Anesthesiology 2010; 113:1220–35

Minimally Invasive Measurement of Cardiac Output during Surgery and Critical Care

A Meta-analysis of Accuracy and Precision

Philip J. Peyton, M.D., M.B.B.S., F.A.N.Z.C.A.,* Simon W. Chong, M.B.B.S.†

ABSTRACT

When assessing the accuracy and precision of a new technique for cardiac output measurement, the commonly quoted criterion for acceptability of agreement with a reference standard is that the percentage error (95% limits of agreement/mean cardiac output) should be 30% or less. We reviewed published data on four different minimally invasive methods adapted for use during surgery and critical care: pulse contour techniques, esophageal Doppler, partial carbon dioxide rebreathing, and transthoracic bioimpedance, to assess their bias, precision, and percentage error in agreement with thermodilution. An English language literature search identified published papers since 2000 which examined the agreement in adult patients between bolus thermodilution and each method. For each method a meta-analysis was done using studies in which the first measurement point for each patient could be identified, to obtain a pooled mean bias, precision, and percentage error weighted according to the number of measurements in each study. Forty-seven studies were identified as suitable for inclusion: N studies, n measurements: mean weighted bias [precision, percentage error] were: pulse contour $N = 24$, $n = 714$: −0.00 l/min [1.22 l/min, 41.3%]; esophageal Doppler $N = 2$, $n = 57$: −0.77 l/min [1.07 l/min, 42.1%]; partial carbon dioxide rebreathing $N = 8$, $n = 167$: −0.05 l/min [1.12 l/min, 44.5%]; transthoracic bioimpedance $N = 13$, $n = 435$: −0.10 l/min [1.14 l/min, 42.9%]. None of the four methods has achieved agreement with bolus thermodilution which meets the expected 30% limits. The relevance in clinical practice of these arbitrary limits should be reassessed.

THERE is increasing interest in better hemodynamic management, incorporating cardiac output measurement, to achieve improvements in patient outcomes during major surgery.[1–3] A number of methods and technologies are now available for minimally invasive or noninvasive cardiac output monitoring in the perioperative period. These include pulse contour and esophageal Doppler devices, the partial carbon dioxide rebreathing ($P_{CO_2}RB$) method, and transthoracic electrical bioimpedance (TEB).[3] However, these methods have not achieved widespread use in routine practice.[4] The reasons for this include cost, of both the devices and their disposable components, invasiveness, and concerns about their accuracy, precision, and reproducibility.

Numerous publications[5–87] have examined the accuracy and precision of the various methods and devices currently available, by comparison with simultaneous paired measurements made using a commonly accepted clinical standard technique. This is usually a more invasive technique, such as right heart or transpulmonary thermodilution. Most such publications over the last decade have employed bias and precision statistics, as described by Bland and Altman,[88] providing the mean difference (bias) and SD of the difference between paired measurements, from which limits of agreement (bias ± 1.96 standard deviations) are obtained. These limits of agreement are often expressed as a proportion of the mean cardiac output (percentage error).

The acceptable limit of agreement in these comparison studies has been unclear. In a review paper published in 1999, Critchley and Critchley[89] suggested that acceptable agreement should be a percentage error of 30% or less, which has become a widely quoted criterion.[5–15,17–19,25–30,46–49,63–66] Numerous studies have been published in the field over the last 10 yr, which include newer methods that were not reviewed by Critchley and Critchley. It is unclear whether currently available methods are consistently achieving this level of agreement. More recent reviews have focused on a single method,[90] and/or have ex-

* Associate Professor, Department of Anaesthesia, Austin Hospital, Melbourne, Australia, and Associate Professor, Department of Surgery, Austin Hospital and University of Melbourne, Melbourne, Australia. † Anaesthesia Registrar, Department of Anaesthesia, Austin Hospital.

Received from the Department of Anaesthesia, Austin Hospital, Melbourne, Australia, and the Department of Surgery, Austin Hospital and University of Melbourne, Melbourne, Australia. Submitted for publication December 10, 2009. Accepted for publication June 14, 2010. Support was provided solely from institutional and/or departmental sources. Dr. Peyton is an applicant in an International Patent Application for a minimally invasive method of cardiac output monitoring (PCT/AU/2008/001696).

