

Continuous cardiac output measurement: arterial pressure analysis versus thermodilution technique during cardiac surgery with cardiopulmonary bypass

S. Lorsomradee,¹ S. R. Lorsomradee,¹ S. Cromheecke² and S. G. De Hert³

1 Consultant Anaesthetist, Department of Anaesthesia, Chiangmai University Hospital, Thailand

2 Consultant Anaesthetist, 3 Professor of Anaesthetics and Vice Chair, Department of Anaesthesia, University Hospital Antwerp, B-2650 Edegem, Belgium

Summary

This study compared cardiac output measured with an arterial pressure-based cardiac output measurement system and a thermodilution cardiac output measurement system. We studied 36 patients undergoing cardiac surgery with cardiopulmonary bypass. Simultaneous arterial pressure-based and thermodilution cardiac output measurements were compared before and after cardiopulmonary bypass, and after phenylephrine administration. Bland-Altman analysis showed good overall agreement between the two methods. Bias (limits of agreement) before and after cardiopulmonary bypass were -0.21 (-2.97 – 2.55) $\text{l}\cdot\text{min}^{-1}$ and 0.01 (-3.79 – 3.81) $\text{l}\cdot\text{min}^{-1}$, respectively. Phenylephrine administration decreased thermodilution cardiac output by a mean (SD) of 11 (16)% and increased arterial pressure-based cardiac output by 55 (34)%. We conclude that arterial pressure-based cardiac output and thermodilution cardiac output measurement systems yield comparable results during cardiac surgery with cardiopulmonary bypass. However, after phenylephrine administration, the two measurement systems provided opposing results.

Correspondence to: Professor S. G. De Hert

E-mail: stefan.dehert@ua.ac.be stefan.de.hert@uza.be

Accepted: 11 February 2007

Continuous measurement of cardiac output is routinely used to monitor changes in cardiovascular function in critically ill patients. Continuous measurement of cardiac output (CCO) using a thermodilution technique generating thermal pulses from a heating filament attached to a pulmonary artery catheter produces a clinically acceptable level of accuracy when compared with the gold standard intermittent bolus technique [1–3]. A new, less invasive method for arterial pressure-based continuous cardiac output (APCO) measurement, using a technique involving determination of the area under the arterial pressure curve, requires only standard radial artery catheterisation and does not necessitate central venous access or injection of a dilution medium for calibration [4]. Comparative studies of these techniques in different patient populations during and after surgery showed the prototype APCO to be comparable to intermittent bolus and continuous thermodilution cardiac output [5–7]. However, it is unclear whether APCO is accurate and reliable after

significant haemodynamic changes such as those that occur after cardiopulmonary bypass (CPB) or vasoconstrictor administration. We hypothesised that the increase in the area under the arterial pressure curve induced by vasoconstrictor administration might interfere with the agreement between APCO and CCO. To address these questions, we compared APCO and CCO values before and after phenylephrine administration during cardiac surgery with CPB.

Methods

The study was approved by the institutional ethical committee and written, informed consent was obtained from all subjects. Thirty-six patients undergoing elective cardiac surgery with CPB were studied prospectively. Exclusion criteria included patients with significant valvular regurgitation or cardiac rhythm disturbances, intra-aortic balloon pumps, intracardiac shunts, aneurysmal

