( $\text{min}^{-1}$ )	$57 \pm 3$	$80 \pm 4$	$P < 0.05^\#$
MAP (mmHg)	$76 \pm 5$	$73 \pm 10$	$P < 0.05^\#$
CVP (mmHg)	$10 \pm 2$	$9 \pm 4$	$P = 0.11$
SVRI ( $\text{dynes} \cdot \text{s/cm}^5/\text{m}^2$ )	$2370 \pm 62$	$1966 \pm 121$	$P < 0.05^\#$
$CI_{TPTD}$ ( $\text{L}/\text{min}/\text{m}^2$ )	$2.4 \pm 0.6$	$2.8 \pm 0.6$	$P < 0.05^\#$
$CI_{Wave}$ ( $\text{L}/\text{min}/\text{m}^2$ )	$2.4 \pm 0.5$	$2.8 \pm 0.6$	$P < 0.05^\#$

CPB: cardiopulmonary bypass; HR: heart rate; MAP: mean arterial pressure; CVP: central venous pressure; SVRI: systemic vascular resistance index;  $CI_{TPTD}$ : cardiac index by transpulmonary thermodilution;  $CI_{Wave}$ : cardiac index by semi-invasive pulse contour analysis; values are given as mean  $\pm$  SD.  $^\#P < 0.05$  (versus T1).

size and the width of the confidence interval of the estimated variable, we calculated the width of the 95% confidence interval of the limits of agreement as recommended by Bland and Altman (as  $\pm 1.96 \cdot \sqrt{(3/n)} \cdot s$ , where  $s$  is the standard deviation of the bias). For our sample size of 50 patients, we calculate a width of the 95% confidence interval of the limits of agreement of 0.51 times the SD (of bias), which is generally thought to be an acceptable narrow 95% confidence interval.

To describe the agreement between  $CI_{TPTD}$  and  $CI_{Wave}$ , Bland-Altman plots for repeated measures were calculated for each time period (T1-T2) before and after CPB. Percentage error was calculated as described by Critchley and colleagues, using the limits of agreement (2SD) of the bias divided by the mean CI values from  $CI_{TPTD}$  and  $CI_{Wave}$ . Bland-Altman plots were also performed for haemodynamic trends ( $\Delta CI_{TPTD}$ ,  $\Delta CI_{Wave}$ ) before and after CPB. Changes of  $CI_{TPTD} < 15\%$  were excluded from analysis as recommended by Critchley and colleagues [15]. Unpaired sample  $t$ -test was used to analyse significant differences of arterial pressure and systemic vascular resistance index (SVRI) related to the periods of measurement.

Software Inc., San Diego, CA, USA, and MedCalc for Windows, version 11.6.1.0, MedCalc Software, Mariakerke, Belgium). To demonstrate the relationship between sample