Address correspondence to Dr. Peyton: Department of Anaesthesia, Austin Hospital, Heidelberg 3084, Melbourne, Australia. phil.peyton@austin.org.au.

cluded relevant patient groups from the analysis.[91] In some reviews, pooling of data from studies where repeated measurements from patients are made makes the reliability of their conclusions uncertain.[89,91]

We conducted a 10-yr review of studies examining the agreement with bolus thermodilution of four currently available methods which are adapted to perioperative and critical care use, for minimally invasive cardiac output monitoring (pulse contour, esophageal Doppler, P_{CO_2}RB, and TEB). To get a global measurement of their accuracy and precision, all studies reporting data from a single measurement on each patient were included in a pooled weighted meta-analysis.

Materials and Methods

A PubMed and Medline search was conducted with search headings such as "cardiac output, pulmonary blood flow, thermodilution, pulse contour, PiCCO, LidCO, PulseCO, FloTrac, Vigileo, esophagal Doppler, carbon dioxide rebreathing, NICO, and thoracic electrical bioimpedence." The search and subsequent bibliographic review was restricted to studies in adult humans, and to published papers (not correspondence or case reports) in English language peer-reviewed journals, in which results were expressed using bias and precision statistics (mean difference and either SD of agreement, 95% limits of agreement, or percentage error). Only studies using comparison with simultaneous measurements of cardiac output or cardiac index by bolus right heart or transpulmonary thermodilution were included. Studies comparing PiCCO (Pulsion Medical Systems, Munich, Germany) with transpulmonary thermodilution were excluded, because the method requires transpulmonary thermodilution for initial calibration and this was considered to bias the comparison.

Where not reported directly, percentage error (% error) for a study was calculated from the SD of agreement and mean cardiac output:

$$\%\ \text{error} = 100 \times 1.96 \times \text{standard deviation of agreement/mean cardiac output} \quad (1)$$

Where mean cardiac output was not provided in tables or text, it was estimated from graphs. The methodology employed was in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, formerly QUOROM) Statement[92] issued by the CONSORT group.[93,94]

A total of 92 publications was found including 96 trials (4 publications made simultaneous comparisons of two methods) comparing one of the four methods against bolus thermodilution with results expressed using bias and precision. These comprised 55 trials for pulse contour, 9 trials for esophageal Doppler, 15 trials for P_{CO_2}RB, and 17 trials for TEB. Significant variations in methodology and statistical

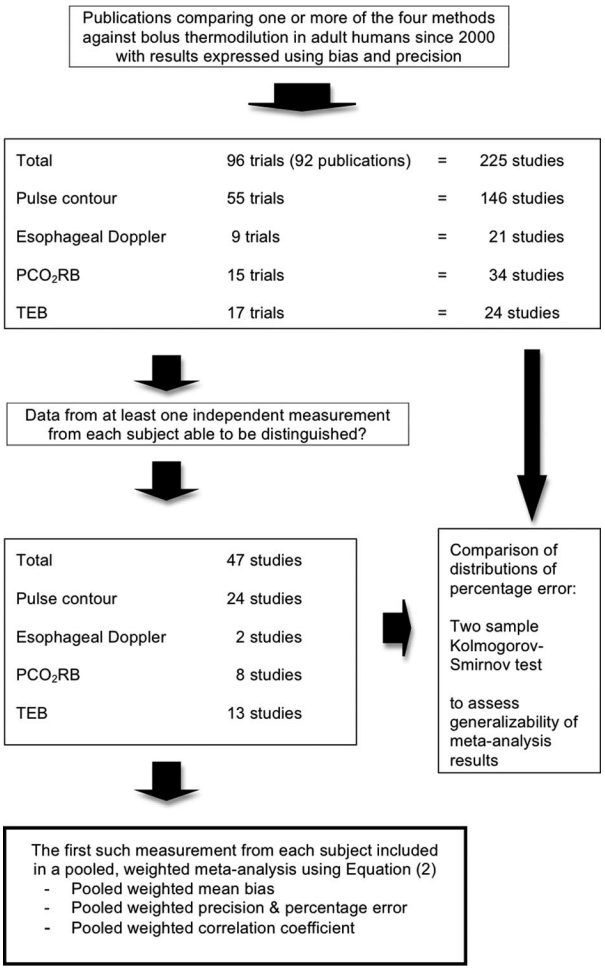

Fig. 1. Flow diagram describing the data analysis protocol. P_{CO_2}RB = partial carbon dioxide rebreathing; TEB = transthoracic electrical bioimpedance.