deformities of the aorta or symptomatic peripheral vascular disease. All patients were given sublingual lorazepam 2.5 mg 90 min before surgery and intramuscular fentanyl $1 \mu\text{g}\cdot\text{kg}^{-1}$ and droperidol $50 \mu\text{g}\cdot\text{kg}^{-1}$ 60 min before surgery. Routine monitoring was started in the operating theatre: five-lead ECG, radial arterial pressure, pulse oximetry, capnography and both blood and bladder temperature monitoring. Anaesthesia was conducted according to institutional standards with sevoflurane, remifentanyl and cisatracurium. In all patients, anaesthesia was induced by mask with sevoflurane and a continuous intravenous infusion of remifentanyl at $0.2\text{--}0.4 \mu\text{g}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, which was continued and to which was added inhaled sevoflurane at an end-tidal concentration of $0.5\text{--}2.0\%$. Muscle relaxation was initiated with a cisatracurium $0.15 \text{ mg}\cdot\text{kg}^{-1}$ bolus followed by top-up doses of $0.03 \text{ mg}\cdot\text{kg}^{-1}$ every 40–60 min. After induction of anaesthesia, a pulmonary artery catheter (Swan Ganz CCO/VIP; Edwards Lifesciences LLC, Irvine, CA, USA) was placed into the right internal jugular vein and was connected to a monitor (Baxter Vigilance monitor, Edwards Lifesciences LLC) for measurement of CCO. The methodology of the CCO measurement, based on the pulsed warm thermodilution technique, has been described previously [8] and involves the release of small pulses of heat from a thermal coil mounted on the pulmonary artery catheter at the level of the right ventricle. To reflect sudden changes in CCO, the Vigilance monitor was set in the STAT-mode, which has been shown to provide accurate measurement of CCO [9, 10]. The CCO is computed from the area under the thermodilution curve and the displayed CCO is updated every 30–60 s.

Radial arterial blood pressure was monitored using a 20G, 48-mm-long catheter (BD Insyte, Becton Dickinson, Madrid, Spain) that was attached to a sensor. This sensor (FloTrac, Edwards Lifesciences LLC) has a bifurcated cable with one limb going to the bedside monitor to display arterial blood pressures and the other going to the Vigileo (software version 1.01; Edwards Lifesciences LLC, Irvine, CA, USA) monitor to analyse data for the APCO. The APCO is based on the assessment of arterial pulse waveform and pulse pressure. Pulse pressure is proportional to stroke volume. The stroke volume is calculated by multiplying the standard deviation of the pulse pressure against a value Chi (χ), which is adjusted for differences in vascular compliance and resistance, and patient-to-patient differences. Pulse rate is derived from the arterial pressure signal. Cardiac output is calculated by multiplying heart rate and stroke volume. Variations in the arterial pressure waveform are measured at a sampling rate of 100 Hz over a 20-s period, which provides approximately 2000 data points. Estimates of the APCO values are calculated and updated at 20-s intervals [11].

Global haemodynamic data, CCO and APCO were recorded simultaneously at the following time points: before skin incision (control), before the start of CPB (pre-CPB), 15 min after weaning from CPB (post-CPB) [12], and at the end of surgery. After median sternotomy and a stabilisation period of 10 min, the effect of phenylephrine administration was studied. Baseline CCO and APCO were recorded simultaneously before phenylephrine administration. Then, an intravenous bolus of phenylephrine $2\text{--}5 \mu\text{g}\cdot\text{kg}^{-1}$ was given [13]. After phenylephrine administration, when the systolic arterial pressure had increased up to 30% above baseline values, simultaneous CCO and APCO were recorded again.

Standardised surgical techniques and cardioprotective strategies were used in all patients and have been described in detail [14]. After the surgical procedure, the heart was paced in atrioventricular sequential mode at a rate of $90 \text{ beats}\cdot\text{min}^{-1}$ and the patients were weaned from CPB. In this study, filling pressures were kept constant (mean central venous pressure $>10 \text{ mmHg}$ and pulmonary capillary wedge pressure $>12 \text{ mmHg}$) throughout the entire observation period with the administration of intravenous fluids (crystalloids and hydroxyethyl starch). Hypotension (mean arterial blood pressure $<60 \text{ mmHg}$) was treated with inotropes and vasoactive drugs (phenylephrine, dobutamine, noradrenaline and milrinone) according to protocols already described [14]. All data were collected by trained observers who did not participate in patient care.

Statistical analysis was performed using the SIGMASTAT 2.03 software package (SPSS, Leuven, Belgium). All data were tested for normal distribution. Differences between data sets were compared against control using one-way analysis of variance. Effects before and after phenylephrine administration were compared using a paired *t*-test. Agreement between the two different methods of measuring cardiac output was assessed with the Bland-Altman analysis [15], using the GRAPHPAD software (version Prism 4) (GraphPad Software Inc, San Diego, CA, USA). Data are expressed as mean (SD). Statistical significance was set at $p < 0.05$.

