Intensive Care Med (1996) 22:312–318

ORIGINAL

B. W. Böttiger
M. Soder
H. Rauch
H. Böhrer
J. Motsch
H. Bauer
E. Martin

Semi-continuous versus injectate cardiac output measurement in intensive care patients after cardiac surgery

Received: 4 May 1994
Accepted: 22 May 1995

B. W. Böttiger (✉) · M. Soder
H. Rauch · H. Böhrer · J. Motsch
H. Bauer · E. Martin
Department of Anaesthesiology,
University of Heidelberg,
Im Neuenheimer Feld 110,
D-69120 Heidelberg, Germany

Abstract *Objective:* Commercially available semi-continuous cardiac output (SCCO) monitoring systems are based on the pulsed warm thermodilution technique. There is evidence that SCCO fails to correlate with standard intermittent bolus cardiac output (ICO) in clinical situations with thermal instability in the pulmonary artery. Furthermore, ventilation may potentially influence thermodilution measurements by enhanced respiratory variations in pulmonary artery blood temperature and by cyclic changes in venous return. Therefore, we evaluated the correlation, accuracy and precision of SCCO versus ICO measurements before and after extubation.
Design: Prospective cohort study.
Setting: Intensive care unit (ICU) of a university hospital.
Patients and participants: 22 cardiac surgical ICU patients.
Interventions: None.
Measurements and results: SCCO and ICO data were obtained at nine postoperative time points while the patients were on controlled mechanical ventilation. Further sets of measurements were taken during the weaning phase 20 min before extubation, and 5 min, 20 min and 1 h after extubation. SCCO and ICO measurements yielded 286 data pairs with a range of 1.8–9.9 l/min for SCCO and 1.9–9.8 l/min for ICO. The correlation between SCCO and ICO was highly significant ($r = 0.92$; $p < 0.01$), accompanied by a bias of −0.052 l/min and a precision of 0.56 l/min. Correlation, accuracy and precision were not influenced by the mode of respiration.
Conclusions: Our results demonstrate excellent correlation, accuracy and precision between SCCO and ICO measurements in postoperative cardiac surgical ICU patients. We conclude that SCCO monitoring offers a reliable clinical method of cardiac output monitoring in ICU patients following cardiac surgery.

Key words Thermodilution cardiac output · Continuous monitoring · Postoperative intensive care · Extubation

Introduction

Monitoring of blood pressure, heart rate, peripheral oxygen saturation, mixed venous oxygen saturation, central venous pressure, pulmonary artery pressure, temperature and cardiac output is considered essential when assessing critically ill patients. Most of these parameters are monitored continuously. In contrast, cardiac output data are generally obtained by the intermittent manual bolus thermodilution technique. Data gathering using this approach may be time-consuming and will result in sporadic values. Furthermore, standard intermittent bolus thermodilution cardiac output (ICO) measurements are ac-

companied by the risk of bacterial contamination via fluid administration [1], by the risk of fluid overload in fluid-sensitive patients, and by several specific user-induced errors [2, 3].

Several approaches to semi-continuous or continuous measurement of cardiac output have been evaluated in the last decade, such as the computerized Fick method [4], transoesophageal or transtracheal Doppler ultrasound [5, 6], peripheral arterial waveform pulse contour analysis [7], transthoracic or transoesophageal bioimpedance techniques [8, 9], intravascular ultrasound [10], wire anemometer, neural networks based on phonocardiograms and "injectless" cold thermodilution techniques [11]. Some of these techniques have been developed for clinical use in critically ill patients [9], but most have failed for technical or economical reasons. The continuous pulsed warm thermodilution technique seems to be clinically feasible. With this device, a safe level [12, 13] of heat is transferred to the blood by a computer-controlled thermal filament mounted on a modified standard Swan-Ganz catheter (IntelliCath, Baxter Healthcare, Irvine, Calif.). In order to obtain immunity to the natural temperature variations in the pulmonary artery, which is considered the background "thermal noise", heat is transferred to the blood in a pseudo-random on-off fashion [13, 14]. The resulting changes in pulmonary artery temperature are recorded by the distal rapid-response thermistor in the pulmonary artery. Without user calibration, the accompanying software system (Vigilance, Baxter Healthcare, Irvine, Calif.) automatically computes a cross-correlation between the filament input sequence, the power and the distal thermistor response to blood warming [14]. From this cross-correlation, the cardiac output is calculated using a modified Stewart-Hamilton equation [14, 15], and this measurement is updated every 30 s. The value displayed on the monitor screen reflects an average of continuous cardiac output (SCCO) measurements from the previous 3–6 min [15]. Therefore, some authors have characterized SCCO as a semi-continuous technique and not as a strictly continuous technique [16]. In addition, traditional ICO data may be obtained through the same equipment using standard procedures and equations.