treatment were found among these. In the 9 publications where cardiac index was reported, this was converted to cardiac output using body surface area, and if the latter was not supplied, an assumed body surface area of 2.0 m^2 was used (the median value among the 22 publications where body surface area was reported). A large number of these trials conducted several studies of a method on each subject (across all publications, these totaled 146 studies for pulse contour, 21 for esophageal Doppler, 34 for P_{CO_2}RB, and 24 for TEB). Some of these publications reported these studies separately, but many presented only a single pool of data from all subjects at multiple time points, and many of these did not state that correction was made for multiple measurements on subjects when calculating overall bias and precision of agreement, as described by statistical authorities.[95–97]

In 47 of these studies, data from at least one single independent measurement on each subject was able to be distinguished, thus making them suitable for inclusion in a pooled, weighted meta-analysis. The first such measurement from each subject in each of these studies was included in this meta-analysis. The process is summarized in figure 1.

Table 1. All Studies in the Review

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Pulse contour method								
Mayer *et al.*[*5]	2009	Cardiac surgery (OP/ICU)	FT	1.1	ITD			
		Non-obese group: After induction				23	***0.18***	***0.27***
		Non-obese group: Before CPB					*0.25*	*0.28*
		Non-obese group: After CPB					*0.18*	*0.38*
		Non-obese group: After sternal closure					*0.12*	*0.32*
		Non-obese group: Arrival in ICU					*0.32*	*0.31*
		Non-obese group: After 4 h in ICU					*0.23*	*0.30*
		Non-obese group: After 12 h in ICU					*0.01*	*0.29*
		Non-obese group: After 24 h in ICU					*0.14*	*0.30*
		Obese group: After induction	FT	1.1		15	***0.13***	***0.30***
		Obese group: Before CPB					*0.15*	*0.40*
		Obese group: After CPB					*0.06*	*0.42*
		Obese group: After sternal closure					*0.13*	*0.41*
		Obese group: Arrival in ICU					*0.26*	*0.39*
		Obese group: After 4 h in ICU					*0.25*	*0.27*
		Obese group: After 12 h in ICU					*0.41*	*0.35*
		Obese group: After 24 h in ICU					*0.43*	*0.34*
Senn *et al.*[*6] (See PiCCO also)	2009	Postoperative cardiac surgery (ICU)	FT	1.03 (Set A)	ITD			
		Set A supine				25	**−0.10**	**0.80**
		Set A head up					−0.30	0.90
		Set A head down					0.20	1.10
		Set A return to supine					0	1.20
		Set B supine	FT	1.07 (Set B)		25	**−0.30**	**0.60**
		Set B head up					−0.30	0.55
		Set B head down					−0.20	0.55
		Set B return to supine					−0.40	0.50
Biancofiore *et al.*[7]	2009	Liver transplant (OP/ICU)	FT	1.1	ITD	290	*−1.30*	*1.40*
Ostergaard *et al.*[*8]	2009	Cardiac surgery (OP)	FT	1	ITD	25	**0.51**	**0.93**
Mutoh *et al.*[9]	2009	Subarachnoid hemorrhage (OP/ICU)	FT	1.14	TPTD	179	−1.14	0.88
Compton *et al.*[*99,101]	2008	Hemodynamically unstable (ICU)	FT	1.1	TPTD	25	**−1.90**	**1.94**
Della Rocca *et al.*[10]	2008	Liver transplant (ICU)	FT	1.1	ITD	126	−0.95	1.41
Mayer *et al.*[*11]	2008	Cardiac surgery (OP/ICU)	FT	1.1	ITD			
		Intraoperative (T1)				40	***0.04***†	***0.29***†
		In ICU (T5–8)					*0.21*	*0.26*