Results

Patient characteristics and surgical data are given in Table 1. Surgery was uneventful in all patients. In 36 patients, a total of 900 pairs of simultaneous cardiac output measurements were recorded. Figure 1 shows the Bland-Altman plots comparing CCO to APCO for all measurements. The bias and the 95% limits of agreement were $0.12 \text{ l}\cdot\text{min}^{-1}$ and $-3.25\text{--}3.49 \text{ l}\cdot\text{min}^{-1}$. Figure 2 shows the Bland-Altman plots of CCO and APCO

Table 1 Patient characteristics and surgical data. Values are number, mean (SD) or median [range].

Age; years	67 [47–82]
Sex ratio; M : F	27 : 9
Body mass index; kg.m ⁻²	26.6 [18.9–36.9]
Left ventricular ejection fraction; %	62 [43–78]
Medical history	
Chronic obstructive pulmonary disease	9 (25%)
Insulin dependent diabetes mellitus	0 (0%)
Non-insulin dependent diabetes mellitus	10 (27.8%)
Intercurrent medication	
Beta-blocker	18 (50%)
Calcium channel blocker	8 (22.2%)
Angiotensin converting enzyme inhibitors	11 (30.6%)
Nitrates	7 (19.4%)
Diuretics	10 (27.7%)
Aspirin	21 (58.3%)
Oral antidiabetic drugs	8 (22.2%)
Insulin	3 (8.3%)
Surgical data	
Aortic clamp time; min	45 (23)
Duration of cardiopulmonary bypass; min	91 (22)

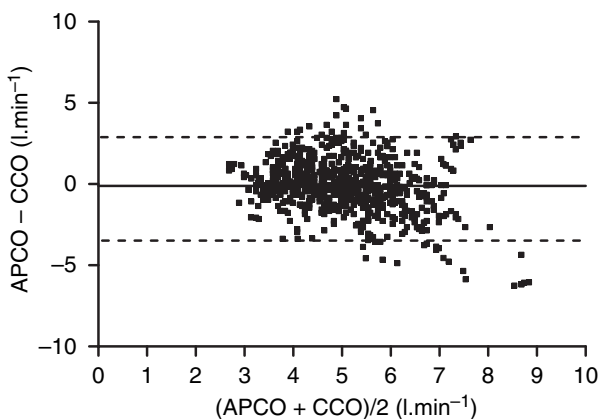


Figure 1 Bland-Altman plots comparing continuous thermodilution cardiac output (CCO) with arterial pressure-based continuous cardiac output (APCO) for all measurements. The solid line indicates the mean bias and the dotted lines represent the limits of agreement.

before and after CPB. The bias and the 95% limits of agreement before CPB were -0.21 l.min^{-1} and -2.97 – 2.55 l.min^{-1} , and after CPB were 0.01 l.min^{-1} and -3.79 – 3.81 l.min^{-1} , respectively. Haemodynamic variables during the study period are summarised in Table 2.

Figure 3 shows CCO and APCO for each subject before and after phenylephrine administration. The CCO decreased, whereas APCO increased, after phenylephrine was given. Mean (SD) CCO was $4.8 (1.3) \text{ l.min}^{-1}$ before phenylephrine administration and significantly decreased to $3.9 (0.9) \text{ l.min}^{-1}$ after phenylephrine administration ($p < 0.001$), whereas the mean (SD) APCO significantly