Under stable patient conditions, good correlation, accuracy and precision between SCCO and ICO measurements have been reported [16–18], which is in accordance with experiments in several animal models [19, 20]. However, these two methods fail to correlate in the early phase after weaning from hypothermic extracorporeal circulation [21], possibly because of systematic errors in thermodilution cardiac output based on increased thermal instability in the pulmonary artery blood temperature ($Temp_{PA}$) during this phase [21–23]. Cyclic variations in $Temp_{PA}$ and cyclic changes in venous return associated with respiration are well-known sources of error in thermodilution cardiac output measurements, because both effects may violate the assumptions made for thermodilution cardiac output algorithms [22, 24, 25]. We therefore evaluated the correlation, accuracy and precision of SCCO monitoring versus the clinical "gold standard" [2, 26] ICO technique in postoperative cardiac surgical patients.

Materials and methods

After institutional approval and informed consent, 22 patients following coronary revascularization were studied according to the principles established in Helsinki. Proper positioning of each pulmonary artery catheter (PAC), which was inserted preoperatively, was confirmed by routine chest X-ray immediately following admission to the intensive care unit (ICU) and by continuous on-line monitoring of the pulmonary artery pressure curve. Standard ICO measurements were performed by injection of ice-cold saline solution (10 ml) through a closed-delivery system (Co-Set, Baxter Healthcare, Irvine, Calif.) at end-expiration, with <4 s injection times. With each injection, the morphology of the resulting thermodilution curve was visualized on the SCCO/ICO monitoring system and inspected for accuracy to exclude artefacts. The reported ICO values represent the average of three measurements, which were all within 10% of each other. SCCO was obtained from the mean of two SCCO measurements immediately before and after measuring ICO. The computer constant of the Vigilance System (software version 3/84) was chosen according to the manufacturer's recommendations.

SCCO and ICO data pairs were obtained 15 min after arrival in the ICU (T_1) and 30 min (T_2), 1 h (T_3), 2 h (T_4), 3 h (T_5), 5 h (T_6), 7 h (T_7), 9 h (T_8) and 11 h (T_9) following T_1. Further sets of measurements were taken 20 min before extubation of the patient's trachea during the P-piece trial (T_{10}), and 5 min (T_{11}), 20 min (T_{12}), and 1 h (T_{13}) after extubation of the trachea. The central blood temperature in the pulmonary artery ($Temp_{PA}$; PAC tip) and the rectal temperature ($Temp_{Rec}$) (Servomed, Hellige, Freiburg, Germany) were determined and recorded at all time points. Patients were sedated postoperatively via continuous infusion of propofol and intermittent bolus administration of opioids until 60 min before the estimated extubation time. Muscle relaxants were not administered during the entire ICU stay. The patients' lungs were mechanically ventilated using intermittent positive pressure ventilation (Servo 900C, Siemens Elema, Solna, Sweden) avoiding positive end-expiratory pressure. The respiratory rate was adjusted to 10 breaths/min assuring a $PaCO_2$ of 35–40 mmHg. The patients were disconnected from the ventilator 30 min before extubation and allowed to breathe spontaneously via the oral endotracheal tube (T-piece trial). The patient's trachea was usually extubated 30 min later, and additional oxygen was administered via a nasal tube during the entire study period. The general treatment of the patients was carried out by independent ICU physicians who were not involved in any study procedures. Electrocautery, rapid volume infusions or infusions via the side arm of the introducer, which are all known as sources of potential errors in thermodilution cardiac output determination [25, 27, 28], were avoided during the measurements.