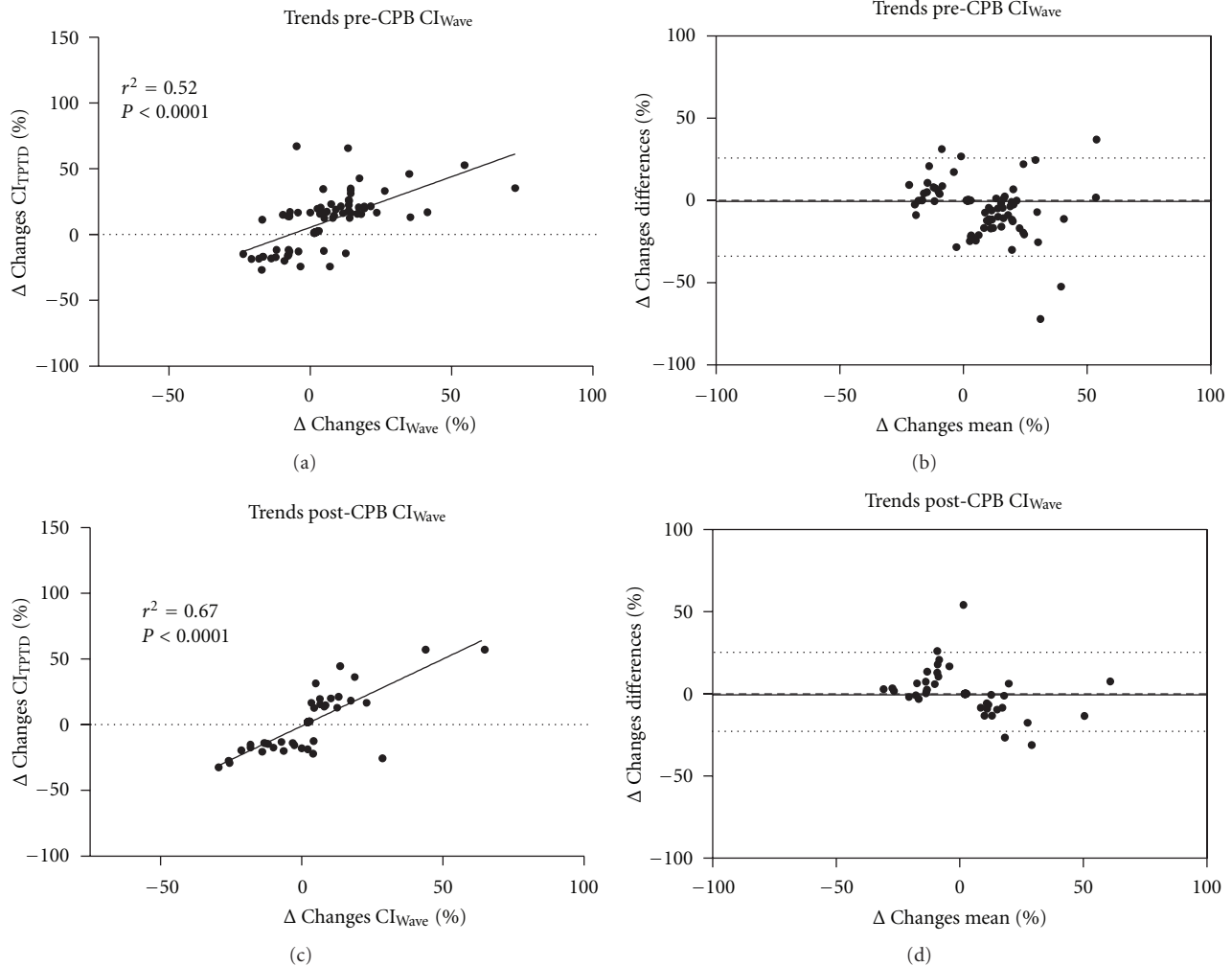


FIGURE 3: Correlation and Bland-Altman analysis of percentage changes in cardiac index measured by transpulmonary thermodilution ( $\Delta CI_{TPTD}$ ) and cardiac index measured by uncalibrated semi-invasive pulse contour analysis ( $\Delta CI_{Wave}$ ) before and after cardiopulmonary bypass (CPB).

### 3. Results

Data of all 50 patients, 37 males and 13 females, were included into final analysis. Age ranged between 40 and 85 years, with a mean age of  $63 \pm 5$  and a mean body mass index of  $26.8 \pm 3.5 \text{ kg} \cdot \text{m}^{-2}$ . Mean left ventricular ejection fraction was  $0.61 \pm 0.07\%$ . A total of 468 data pairs (T1: 245, T2: 223) were obtained during the study period. Haemodynamic variables are shown in Table 1.