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Mehta *et al.*[*12]	2008	Cardiac surgery (OP)	FT	1.07	ITD			
		Before induction				12	**−0.54**	**0.56**
		After induction					−0.37	0.50
		Beforet sternotomy					−0.42	0.75
		LIMA LAD anastomosis					−0.25	0.59
		Left side anastomosis					−0.31	0.64
		Right side anastomosis					−0.41	0.50
		Aftert protamine					0.06	0.75
		After sternal closure					0.09	0.70
Zimmermann *et al.*[*13]	2008	Cardiac surgery (OP/ICU)	FT	1.01	ITD			
		After induction				30	**0.73**	**1.29**
		After sternal split					0.19	1.38
		After extracorporeal circulation					−0.09	1.74
		At skin closure					−0.19	1.35
		30 min after ICU admission					−0.39	1.40
		3 h after ICU admission					−0.79	1.63
		6:30 a.m. after extubation					−0.64	1.52
Staier *et al.*[*14]	2008	Cardiac surgery (OP)	FT	1.07	ITD			
		After induction				30	**0.16**	**0.70**
		After sternotomy					−0.06	0.89
		5 min aftert end of extracorporeal circulation					−0.26	1.40
		After closure of chest					0.24	1.07
McGee *et al.*[15]	2007	ICU After cardiac surgery/medical (ICU)	FT	1.01 (estimated)	ITD	561	0.20	1.28
Cannesson *et al.*[16]	2007	Cardiac surgery (OP/ICU)	FT	1.07	ITD	166	0.26	0.87
Sakka *et al.*[*45]	2007	Ventilated septic shock (ICU)	FT	1.07	TPTD	24	**−0.87**	**2.30**
de Waal *et al.*[*17]	2007	Cardiac surgery (OP/ICU)	FT	1.01	TPTD			
		After induction of anesthesia				22	**−0.08**	**0.90**
		After sternotomy					0.57	0.74
		Immediately after volume load					−0.14	0.98
		20 min after this volume load					−0.42	0.93
		15 min after weaning from CPB					0.05	0.83
		After retransfusion of autologous blood					−0.09	0.85
		After arrival at ICU					0.12	0.64
		Immediately after second volume load					0.11	0.86
		20 min after this second volume load					−0.14	0.92
Prasser *et al.*[18]	2007	Neurosurgical (ICU)	FT	1.03	ITD	164	−0.02	1.46
Mayer *et al.*[*19]	2007	Postoperative cardiac surgery (OP/ICU)	FT	1.03	ITD			
		After induction				40	***0.52***	***0.57***
		Before CPB					*0.47*	*0.38*
		After CPB					*0.51*	*0.64*
		After sternal closure					*0.41*	*0.58*
		Arrival in ICU					*0.48*	*0.54*
		4 h in ICU					*0.54*	*0.68*
		8 h in ICU					*0.35*	*0.68*
		24 h in ICU					*0.44*	*0.63*

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Manecke *et al.*[20]	2007	Postoperative cardiac surgery (ICU)	FT	1.03	ITD	295	0.55	0.98
Breukers *et al.*[21]	2007	Postoperative cardiac surgery (ICU)	FT	1.03	ITD	56	0.14	1.00
Button *et al.**[22] (See PiCCO also)	2007	Cardiac surgery (OP/ICU)	FT	1.07	ITD			
		After induction of anesthesia				31	**0.60**	**0.90**
		After sternotomy					0.40	0.95
		At skin closure					0.10	1.20
		8 h after start of surgery					0.20	1.25
		12 h after start of surgery					0.10	1.30
		24 h after start of surgery					0.10	1.20
Chakravarthy *et al.*[23] (See PiCCO also)	2007	Cardiac surgery (OP)	FT	N/A	ITD	438	0.15	0.33
Opdam *et al.*[24]	2007	Postoperative cardiac surgery (ICU)	FT	1.03	ITD	218	0.01	0.60
Sander *et al.**[25]	2006	Cardiac surgery (OP/ICU)	FT	1.03 (estimated)	ITD			
		After induction of anesthesia				30	**−0.20**	**1.40**
		After sternotomy					−1.00	1.80
		1 h after ICU admission					−0.70	1.00
		6 h after ICU admission					−0.60	1.40
Breukers *et al.*[26]	2009	Cardiac surgery ICU	MF		ITD	119	0.36	1.42
Senn *et al.*[6] (See FloTrac also)	2009	Postoperative cardiac surgery (ICU)	PiCCO		ITD	200		
		Set A supine					−0.20	0.70
		Set A head up					−0.10	0.55
		Set A head down					−0.30	0.80
		Set A return to supine					−0.20	0.70
		Set B supine	PiCCO				−0.30	0.60
		Set B head up					0.10	0.50
		Set B head down					−0.40	0.70
		Set B return to supine					−0.30	0.65
Compton *et al.*[27]	2008	Medical (ICU)	HDI		ITD & TPTD	102	−2.03	1.34
Yamashita *et al.**[28]	2008	Cardiac surgery & PGE_1 infusions (OP)	PiCCO		ITD			
		PGE_1 infusion 0.01 μg/kg/min				20	**−0.31**	**0.46**
		PGE_1 infusion 0.02 μg/kg/min					−0.62	0.70
		PGE_1 infusion 0.04 μg/kg/min					−0.61	0.62
		After PGE_1 infusion					−0.14	0.34
de Wilde *et al.*[29] (See LidCO also)	2007	Cardiac surgery (OP)	PiCCO		ITD	199	−0.14	0.87
Button *et al.*[22] (See FloTrac also)	2007	Cardiac surgery (OP/ICU)	PiCCO		ITD	186		
		After induction of anesthesia					0.50	0.75
		After sternotomy					0.40	0.85
		At skin closure					0.30	1.50
		8 h after start of surgery					0.20	1.90
		12 h after start of surgery					0.20	1.25
		24 h after start of surgery					0.10	1.55