The statistical analysis was performed using linear regression for the data pairs and Pearson's correlation coefficient, including bias and precision, for each time point according to the recommendations of Bland and Altman [29]. Bias was calculated as the mean difference between ICO and SCCO. Precision represents the standard deviation (SD) of the average of the biases [29]. $P<0.05$ was considered statistically significant. The data are presented as mean ± SD. The data in Fig. 2 are mean ± standard error of the mean (SEM).

Table 1 Correlation, bias and precision between intermittent standard cardiac output and semi-continuous cardiac output measurements. The correlation between intermittent standard bolus thermodilution cardiac output and semi-continuous cardiac output was highly significant ($r = 0.92$; $P < 0.01$), accompanied by an excellent bias of −0.052 l/min, and a precision of 0.56 l/min for all data pairs. The accuracy of SCCO did not change significantly within the entire study period

Time point		Correlation r	Bias (l/min)	Precision (l/min)
T_1	15 min after arrival in the ICU	0.81	−0.109	0.716
T_2	30 min after T_1	0.93	−0.077	0.469
T_3	1 h after T_1	0.91	0.091	0.488
T_4	2 h after T_1	0.90	−0.014	0.552
T_5	3 h after T_1	0.89	0.132	0.721
T_6	5 h after T_1	0.95	−0.023	0.541
T_7	7 h after T_1	0.96	0.085	0.493
T_8	9 h after T_1	0.92	0.018	0.624
T_9	11 h after T_1	0.97	−0.164	0.391
T_{10}	20 min before extubation	0.93	0.027	0.521
T_{11}	5 min after extubation	0.93	−0.186	0.643
T_{12}	20 min after extubation	0.92	−0.186	0.618
T_{13}	1 h after extubation	0.94	−0.195	0.538

Results

The patients' ages ranged from 49 to 73 years (61 ± 7 years) and their weights from 54 to 91 kg (74 ± 10 kg). SCCO and ICO measurements yielded 286 data pairs with a range of 1.8–9.9 l/min for SCCO and 1.9–9.8 l/min for ICO. All cardiac output data obtained were included in the analysis. The correlation between SCCO and ICO was highly significant ($r = 0.92$; $p < 0.01$; Table 1) accompanied by a bias of −0.052 l/min and a precision of 0.56 l/min (Fig. 1). This was not significantly altered by the different respiratory settings before, during or after weaning from mechanical ventilation (Table 1). We did not observe any relevant differences in correlation, accuracy or precision for the different levels of mean cardiac output (Table 1, Fig. 2).

Following weaning from mechanical ventilation we found a slight increase in mean cardiac output when the patients were breathing spontaneously after extubation of the trachea (T_{11-13}). This insignificant trend in cardiac output was reflected by both methods (Fig. 2). After extubation (T_{11}), we found only a small and insignificant increase in precision (0.643 l/min) (Table 1). The correlation between SCCO and ICO was neither affected by the typical postoperative changes in $Temp_{PA}$ and $Temp_{Rec}$, which included mean central blood temperatures between 35.5 ± 0.8 °C and 38.2 ± 0.5 °C and individual temperatures between 33.2 °C and 39.6 °C (Table 2), nor by the changes in central blood temperature following weaning from mechanical ventilation (Table 2, Fig. 2). Neither ICO nor SCCO failed at any time point and we did not observe any adverse conditions when SCCO measurements could not be performed. Furthermore, we did not recognize any adverse effects of the SCCO/ICO pulmonary artery catheter and the SCCO/ICO monitoring equipment.