There was a significant correlation between  $CI_{Wave}$  and  $CI_{TPTD}$  before (T1) and after (T2) cardiopulmonary bypass (Figure 2). Correlations, bias, LOAs, and percentage errors for each time period (T1-T2) are summarized in Table 2. PLR manoeuvre before CPB (PLR 1) was performed in 47/50 patients and in 42/50 patients after CPB (PLR 2), respectively. Patients who increased their  $SVI_{TPTD} > 15\%$  during PLR were defined as responders. We observed 24 responders during PLR 1 (51%) and 23 responders during

PLR 2 (55%), respectively. There was a significant correlation between  $CI_{Wave}$  and  $CI_{TPTD}$  ( $r^2 = 0.76$ ,  $P < 0.0001$ ) at PLR 1. Correlations and Bland Altman analysis with bias, LOAs, and percentage errors for PLR before (PLR 1) and after (PLR 2) CPB are presented in Table 2.

The percentage changes for  $\Delta CI_{Wave}$  versus  $\Delta CI_{TPTD}$  are presented in Figure 3. Bland-Altman analysis showed a significant correlation for  $\Delta CI_{Wave}$  versus  $\Delta CI_{TPTD}$  in T1, with LOAs from  $-34\%$  to  $+26\%$ . After CPB (T2), correlation coefficients of changes in  $\Delta CI_{Wave}$  versus  $\Delta CI_{TPTD}$  again were statistically significant, with LOAs ranging from  $-23\%$  to  $+25\%$  (Figure 3). There was a significant relationship between  $CI_{Wave}$  and SVRI before ( $CI_{Wave}$ :  $r^2 = 0.27$ ,  $P < 0.0001$ ) and after ( $CI_{Wave}$ :  $r^2 = 0.12$ ,  $P < 0.0001$ ) CPB. No significant correlation between MAP and  $CI_{Wave}$  was observed before ( $CI_{Wave}$ :  $r^2 = 0.003$ ,  $P = 0.42$ ) and after ( $CI_{Wave}$ :  $r^2 < 0.006$ ,  $P = 0.25$ ) CPB. Unpaired  $t$ -test showed a significant difference between SVRI before and after CPB ( $P < 0.05$ ).

TABLE 2: Bland-Altman analysis showing 95% limits of agreement, confidence interval, and percentage error before (T1) and after (T2) cardiopulmonary bypass and during passive leg raising before (PLR 1) and after (PLR 2) bypass.

	T1	T2	PLR 1	PLR 2
$n_{\text{data}}/n_{\text{patient}}$	$n = 245/n = 50$	$n = 223/n = 50$	$n = 132/n = 47$	$n = 123/n = 42$
	CI <sub>Wave</sub>	CI <sub>Wave</sub>	CI <sub>Wave</sub>	CI <sub>Wave</sub>
Mean (L/min/m <sup>2</sup> )	2.38	2.78	2.26	2.76
Bias (L/min/m <sup>2</sup> )	0.01	0.007	0.05	0.03
SD of bias (L/min/m <sup>2</sup> )	0.37	0.35	0.34	0.34
CI of LOA (L/min/m <sup>2</sup> )	0.17	0.16	0.10	0.11
95% limits of agreement (L/min/m <sup>2</sup> )	-0.71 to +0.73	-0.69 to +0.68	-0.63 to +0.72	-0.69 to +0.63
Percentage error (%)	31	25	30	25

CI<sub>Wave</sub>: cardiac index by semi-invasive pulse contour analysis; CI<sub>TPD</sub>: cardiac index by transpulmonary thermodilution; CI of LOA: confidence interval of the limits of agreement; PLR: passive leg raising.

#### 4. Discussion

Main findings of the present study are that the semi-invasive monitoring device was able to reliably measure CI compared with transpulmonary thermodilution before and after CPB. There was a weak but significant correlation between semi-invasive CI by arterial waveform analysis and systemic vascular resistance index. The semi-invasive monitoring system was able to track haemodynamic changes and trends before and after CPB.