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Chakravarthy *et al.*[23] (See FloTrac also)	2007	Cardiac surgery (OP)	PiCCO		ITD	438	−0.13	1.12
Ostergaard *et al.*[*30]	2006	Cardiac surgery (OP/ICU)	PiCCO		ITD	25	**0.07**	**1.10**
Felbinger *et al.*[31]	2005	Cardiac surgery (ICU)	PiCCO		ITD	53	0.44	0.52
Sander *et al.*[*32]	2005	Cardiac surgery (OP)	PiCCO		ITD	45	**−1.40**	**1.70**
Wouters *et al.*[33]	2005	Cardiac surgery (OP)	PiCCO		ITD	224	1.08	0.75
de Vaal *et al.*[*34]	2005	Postoperative cardiac surgery (ICU)	MF uncalibrated		ITD	24	**0.37**	**1.58**
			MF calibrated		ITD	24	0.08	0.70
Della Rocca *et al.*[*35]	2003	Lung transplant (OP)	PiCCO		ITD			
		Before incision				58	**0.26**	**0.57**
		During 1st lung implantation					0.07	0.61
		After 1st lung reperfusion					0.01	0.93
		During 2nd lung implantation					0.02	0.79
		After reperfusion of 2nd lung					0	0.68
		End of surgery					0.09	0.69
Tzenkov *et al.*[*36]	2003	Liver transplant (OP)	PiCCO		ITD			
		Basal				35	**0.71**	**1.15**
		10 min before portal clamping					0.26	1.16
		10 min after portal clamping					0.50	1.01
		10 min before caval clamping					0.91	1.20
		10 min after caval clamping					0.64	0.85
		10 min before graft reperfusion					0.59	1.25
		10 min after graft reperfusion					−1.08	1.43
		60 min after graft reperfusion					0.35	1.38
		End of biliary tree reconstruction					−0.68	1.17
		End of surgical intervention					−0.72	0.81
Mielck *et al.*[37] (See Partial CO_2 also)	2003	Cardiac surgery (ICU)	PiCCO		ITD	96	−0.40	1.39
Della Rocca *et al.*[*38]	2002	Liver transplant (OP)	PiCCO		ITD			
		After induction of anesthesia				62	**0.02**	**0.74**
		During the anhepatic phase					0.09	0.99
		End of surgery					0.07	0.80
Romano *et al.*[*39]	2002	Cath lab patients	PRAM		ITD	18	***−0.15***	***0.35***
Felbinger *et al.*[40]	2002	Cardiac surgery (ICU)	PiCCO		ITD	360	*0.62*	*0.91*
			PiCCOnew		ITD	360	*0.28*	*0.66*
Rauch *et al.*[41]	2002	Cardiac surgery (OP/ICU)	PiCCO		ITD	380	−0.14	1.16
Segal *et al.*[42]	2002	General ICU (ICU)	PiCCO		ITD	190	0.27	0.67