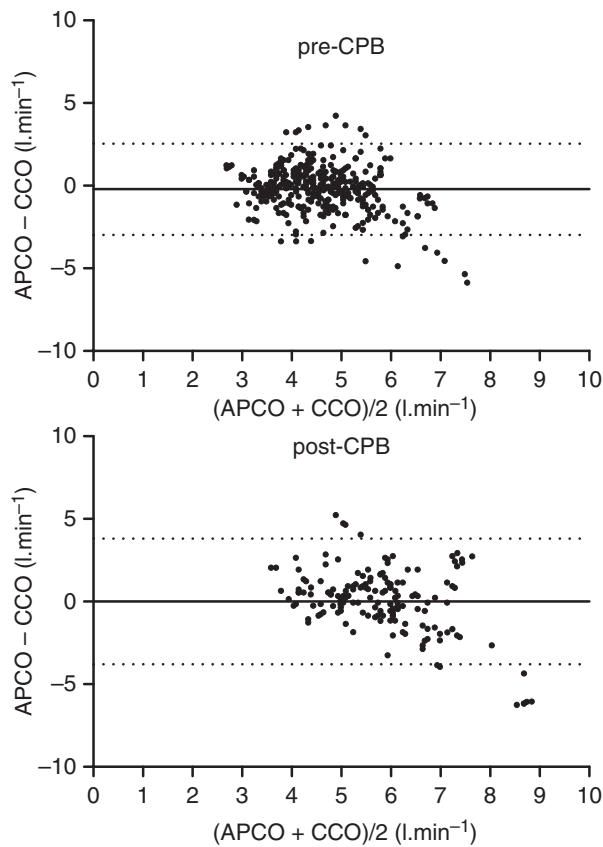


Figure 2 Bland-Altman plots comparing continuous thermodilution cardiac output (CCO) with arterial pressure-based continuous cardiac output (APCO) before and after cardiopulmonary bypass (CPB). The solid line indicates the mean bias and the dotted lines represent the limits of agreement.

increased from $4.0 (0.9) \text{ l.min}^{-1}$ before to $6.0 (1.3) \text{ l.min}^{-1}$ after phenylephrine administration ($p < 0.001$) (Table 3).

Discussion

This findings of this study indicate that APCO and CCO overall yield comparable results during cardiac surgery with CPB. However, after phenylephrine administration, the two methods of measurement showed changes in opposite directions.

The APCO and CCO provided similar results at all time points during the study period. This finding contrasts to observations obtained with another method of arterial pulse contour analysis of cardiac output, which provided an underestimate and required recalibration [16]. The reliability of APCO using the Vigileo system during the profound haemodynamic changes associated with weaning from CPB makes it practical for clinical use in cardiac anaesthesia.

	Before incision (n = 36)	Before CPB (n = 36)	15 min after CPB (n = 36)	At the end of surgery (n = 36)
Heart rate; beats.min ⁻¹	66 (12)	70 (13)	92 (5)*	92 (6)*
Mean arterial pressure; mmHg	69 (8)	67 (7)	72 (7)	73 (7)
Central venous pressure; mmHg	12 (3)	12 (3)	13 (3)	14 (3)
CCO; l.min ⁻¹	4.6 (1.4)	4.6 (1.2)	5.8 (1.9)*	5.9 (1.3)*
APCO; l.min ⁻¹	4.8 (1.4)	4.7 (0.9)	5.7 (1.0)*	5.4 (1.1)*
Thermodilution-based stroke volume; ml.beat ⁻¹	72 (21)	67 (19)	64 (21)*	64 (15)*
Arterial pressure-based stroke volume; ml.beat ⁻¹	73 (22)	67 (17)	61 (11)*	58 (12)*
Core temperature; °C	36.3 (0.4)	36.1 (0.4)	36.2 (0.5)	36.2 (0.5)

Table 2 Haemodynamic data. Values are mean (SD).

CCO, continuous thermodilution cardiac output; APCO, arterial pressure-based continuous cardiac output; CPB, cardiopulmonary bypass; SV, stroke volume.

*Significantly different from 'Before incision' values, $p < 0.05$.