The semi-invasive FloTrac/Vigileo-system was developed to continuously determine CI and stroke volume by arterial waveform analysis without the need for calibration. As described elsewhere [11], this system is based on a special software algorithm which calculates CI continuously by analysis of the arterial blood pressure tracing. Before starting the system, patient specific data like age, gender, and body surface area are required. With respect to the three major vascular properties: impedance, compliance, and resistance, determination of cardiac output from arterial waveform analysis is also influenced by the inverse relationship between aortic diameter and pressure [16, 17]. This relationship is reflected in the FloTrac/Vigileo-algorithm by using several variables like demographic data, mean arterial pressure, and shape of the arterial waveform to calculate an essential part of the algorithm: a special equation named chi ( $\chi$ ). With respect to rapid changes in vascular tone, the software version investigated in the present study is able to recalculate  $\chi$  every 60 seconds.

Monitoring of haemodynamic variables is mostly related to invasive procedures, sometimes time-consuming, difficult to establish and associated with method-related complications and limitations, respectively [4]. Therefore, a semi-invasive, quick available, and easy to install method for continuous estimation of haemodynamic variables may be advantageous for the clinician in the decision making process of patients' therapy. Furthermore, besides determination of absolute values of CI, accurate tracking of haemodynamic trends could also be extremely valuable while performing goal-directed therapy. However, sufficient accuracy of a

monitoring system is a prerequisite before use in daily clinical routine. To date, several studies investigated the semi-invasive monitoring device in varying clinical conditions exhibiting equivocal results [12, 14]. We studied the "third-generation" software in patients undergoing elective coronary artery surgery and during a passive leg raising manoeuvre both before and after cardiopulmonary bypass.

Applying the criteria as recommended by Critchley and colleagues [18], we regarded the semi-invasive device as interchangeable with the reference technique if the percentage error did not exceed 30%. Before bypass, the semi-invasive device narrowly missed the strict requirements as recommended by these authors. These limits, however, have been criticized extensively by recent literature due to lack of determination of precision and nonconsideration of haemodynamic trends [19]. In this context, recent literature demonstrated less accuracy of CI by arterial waveform analysis in presence of low vascular resistance [12, 13, 20]. Accordingly, we observed a weak correlation between CI measured by semi-invasive arterial waveform analysis and systemic vascular resistance index both before and after cardiopulmonary bypass. It must be noted, however, that this observation is based on only few data points from a small number of patients. Interestingly, we observed interchangeable results for CI generated by semi-invasive monitoring device and transpulmonary thermodilution especially after cardiopulmonary bypass; a study period typically exhibiting lower values of systemic vascular resistance index. An explanation of these conflicting results may be that in one of the studies cited above patients with septic shock were enrolled, certainly presenting different systemic vascular resistance indices compared to our patients after cardiopulmonary bypass [12]. Furthermore, from a clinical point of view, CI will be higher in presence of lower systemic vascular resistance. These findings will explain the relationship found in our study, especially since we obtained interchangeability between arterial waveform analysis and transpulmonary thermodilution. With respect to other variables influencing vascular tone, several studies

demonstrated failure of arterial waveform analysis in presence of vasoactive agents or high mean arterial pressure [21–23]. Interestingly, we did not observe a relationship between CI by semi-invasive arterial waveform analysis and mean arterial pressure. To investigate the ability of the semi-invasive device for tracking rapid changes in CI even in presence of lower systemic vascular resistance, a passive leg raising manoeuvre was performed both before and after cardiopulmonary bypass. We obtained a significant correlation between CI by arterial waveform analysis and CI by transpulmonary thermodilution during the passive leg raising manoeuvres. During the first manoeuvre, the semi-invasive monitoring system failed by a narrow margin to achieve interchangeability with the reference technique, but after cardiopulmonary bypass accuracy was sufficient. However, beside determination of absolute values of CI, a monitoring system should be able to track haemodynamic trends to reflect therapeutic interventions. Therefore, we calculated trends in CI for both monitoring systems and excluded changes of CI obtained by transpulmonary thermodilution <15% from further analysis as recommended by recent literature [15]. The semi-invasive device showed a good ability for following trends before and after cardiopulmonary bypass.