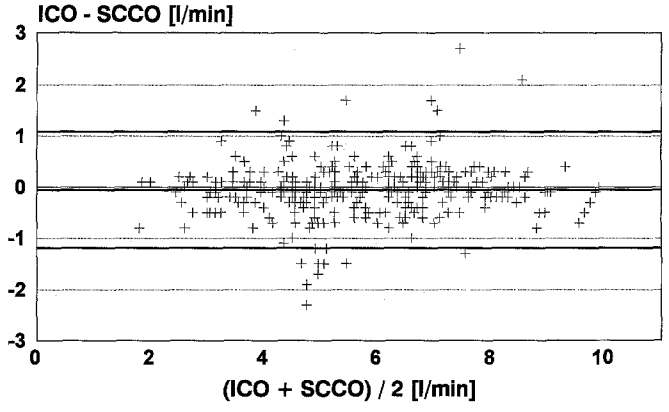

Fig. 1 Evaluation of standard intermittent bolus thermodilution cardiac output (*ICO*) versus semi-continuous cardiac output (*SCCO*) monitoring revealed an excellent accuracy (bias −0.052 l/min) and precision (0.56 l/min) in ICU patients following cardiac surgery

Discussion

Our results demonstrate an excellent correlation, accuracy and precision between SCCO and the clinical "gold standard" ICO measurements in ICU patients following coronary revascularization. This was observed during the entire study period, including time points before, during and after weaning from mechanical ventilation. The observed changes in mean central blood temperature over time did not influence these findings.

These data are in accordance with the preliminary findings of Lichtenthal et al., who compared standard ICO with SCCO measurements in 16 ICU patients after cardiac surgery [17]. They included 165 data pairs and reported a correlation of $r = 0.84$ and an excellent bias of −0.008 l/min, while the precision was acceptable [17]. Davis and Sakuma obtained 94 intra- and postoperative (24 h ICU) data sets from 20 cardiac surgical patients [16]. The preliminary data of these researchers showed an

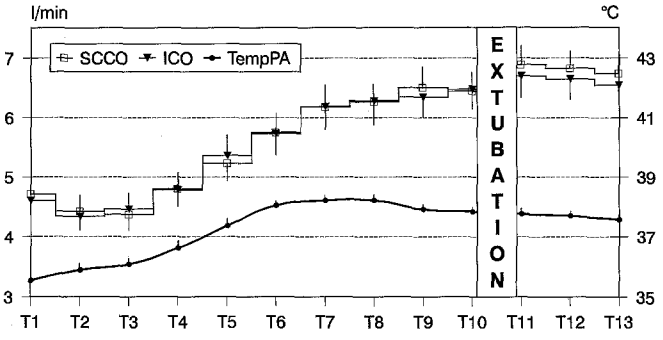

Fig. 2 The correlation between standard intermittent bolus thermodilution cardiac output (*ICO*) and semi-continuous cardiac output (*SCCO*) was not affected by the postoperative changes in pulmonary artery blood temperature ($TEMP_{PA}$). The data in this figure are presented as mean ± SEM

overall bias of 0.08 l/min and a precision of 0.66 l/min. Furthermore, Yelderman and coworkers investigated SCCO in 54 ICU patients, 42 of them following cardiac surgical procedures [30]. They reported a correlation of 0.94 and a bias of 0.02 l/min based on 222 data pairs [30].

Because ICO and SCCO are based on the thermodilution principle, both methods may include identical systematic errors [2, 25]. Thus, it is of great interest to search for an independent reference method. Since this is very difficult in a clinical ICU setting, most investigators use ICO measurements for comparison [12–18]. ICO has been verified to correlate well with other methods of measuring cardiac output [26, 31], and it still represents the "gold standard" of clinical cardiac output monitoring [2]. Schmid and Tornic [18] compared ICO and SCCO with a traditional thermodilution reference system, which has been tested and confirmed by comparing it in vivo with the Fick principle as well as in vitro with electromagnetic flowmetry. Their preliminary data suggest that SCCO measurement is less accurate ($r = 0.85$; bias ± SD = 0.01 ± 0.9 l/min) than ICO measurement ($r = 0.97$; bias ± SD = −0.12 ± 0.41 l/min) in a clinical setting. When SCCO and ICO were compared with electromagnetic measurement of aortic blood flow during cardiac surgery, the preliminary data showed that the SCCO technique appeared to have a slightly better accuracy (bias 0.12 l/min, precision 0.51 l/min) than the ICO technique (bias 0.33 l/min, precision 0.81 l/min) [32].