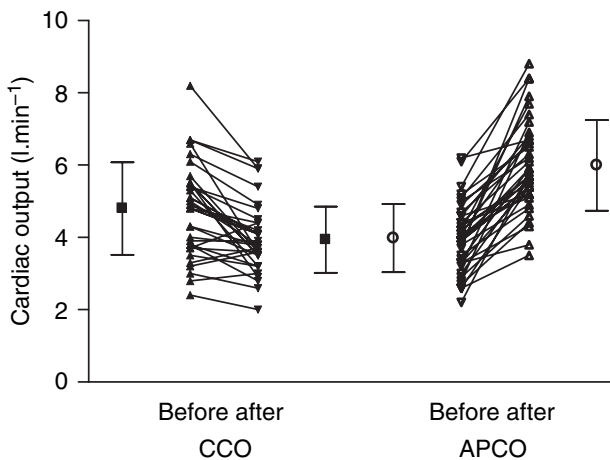


Figure 3 Individual changes in continuous thermodilution cardiac output (CCO) and arterial pressure-based continuous cardiac output (APCO) before and after phenylephrine administration. The points with error bars represent the mean (SD) values of continuous thermodilution cardiac output (CCO) (■) and arterial pressure-based continuous cardiac output (APCO) (○) before and after phenylephrine administration.

The fact that no additional invasive lines are necessary for its calibration, as is the case for other methods of APCO measurement, makes the Vigileo system a simple and less invasive tool for cardiac output measurement [17–19]. These features may contribute to the extension of cardiac output monitoring to patients who currently are not monitored with a pulmonary artery catheter during surgery.

Phenylephrine is a direct α_1 adrenoceptor agonist. Its primary effects are peripheral vasoconstriction with a concomitant increase in systemic vascular resistance and arterial blood pressure, and a slight decrease in cardiac output [20]. In the present study, phenylephrine admin-

Table 3 Haemodynamic effects of phenylephrine administration. Value are mean (SD).

	Before phenylephrine (n = 36)	After phenylephrine (n = 36)	p values
Heart rate; beats.min ⁻¹	69 (13)	69 (14)	0.883
Mean arterial pressure; mmHg	65 (6)	84 (7)	< 0.001*
Central venous pressure; mmHg	13 (3)	13 (4)	0.432
CCO; l.min ⁻¹	4.8 (1.3)	3.9 (0.9)	< 0.001*
APCO; l.min ⁻¹	4.0 (0.9)	6.0 (1.3)	< 0.001*
Thermodilution-based stroke volume; ml.beat ⁻¹	71 (18)	62 (20)	0.002*
Arterial pressure-based stroke volume; ml.beat ⁻¹	60 (18)	86 (21)	< 0.001*
Temperature; °C	36.2 (0.5)	36.1 (0.5)	0.169

CCO, continuous thermodilution cardiac output; APCO, arterial pressure-based continuous cardiac output.

*Significantly different from 'before phenylephrine' values, $p < 0.05$.

istration increased mean arterial pressure and decreased CCO as expected. However, APCO values increased. This is probably related to the fact that phenylephrine increased the area under the arterial pressure curve, hence increasing the APCO. A similar phenomenon has been reported with other systems using pulse contour analysis [21, 22]. The increase in the APCO may also occur in other situations in which systemic vascular resistance is increased, e.g. after median sternotomy [23].

In conclusion, the results of this study show that continuous cardiac output measurement with an arterial pressure-based method using the Vigileo system and a thermodilution-based method give comparable results for cardiac output measurement during cardiac surgery with CPB. However, during periods of vasoconstriction, APCO may become less reliable.