Some limitations of our study should be noted. We investigated patients with preserved left ventricular function undergoing elective coronary artery surgery without ongoing pharmacologic support, and we excluded patients with haemodynamic instability or in shock. Therefore, our results cannot be directly transferred to patients with impaired left ventricular function or inotropic and vasoactive support.

With respect to clinical relevance, several studies could demonstrate that an individual tailored therapy was associated with reduced perioperative morbidity. Determination of cardiac index continuously is an important target while performing goal-directed therapy.

In conclusion, the present study could demonstrate reliable measurement of cardiac index and haemodynamic trends by semi-invasive arterial waveform analysis in patients undergoing elective coronary surgery and with preserved left ventricular function. Therefore, our results support the use of less invasive haemodynamic monitoring systems.

## Conflict of Interests

No author has a conflict of interests with regard to any device employed in this study.

## Acknowledgments

B. Bein and M. Malbrain are members of the medical advisory board of Pulsion Medical Systems (Munich, Germany) and have received honoraria for consulting and giving lectures. All other authors declare no competing interests. There were no commercial funding sources supporting the submitted study. The authors are indebted to Volkmar Hensel-Bringmann and Bernd Kuhr for excellent technical assistance and logistic support.

## References

- [1] J. Mayer, J. Boldt, A. M. Mengistu, K. D. Röhm, and S. Suttner, "Goal-directed intraoperative therapy based on autocalibrated arterial pressure waveform analysis reduces hospital stay in high-risk surgical patients: a randomized, controlled trial," *Critical Care*, vol. 14, no. 1, article R18, 2010.
- [2] A. Rhodes, M. Cecconi, M. Hamilton et al., "Goal-directed therapy in high-risk surgical patients: a 15-year follow-up study," *Intensive Care Medicine*, vol. 36, no. 8, pp. 1327–1332, 2010.
- [3] O. Jans, C. Tollund, M. Bundgaard-Nielsen, C. Selmer, J. Warberg, and N. H. Secher, "Goal-directed fluid therapy: stroke volume optimisation and cardiac dimensions in supine healthy humans," *Acta Anaesthesiologica Scandinavica*, vol. 52, no. 4, pp. 536–540, 2008.
- [4] A. P. Wheeler, G. R. Bernard, B. T. Thompson et al., "Pulmonary-artery versus central venous catheter to guide treatment of acute lung injury," *The New England Journal of Medicine*, vol. 354, no. 21, pp. 2213–2224, 2006.
- [5] J. D. Sandham, R. D. Hull, R. Frederick Brant et al., "A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients," *The New England Journal of Medicine*, vol. 348, no. 1, pp. 5–14, 2003.
- [6] C. Richard, J. Warszawski, N. Anguel et al., "Early use of the pulmonary artery catheter and outcomes in patients with shock and acute respiratory distress syndrome: a randomized controlled trial," *Journal of the American Medical Association*, vol. 290, no. 20, pp. 2713–2720, 2003.
- [7] M. Sander, C. D. Spies, H. Grubitzsch, A. Foer, M. Müller, and C. von Heymann, "Comparison of uncalibrated arterial waveform analysis in cardiac surgery patients with thermodilution cardiac output measurements," *Critical Care*, vol. 10, no. 6, article R164, 2006.
- [8] S. Friessecke, A. Heinrich, P. Abel, and S. B. Felix, "Comparison of pulmonary artery and aortic transpulmonary thermodilution for monitoring of cardiac output in patients with severe heart failure: validation of a novel method," *Critical Care Medicine*, vol. 37, no. 1, pp. 119–123, 2009.
- [9] S. Ritter, A. Rudiger, and M. Maggiorini, "Transpulmonary thermodilution-derived cardiac function index identifies cardiac dysfunction in acute heart failure and septic patients: an observational study," *Critical Care*, vol. 13, no. 4, article R133, 2009.
- [10] B. Pratt, L. Roteliuk, F. Hatib, J. Frazier, and R. D. Wallen, "Calculating arterial pressure-based cardiac output using a novel measurement and analysis method," *Biomedical Instrumentation and Technology*, vol. 41, no. 5, pp. 403–411, 2007.
- [11] B. Hashim and A. B. Lerner, "The FloTrac system-measurement of stroke volume and the assessment of dynamic fluid loading," *International Anesthesiology Clinics*, vol. 48, no. 1, pp. 45–56, 2010.
- [12] X. Monnet, N. Anguel, B. Naudin, J. Jabot, C. Richard, and J. L. Teboul, "Arterial pressure-based cardiac output in septic patients: different accuracy of pulse contour and uncalibrated pressure waveform devices," *Critical Care*, vol. 14, no. 3, article R109, 2010.
- [13] S. G. Sakka, J. Kozieras, O. Thuemer, and N. van Hout, "Measurement of cardiac output: a comparison between transpulmonary thermodilution and uncalibrated pulse contour analysis," *British Journal of Anaesthesia*, vol. 99, no. 3, pp. 337–342, 2007.