Despite good correlation, accuracy and precision between SCCO and ICO in various clinical and experimental settings, we recently observed a lack of correlation in the early phase after weaning from hypothermic extracorporeal circulation (ECC) [21]. We hypothesized that thermal instability in combination with increased respiratory variations in pulmonary artery blood temperature due to inhomogeneous rewarming in the early phase after ECC may influence both thermodilution methods. Further significant differences between SCCO and ICO measurements were observed by Spackman and Abenstein during the use of an upper-body warming blanket in patients undergoing aortic reconstructive surgery [23]. Ventilation may influence thermodilution measurements by increasing thermal noise with cyclic variations in $Temp_{PA}$ and by inducing cyclic changes in venous return [22, 24]. The influence of controlled mechanical versus spontaneous ventilation on SCCO has not been investigated previously. Thus, we focused on the phase before and after extubation of the trachea. Our results demonstrate a good correlation, accompanied by an excellent accuracy and precision between SCCO and ICO measurements during the entire study period. We were able to exclude the possibility that the ventilatory setting may have a relevant influence on the correlation and accuracy of both methods.

The true cardiac output in patients may have changed during the determination period of one SCCO and ICO data pair, because both methods cannot be performed simultaneously. In contrast to most previous investigators [16, 17], we measured SCCO before and after the ICO measurements and recorded the mean of these two values as SCCO. If cardiac output had changed, the mean of both SCCO values should represent cardiac output dur-

Table 2 Mean pulmonary artery blood temperatures ($Temp_{PA}$) and mean rectal temperatures ($Temp_{Rec}$) obtained from the patients during the entire study period. The data are presented as mean ± SD (range)

Time point	$Temp_{PA}$	$Temp_{Rec}$
T_1 15 min after arrival in the ICU	35.5 ± 0.8 (33.2–36.6)	35.9 ± 0.8 (34.5–37.7)
T_2 30 min after T_1	35.9 ± 0.8 (33.8–36.9)	35.9 ± 0.8 (33.8–37.0)
T_3 1 h after T_1	36.1 ± 0.9 (34.0–37.6)	36.0 ± 0.9 (34.1–37.4)
T_4 2 h after T_1	36.6 ± 1.1 (34.5–38.8)	36.4 ± 1.0 (34.6–38.2)
T_5 3 h after T_1	37.4 ± 0.9 (35.6–38.9)	37.0 ± 0.9 (35.3–39.0)
T_6 5 h after T_1	38.0 ± 0.5 (36.9–38.9)	38.2 ± 0.5 (37.2–39.2)
T_7 7 h after T_1	38.2 ± 0.6 (37.1–39.2)	38.4 ± 0.6 (37.4–39.4)
T_8 9 h after T_1	38.2 ± 0.5 (37.3–39.6)	38.5 ± 0.5 (37.8–39.5)
T_9 11 h after T_1	37.9 ± 0.4 (36.9–38.7)	38.2 ± 0.5 (37.2–39.1)
T_{10} 20 min before extubation	37.8 ± 0.5 (36.8–39.0)	38.1 ± 0.5 (37.2–39.2)
T_{11} 5 min after extubation	37.8 ± 0.6 (36.5–39.2)	38.0 ± 0.7 (36.5–39.3)
T_{12} 20 min after extubation	37.7 ± 0.6 (36.5–39.3)	38.0 ± 0.6 (36.8–39.4)
T_{13} 1 h after extubation	37.6 ± 0.6 (36.2–39.0)	37.8 ± 0.7 (36.3–39.4)

ing the time of ICO measurement more accurately. To obtain ICO data, the average of three measurements initiated at end-expiration was used. This is in accordance with the recommendations for clinical ICO measurement [26]. However, ICO measurements determined at end-expiration may have led to a systematic bias, which unpredictably may lead to underestimation [33–36] or overestimation [25, 37] of cardiac output, depending on the volume and haemodynamic status of the patient on the individual ventilatory setting [38, 39]. Averaging of three or four measurements equally distributed over the ventilatory cycle has been recommended for more accurate ICO estimation [38, 39]. We cannot exclude that the timing of ICO measurements may have had an impact in our individual clinical situation. However, the haemodynamic, ventilatory and volume variables of our patients changed extensively during the study period, which may have equalized systematic errors.