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Jansen *et al.*[43]	2001	Cardiac surgery (OP)	MF		ITD	490	−0.10	0.50
Hirschl *et al.**[44] (See bioimpedance also)	2000	ICU patients (ICU)	MF		ITD	29	**0.65**	**1.20**
Zollner *et al.*[45]	2000	Cardiac surgery (ICU)	PiCCO		ITD	228	0.31	1.25
Missant *et al.*[46]	2008	Cardiac surgery (OP)	PulseCO		ITD	149	−0.03	0.65
Costa *et al.*[47]	2008	Liver transplant (ICU)	PulseCO		ITD	151	−0.29	1.08
de Wilde *et al.*[29] (See PiCCO also)	2007	Cardiac surgery (OP)	PulseCO		ITD	199	0.17	0.69
Garcia-Rodriguez *et al.*[48]	2002	Surgical (ICU)			ITD			
		Peripheral administration of lithium	NR			402	−0.54	0.95
		Central administration of lithium	NR			402	−0.53	0.63
Esophageal Doppler method								
Lafanachere *et al.**[79]	2006	Infrarenal aortic surgery (OP)	Hemosonic 100		ITD			
		After probe insertion				22	**−0.10**	**0.89**
		Preclamping					−0.13	1.18
		10 min after clamping					−0.43	1.04
		Before declamping					−0.54	1.05
		10 min after declamping					−0.18	1.00
		End of surgery					−0.15	1.00
Sharma *et al.**[80]	2005	Cardiac surgery (postoperative)	TECO		ITD			
		T1 (0 min)				35	**−1.18**	**1.37**
		T2 (30 min)					−1.17	1.35
		T3 (60 min)					−1.22	1.37
		T4 (90 min)					−1.15	1.37
Collins *et al.*[81]	2005	Cardiac surgery (OP)	Hemosonic 100		ITD	300		
		After probe insertion					0.10	1.00
		Before heart displacement					−0.60	1.00
		During heart displacement					−0.50	0.80
		Before sternal closure					−0.70	0.70
Kim *et al.*[82]	2004	Escharectomy for major burns (OP)	CardioQ		ITD	92	−0.77	1.37
Hullett *et al.*[83]	2003	Cardiac surgery (OP)	CardioQ		ITD	331	−0.56	0.64
Jaeggi *et al.*[84]	2003	Postoperative cardiac surgery (ICU)	Hemosonic 100		ITD	85	0.46	1.60
Moxon *et al.*[85]	2003	Postoperative cardiac surgery (ICU)	Hemosonic 100		ITD	47	0.23	1.06
Leather *et al.*[86]	2001	Radical prostatectomy (OP)	ODM II		ITD			
		Before epidural anesthetic administered				14	−0.89	0.89
		After epidural anesthetics administered				14	0.55	1.88
Penny *et al.*[87]	2000	Preeclampsia pts	CardioQ		ITD	17	−2.00	1.50

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Partial CO_2 rebreathing (PCO_2RB) method								
Kotake *et al.*[49]	2009	Aortic surgery (OP)	NICO (version 4.2)		ITD	182	0.18	0.88
			NICO (version 5.0)		ITD	194	0.18	0.83
Killick *et al.*[50]	2008	Postoperative cardiac Surgery (ICU)			ITD	113	−0.60	0.86
Peyton *et al.**[51]	2008	Cardiac surgery (OP)			ITD			
		Group 1 (increase in respiratory rate)					−0.06	0.87
		Group 2 (decrease in respiratory rate)				12	**0.25**	**0.86**
Ng *et al.*[52]	2007	Thoracic surgery (OP)	NICO		ITD	76	−0.29	0.76
Tachibana *et al.**[53]	2005	Postoperative cardiac surgery (ICU)	NICO		ITD			
		35 s rebreathing system				13	**0.02**	**1.06**
		50 s rebreathing system					−0.34	1.08
Rocco *et al.*[54]	2004	ICU	NICO		ITD	36	−1.20	1.50
Tachibana *et al.**[55]	2003	Postoperative cardiac surgery (ICU)	NICO		ITD			
		Tidal volume 12 ml/kg, RR 10				25	**0.09**	**1.00**
		Tidal volume 6 ml/kg, RR 20					−0.67	0.73
		Tidal volume 6 ml/kg, RR 10					−1.73	1.27
		SIMV/PSV ventilation					0.18	1.41
		PSV/long loop ventilation					0.80	1.26
		PSV/short loop ventilation					1.20	1.80
Mielck *et al.*[37] (See PiCCO also)	2003	Postoperative cardiac surgery (ICU)	NICO		ITD	33	−0.64	1.39
Kotake *et al.**[56]	2003	Aortic surgery (OP)	NICO		ITD			
		After induction				28	**−0.10**	**0.61**
		During aortic cross-clamping					−0.52	0.95
		At reperfusion of unilateral iliac artery					−0.99	0.86
		During peritoneal closure					−0.72	0.97
Tachibana *et al.**[57]	2002	Postoperative cardiac surgery (ICU)	NICO		ITD			
		VCV large tidal volume				25	**0.18**	**1.04**
		VCV small tidal volume					−1.67	1.06
		PCV large tidal volume					0.37	1.17
		PCV small tidal volume					−1.64	1.19
		VCV $F_{IO_2} = 1$					0.19	1.12
		VCV high PEEP					0.37	0.81
		VCV long loop					0.48	1.27
		VCV short loop					1.30	1.15
		PSV					0.52	1.02
Murias *et al.*[58]	2002	ICU	NICO		ITD	22	**0.18**	**1.39**
Odenstedt *et al.*[59]	2002	ICU	NICO		ITD	74	−0.05	0.96
Binder *et al.*[60]	2001	Postoperative cardiac surgery (ICU)			ITD	358	−0.05	0.70
Nilsson *et al.**[61]	2001	Postoperative cardiac surgery (ICU)	NICO		ITD	30	**0.16**	**0.90**
van Heerden *et al.**[62]	2000	Postoperative cardiac surgery (ICU)	NICO		ITD	12	**−0.73**	**2.05**