References

- 1 Lefrant JY, Bruelle P, Ripart J, et al. Cardiac output measurement in critically ill patients: comparison of continuous and conventional thermodilution technique. *Canadian Journal of Anaesthesia* 1995; **42**: 972–6.
- 2 Jacquet L, Hanique G, Glorieux D, Matte P, Goenen M. Analysis of the accuracy of continuous thermodilution cardiac output measurement. *Intensive Care Medicine* 1996; **22**: 1125–9.
- 3 Rodig G, Keyl C, Liebold A, Hobbhahn J. Intra-operative evaluation of a continuous versus intermittent bolus thermodilution technique of cardiac output measurement in cardiac surgical patients. *European Journal of Anaesthesiology* 1998; **15**: 196–201.
- 4 Manecke GR. Edwards FloTrac sensor and Vigileo monitor: easy, accurate, reliable cardiac output assessment using the arterial pulse wave. *Expert Review of Medical Devices* 2005; **2**: 523–7.
- 5 Manecke GR, Peterson M, Auger WR. Cardiac output determination using arterial pulse: a comparison of a novel algorithm against continuous and intermittent thermodilution. *Critical Care Medicine* 2004; **32**: A43.
- 6 McGee WT, Horswell J, Janvier G. Validation of a continuous cardiac output measurement using arterial pressure waveforms. *Critical Care* 2005; **9**: A62.
- 7 Horswell J, Worley T. Continuous cardiac output measured by arterial pressure analysis in surgical patients. *Anesthesiology* 2005; **103**: A834.
- 8 Yelderian M, Quinn MD, McKown RC. Thermal safety of a filamented pulmonary artery catheter. *Journal of Clinical Monitoring* 1992; **8**: 147–9.
- 9 Lazor MA, Pierce ET, Stanley GD, Cass JL, Halpern EF, Bode RH Jr. Evaluation of the accuracy and response time of STAT-mode continuous cardiac output. *Journal of Cardiothoracic and Vascular Anesthesia* 1997; **11**: 432–6.
- 10 Singh A, Juneja R, Mehta Y, Trehan N. Comparison of continuous, stat, and intermittent cardiac output measurement in patients undergoing minimally invasive direct coronary arterial bypass surgery. *Journal of Cardiothoracic and Vascular Anesthesia* 2002; **16**: 186–90.
- 11 Headley JM. Arterial pressure-based technologies: a new trend in cardiac output monitoring. *Critical Care Nursing Clinics of North America* 2006; **18**: 179–87.
- 12 De Hert SG, Rodrigus IE, Haenen LR, et al. Recovery of systolic and diastolic left ventricular function early after cardiopulmonary bypass. *Anesthesiology* 1996; **85**: 1063–75.
- 13 De Hert SG, Gillebert TC, ten Broecke PW, Moulijn AC. Length-dependent regulation of left ventricular function in coronary surgery patients. *Anesthesiology* 1999; **91**: 379–87.
- 14 De Hert SG, Van der Linden PJ, Cromheecke S, et al. Choice of primary anesthetic regimen can influence intensive care unit length of stay after coronary surgery with cardiopulmonary bypass. *Anesthesiology* 2004; **101**: 9–20.
- 15 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; **i**: 307–10.
- 16 Sander M, von Heymann C, Foer A, et al. Pulse contour analysis after normothermic cardiopulmonary bypass in cardiac surgery patients. *Critical Care* 2005; **9**: 729–34.
- 17 Jonas MM, Tanser SJ. Lithium dilution measurement of cardiac output and arterial waveform analysis: as indicator dilution calibrated beat-by-beat system for continuous estimation of cardiac output. *Current Opinion in Critical Care* 2002; **8**: 257–61.
- 18 Orme RM, Pigott DW, Mihm FG. Measurement of cardiac output by transpulmonary arterial thermodilution using a long radial artery catheter. A comparison with intermittent pulmonary artery thermodilution. *Anaesthesia* 2004; **59**: 590–4.
- 19 de Wilde RB, Breukers RB, van den Berg PC, Jansen JR. Monitoring cardiac output using the femoral and radial arterial pressure waveform. *Anaesthesia* 2006; **61**: 743–6.
- 20 Estafanous FG, Barash PG, Reves JG. *Cardiac Anesthesia. Principles and Clinical Practice*, 2nd edn. Philadelphia: Lippincott, Williams & Wilkins, 2001.
- 21 Berberian G, Quinn TA, Vigilance DW, et al. Validation study of PulseCO system for continuous cardiac output measurement. *ASAIO Journal* 2005; **51**: 37–40.
- 22 Pittman J, Bar-Yosef S, SumPing J, Sherwood M, Mark J. Continuous cardiac output monitoring with pulse contour analysis: a comparison with lithium indicator dilution cardiac output measurement. *Critical Care Medicine* 2005; **33**: 2015–21.
- 23 Felbinger TW, Goepfert MS, Goresch T, Goetz AE, Reuter DA. Accuracy of pulse contour cardiac index measurements during changes of preload and aortic impedance. *Der Anaesthesist* 2005; **54**: 755–62.