It has to be taken into consideration that the cardiac output value displayed on the SCCO monitor is an average of the previous 3–6 min [15]. Animal investigations suggest that acute haemodynamic alterations are satisfactorily detected by SCCO measurement [19, 20]. However, sudden physiological changes in cardiac output may not be exactly reflected and displayed by the SCCO software version used. If there is evidence of sudden relevant changes in cardiac output, acutely performed ICO measurements may then prove to be superior.

No side-effects or further limitations of the SCCO catheter or monitoring system were recognized during the entire study period. Concerning the safety of this new device, the amount of heat transferred to the blood by the thermal filament is thought to be within a safe range for patients [12, 13, 40]. The surface temperature usually increases no more than 4–7 °C above the actual blood temperature. The absolute temperature is limited to 44 °C, which is continuously controlled via internal inhibitory feedback mechanisms [13, 15]. Only a thin layer of blood directly exposed to the filament is heated in this way, and the change in whole blood temperature measured at the distal thermistor is usually less than 0.05 °C. Lichtenthal et al. studied the safety of SCCO monitoring in comparison to a standard Paceport catheter during continuous use over 7 days in sheep [12]. They neither observed any increase in body temperature, nor did they find any effects on serum levels of total creatine kinase and isoenzymes, protein, glucose, urea nitrogen, creatinine, cholesterol, bilirubin, uric acid, electrolytes, osmolarity, plasma haemoglobin or thromboxane. No differences were observed in the coagulation parameters or in the gross and microscopic local findings in the vena cava and the heart [12] (for detailed technical and safety considerations of the SCCO system, please see references 12, 13 and 15).

In patients undergoing nuclear magnetic resonance imaging, the manufacturer's recommendations include that the thermal filament-mounted catheter should be removed to prevent damage or melting of the catheter. Because there are no recommendations in terms of handling the indwelling catheter with the thermal filament in the case of electrical cardioversion or defibrillation, it should be noted that emergency external defibrillation due to ventricular fibrillation was performed in one of our patients with the catheter in place. This happened without any side-effects, and both SCCO and ICO measurements were continued after external defibrillation.

Despite possible benefits, the cost/benefit ratio of a new technology has to be taken into consideration. The catheter used is about twice as expensive as a normal PAC. One may argue that similar information may be obtained from continuous mixed venous oxygen saturation and ICO. However, we believe that in the clinical ICU routine, ICO data are usually not obtained often enough. The chance of missing relevant changes in cardiac output is far greater when using only ICO. Obtaining ICO data in ICU patients involves personnel resources and indicator delivery systems, which increase costs. An advantage of this new system is that there is no need for calibration and that special user training or experience is not required. SCCO monitoring may further reduce the risk of bacterial contamination or volume overloading [1–3], which may be relevant in the case of frequent ICO measurements. Possible errors of the ICO method induced by indicator loss [3, 25] or respiratory variations in cardiac output [22, 33–39] are eliminated by the averaging SCCO algorithm. However, the effects of rapid volume infusions or fever with high temperatures, which call for a reduction in the relative amount of heat delivered by the thermal filament, on the accuracy of SCCO has to be focused in further investigation. Theoretically, reducing the amount of heat may not decrease the accuracy of the device, because the binary pseudo-random code of heat delivery is relevant for signal processing and not the absolute amount [14, 15]. It is not known whether SCCO monitoring has any impact on therapeutic strategy or patient outcome. However, the impact on outcome is also unknown for pulmonary artery catheterization in general. We would not recommend routine SCCO monitoring for every patient who needs pulmonary artery pressure monitoring, but we feel that the SCCO data displayed at bedside may be of clinical use in selected patients. However, the specific limitations of this SCCO system, i.e. the averaging algorithm and the semi-continuous data presentation with the software version investigated, have to be taken into consideration. In situations where immediate information about the patients' actual cardiac output is required, ICO can be obtained by the same system without further equipment.