(*continued*)

Table 1. Continued

Reference	Year	Population	Device	Version	Reference	Data Points	Bias	Precision
Transthoracic electrical bioimpedance (TEB) method								
Raue *et al.*[*63]	2009	Surgical ICU sepsis	NR		TPTD	30	**−0.30**	**1.90**
Mekis *et al.*[*64]	2008	Cardiac surgery (OP/ICU)	Aesculon		ITD			
		Before skin incision				14	**0.20**	**0.32**
		After skin closure				64	−0.57	0.92
		In ICU				29	0.26	0.68
Gujjar *et al.*[65]	2008	Postoperative cardiac surgery (ICU)	Nicomon		ITD	197	−0.07	0.68
Zoremba *et al.*[*66]	2007	Postoperative patients (ICU)	Aesculon		ITD	25	**−0.05**	**0.71**
			Aesculon		TPTD		0.22	0.78
Heringlake *et al.*[*67]	2007	Cardiac surgery (OP/ICU)	Aesculon		ITD			
		After induction of anesthesia				29	**0.40**	**1.60**
		After ICU admission					−0.40	1.80
Shoemaker *et al.*[68]	2006	Trauma patients (OP/ICU)	IQ/PhysioFlow		ITD	907	−0.14	0.94
Suttner *et al.*[*69]	2006	Postoperative cardiac surgery (ICU)	Aesculon		ITD			
		Hemodynamically stable group				40	**−0.06**	**0.47**
		Hemodynamically unstable group				34	**0.12**	**0.68**
Engoren *et al.*[*70]	2005	ICU patients (ICU)	BioZ		ITD	46	**−1.00**	**1.30**
Albert *et al.*[*71]	2004	Heart failure (ICU)	NR		ITD	29	**−0.08**	**0.69**
Cotter *et al.*[*72]	2004	Cath lab/cardiac surgery (OP/ICU)	NICaS		ITD			
		Cath lab				40	***0.00***	***0.37***
		Coronary artery bypass grafting				208	*−0.02*	*0.35*
		ICU congestive heart failure				174	*0.03*	*0.35*
Drazner *et al.*[*73]	2002	Heart failure cath lab patients	BioZ		ITD	50	**0.03**	**1.10**
Sageman *et al.*[74]	2002	Postoperative cardiac surgery (ICU)	BioZ		ITD	216	*−0.07*	*0.20*
Spiess *et al.*[*75]	2001	Cardiac surgery (OP)	BioZ		ITD			
		After induction of anesthesia				45	***−0.02***	***0.29***
		Mediastinum open					*−0.42*	*0.57*
		After CPB					*−0.53*	*0.64*
		At end of case					*−0.67*	*0.74*
Imhoff *et al.*[76]	2000	Postoperative surgical patients (ICU)	Prototype		ITD	109	−1.60	2.45
Hirschl *et al.*[*44] (See PiCCO also)	2000	ICU patients	Cardioscreen		ITD	29	**1.20**	**0.75**
Barin *et al.*[77]	2000	Cath lab patients	RheoCardio Monitor		ITD	80	−0.31	0.76
Critchley *et al.*[*78]	2000	ICU patients	BoMed		ITD	24	**−1.49**	**2.08**

Data for bias and precision included in the pooled weighted meta-analysis are indicated in bold. Data in italics are cardiac index (l/min/m^2). All other data are cardiac output (l/min).

* Study included in pooled weighted analysis; † Cardiac output estimated from data.