- [14] D. De Backer, G. Marx, A. Tan et al., "Arterial pressure-based cardiac output monitoring: a multicenter validation of the third-generation software in septic patients," *Intensive Care Medicine*, vol. 37, no. 2, pp. 233–240, 2011.
- [15] L. A. Critchley, A. Lee, and A. M. H. Ho, "A critical review of the ability of continuous cardiac output monitors to measure trends in cardiac output," *Anesthesia and Analgesia*, vol. 111, no. 5, pp. 1180–1192, 2010.
- [16] N. Winer, J. R. Sowers, and M. A. Weber, "Gender differences in vascular compliance in young, healthy subjects assessed by pulse contour analysis," *Journal of Clinical Hypertension*, vol. 3, no. 3, pp. 145–152, 2001.
- [17] G. J. Langewouters, K. H. Wesseling, and W. J. A. Goedhard, "The pressure dependent dynamic elasticity of 35 thoracic and 16 abdominal human aortas in vitro described by a five component model," *Journal of Biomechanics*, vol. 18, no. 8, pp. 613–620, 1985.
- [18] L. A. H. Critchley and J. A. J. H. Critchley, "A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques," *Journal of Clinical Monitoring and Computing*, vol. 15, no. 2, pp. 85–91, 1999.
- [19] P. Squara, M. Cecconi, A. Rhodes, M. Singer, and J. D. Chiche, "Tracking changes in cardiac output: methodological considerations for the validation of monitoring devices," *Intensive Care Medicine*, vol. 35, no. 10, pp. 1801–1808, 2009.
- [20] K. Yamashita, T. Nishiyama, T. Yokoyama, H. Abe, and M. Manabe, "The effects of vasodilation on cardiac output measured by PiCCO," *Journal of Cardiothoracic and Vascular Anesthesia*, vol. 22, no. 5, pp. 688–692, 2008.
- [21] O. Hamzaoui, X. Monnet, C. Richard, D. Osman, D. Chemla, and J. L. Teboul, "Effects of changes in vascular tone on the agreement between pulse contour and transpulmonary thermodilution cardiac output measurements within an up to 6-hour calibration-free period," *Critical Care Medicine*, vol. 36, no. 2, pp. 434–440, 2008.
- [22] B. Bein, P. Meybohm, E. Cavus et al., "The reliability of pulse contour-derived cardiac output during hemorrhage and after vasopressor administration," *Anesthesia and Analgesia*, vol. 105, no. 1, pp. 107–113, 2007.
- [23] S. Eleftheriadis, Z. Galatoudis, V. Didilis et al., "Variations in arterial blood pressure are associated with parallel changes in FlowTrac/Vigileo-derived cardiac output measurements: a prospective comparison study," *Critical Care*, vol. 13, no. 6, p. R179, 2009.