In conclusion, we have demonstrated that SCCO measurement offers a reliable and safe clinical method for the determination of cardiac output in postoperative cardiac surgical ICU patients. Further studies are required that focus on the accuracy of updated SCCO software ver-

sions in haemodynamically unstable patients. Moreover, subgroups of patients may be identified, in whom SCCO monitoring may optimize treatment.

Acknowledgements The authors wish to express their gratitude to Reiner Amann, M.D., Christine Geiger, M.D. and Elisabeth Engelmann, M.D., Department of Anaesthesiology, University of Heidelberg, for cooperation in data collection and additional thanks to the nursing staff of the ICU.

References

1. Mermel LA, Maki DG (1994) Infectious complications of Swan-Ganz pulmonary artery catheters. Am Rev Respir Crit Care Med 149:1020–1036
2. Lavett JM, Reploge RL (1979) Thermodilution cardiac output: a critical analysis and review of the literature. J Surg Res 27:392–404
3. Renner RE, Morton MJ, Sakuma GY (1993) Indicator amount, temperature, and intrinsic cardiac output affect thermodilution cardiac output accuracy and reproducebility. Crit Care Med 21:586–597
4. Keinänen O, Takala J, Kari A (1992) Continuous measurement of cardiac output by the Fick principle: clinical validation in intensive care. Crit Care Med 20:360–365
5. Hausen B, Schäfers HJ, Rohde R, Haverich A (1992) Clinical evaluation of transtracheal Doppler for continuous cardiac output estimation. Anesth Analg 74:800–804
6. Perrino AC, O'Connor T, Luther M (1994) Transtracheal Doppler cardiac output monitoring: comparison to thermodilution during noncardiac surgery. Anesth Analg 78:1060–1066
7. Tannenbaum GA, Mathews D, Weissman C (1993) Pulse contour cardiac output in surgical intensive care unit patients. J Clin Anesth 5:471–478
8. Balestra B, Malacrida R, Leonardi L, Suter P, Marone C (1992) Esophageal electrodes allow precise measurement of cardiac output by bioimpedance. Crit Care Med 20:62–67
9. Shoemaker WC, Wo CCJ, Bishop MH, Appel PL, Van de Water JM, Harrington GR, Wang X, Patil RS (1994) Multicenter trial of a new thoracic electrical bioimpedance device for cardiac output estimation. Crit Care Med 22:1907–1912
10. Segal J, Gaudiani V, Nishimura T (1991) Continuous determination of cardiac output using a flow-directed Doppler pulmonary artery catheter. J Cardiothorac Vasc Anesth 5:309–315
11. Baum VC, Chait HI, Williams JP (1994) Continual measurement of cardiac output during cardiac surgery by heat exchange (abstract). Anesthesiology 81[3A]:A516
12. Lichtenthal PR, Marchand B, Gordon D, Leissing N, Konno M (1992) A safety comparison between a new continuous cardiac output (CCO) monitoring system and a standard pulmonary artery catheter in sheep (abstract). Anesthesiology 77[3A]:A473
13. Yelderman M, Quinn MD, McKown RC (1992) Thermal safety of a filamented pulmonary artery catheter. J Clin Monit 8:147–149
14. Yelderman M (1990) Continuous measurement of cardiac output with the use of stochastic system identification techniques. J Clin Monit 6:322–332
15. Yelderman M (1993) Continuous cardiac output by thermodilution. Int Anesthesiol Clin 31:127–140
16. Davis RF, Sakuma G (1992) Comparison of semi-continuous thermodilution to intermittent bolus thermodilution cardiac output determinations (abstract). Anesthesiology 77[3A]:A477
17. Lichtenthal PR, Wade LD (1993) Clinical evaluation of a continuous cardiac output system in post-OP cardiac surgical patients (abstract). Crit Care Med 21 [Suppl]:S214
18. Schmid ER, Tornic M (1994) Accuracy of continuous cardiac output monitoring by thermodilution (abstract). Anesthesiology 81[3A]:A519
19. Ryan MK, Fan YP, Lee TS, Bongard FS (1993) Comparison of continuous vs manual bolus cardiac output following hemodynamic alterations in a porcine model (abstract). Anesthesiology 79[3A]:A469
20. Yelderman M, Quinn MD, McKown RC (1992) Continuous thermodilution cardiac output measurement in sheep. J Thorac Cardiovasc Surg 104:315–320
21. Böttiger BW, Rauch H, Böhrer H, Motsch J, Soder M, Fleischer F, Martin E (1995) Continuous versus intermittent cardiac output measurement in cardiac surgical patients undergoing hypothermic cardiopulmonary bypass. J Cardiothorac Vasc Anesth 9:505–411
22. Latson TW, Whitten CW, O'Flaherty D (1993) Ventilation, thermal noise, and errors in cardiac output measurements after cardiopulmonary bypass. Anesthesiology 79:1233–1243
23. Spackman TN, Abenstein JP (1993) Continuous cardiac output may be more accurate than bolus thermodilution output during the use of an upper-body warming blanket (abstract). Anesthesiology 79[3A]:A473
24. Wessel HU, James GW, Paul MH (1966) Effects of respiration and circulation on central blood temperature of the dog. Am J Physiol 211:1403–1412
25. Nishikawa T, Dohi S (1993) Errors in the measurement of cardiac output by thermodilution. Can J Anaesth 40: 142–153
26. Stetz CW, Miller RG, Kelly GE (1982) Reliability of the thermodilution method in the determination of cardiac output in clinical practice. Am Rev Respir Dis 126:1001–1004
27. Boyd O, Mackay J, Newman P, Bennett ED, Grounds RM (1994) Effects of insertion depth and use of the sidearm of the introducer sheath of pulmonary artery catheters in cardiac output measurement. Crit Care Med 22: 1132–1135
28. Wetzel RC, Latson TW (1985) Major errors in thermodilution cardiac output measurement during rapid volume infusion. Anesthesiology 62:684–687
29. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet I:307–310
30. Yelderman ML, Ramsay MA, Quinn MD, Paulsen AW, McKown RC, Gillman PH (1992) Continuous thermodilution cardiac output measurement in intensive care unit patients. J Cardiothorac Vasc Anesth 6:270–274
31. Weisel RD, Berger RL, Hechtman HB (1975) Measurement of cardiac output by thermodilution. N Engl J Med 292: 682–684
32. Hogue CW, Cerza RF, Rosenbloom M, Lappas DG (1993) Comparison of continual thermodilution cardiac output with electromagnetometry (abstract). Anesthesiology 79[3A]:A467
33. Armengol J, Man GCW, Balsys AJ, Wells AL (1981) Effects of the respiratory cycle on cardiac output measurements: reproducibility of data enhanced by timing the thermodilution injections in dogs. Crit Care Med 9: 852–854

34. Snyder JV, Powner DJ (1982) Effects of mechanical ventilation on the measurement of cardiac output by thermodilution. Crit Care Med 10:677–682
35. Stevens JH, Raffin TA, Mihm FG et al. (1985) Thermodilution cardiac output measurement. Effects of the respiratory cycle on its reproducibility. JAMA 253: 2240–2242
36. Thrush DN, Varlotta D (1992) Thermodilution cardiac output. Comparison between automated and manual injection of indicator. J Cardiothorac Vasc Anesth 6:17–19
37. Woods M, Scott RN, Harken AH (1976) Practical considerations for the use of a pulmonary artery thermistor catheter. Surgery 79:469–475
38. Jansen JRC, Versprille A (1986) Improvement of cardiac output estimation by the thermodilution method during mechanical ventilation. Intensive Care Med 12:71–79
39. Jansen JRC, Schreuder JJ, Settels JJ, Kloek JJ, Versprille A (1990) An adequate strategy for the thermodilution technique in patients during mechanical ventilation. Intensive Care Med 16:422–425
40. Ham TH, Shen SC, Fleming EM, Castle WB (1948) Studies in destruction of red blood cells. IV. Thermal injury. Blood 3:373–403