Aesculon = Aesculon® (Osypka Medical, Berlin, Germany); BioZ = BioZ (CardioDynamics, San Diego, CA); BoMed = BoMed NCCOM3-R7S (BoMed Medical Manufacturing, Irvine, CA); Cardioscreen = Cardioscreen (Mebetatechnik, Ilmenau, Germany); Cardio Q = Cardio Q (Deltex Medical Ltd., Chichester, UK); Cath lab = cardiac catherization laboratory; CPB = cardiopulmonary bypass; FT = FloTrac/Vigileo (Edwards Lifesciences, Irvine CA); HDI = HDI/Pulse Wave CR-2000 Cardiovascular Profiling Instrument (Hypertension Diagnostics, Inc., Eagan, MN); Hemosonic 100 = Hemosonic 100 (Arrow International, Everett, MA); ICU = intensive care unit; IQ/Physioflow = IQ (Noninvasive Medical Technologies LLC, Las Vegas, NV); ITD = intermittent right heart thermodilution; MF = Modelflow; NICaS = NICaS (NI Medical, Hod-Hasharon, Israel); NICO = NICO (Respironics, Pittsburgh, PA); NR = not reported; ODM II = ODM II (Abbot Laboratories, North Chicago, IL); OP = operative; PCV = pressure controlled ventilation; PGE_1 = prostaglandin E_1; Physio Flow (VasoCOM, Bristol, PA); PiCCO = PiCCO (Pulsion Medical Systems, Munich, Germany); PRAM = pressure recording analytical method; PSV = pressure support ventilation; PulseCO = PulseCO (LiDCO Ltd., Cambridge, UK); RheoCardioMonitor = RheoCardioMonitor (Rheo-Graphic PTE, Singapore); *RR* = respiratory rate; SIMV = synchronized intermittent mandatory ventilation; *T* = time; TECO = Transesophageal cardiac output (Medicina, Berkshire, UK); TPTD = transpulmonary thermodilution; VCV = volume controlled ventilation.

Statistical Analysis

For each method, the reported bias (method – thermodilution), mean cardiac output, variance of agreement (SD of agreement squared), and correlation coefficient were weighted according to the number of subjects in each study, and a pooled weighted value for each was derived, according to

$$\text{Pooled } x = \sum_{i=0}^{i=N-1}\left[\frac{x_i \cdot (n_i - 1)}{\sum_{i=0}^{i=N-i}(n_i - 1)}\right] \quad (2)$$

where n_i and x_i are, respectively, the number of measurements and the variable to be pooled (bias, mean cardiac output, variance of agreement, or correlation coefficient) in study i among N studies for that method.

The pooled weighted precision (one SD) of agreement was calculated (square root of the pooled weighted variance) and pooled weighted percentage error then calculated according to Eq 1. Confidence limits for the bias and percentage error were calculated as described by Bland and Altman.[88] The pooled weighted correlation coefficient was calculated as described by Hunter and Schmidt.[98]

To help assess the generalizability of the meta-analysis, the distribution of percentage error among the single measurement studies included in the pooled weighted meta-analysis was compared with that of all sets of data for that method listed in table 1, using a two-sample Kolmogorov-Smirnov test. This was performed using OriginPro 8.1 statistical software (Origin Lab, Northampton, MA). The database was constructed and all pooled calculations performed using Microsoft Excel 2008 (Microsoft Corporation, Redmond, WA).

Results

Table 1 lists those studies included in the review for each of the methods, along with the location of the data collection for each study (operating theater, intensive care unit) and clinical situation where relevant. Where multiple studies at different time points were reported, they are listed separately. The number of data points *n* for each study, bias, and precision (defined as one SD of the difference between paired measurements by the method and thermodilution) are listed.

In the pooled weighted calculation of bias, precision, and percentage error, 24 studies were found to provide suitable data for the pulse contour method, 8 studies for P_{CO_2}RB, and 13 studies for TEB. Only two studies met the criteria for inclusion among those examining esophageal Doppler. These data are listed in bold type in table 1. Results for mean weighted pooled bias, precision, and percentage error are shown in table 2. Bias was negligible for all methods except esophageal Doppler. Percentage error was lowest for pulse contour methods (41.3%) and highest for P_{CO_2}RB (44.5%), but these differences did not reach statistical significance.

Of these 47 studies, slightly over half provided data suitable for a pooled weighted calculation of correlation: 12 studies for the pulse contour method, 5 studies for P_{CO_2}RB, 8 studies for TEB, and both studies for esophageal Doppler. Results are shown in table 3. The pooled weighted correlation coefficient was lowest for PCO_2RB (0.57) and highest for TEB (0.79).

The distributions of percentage error for those studies included in the pooled weighted meta-analysis and for all data sets in all the studies listed in table 1 are plotted in figure 2. Kolmogorov-Smirnov testing for each method revealed no significant differences between the distributions (pulse contour: [Kolmogorov-Smirnov statistic] $D = 0.116$, $P = 0.91$; esophageal Doppler: $D = 0.429$, $P = 0.81$; P_{CO_2}RB: $D = 0.191$, $P = 0.94$; TEB: $D = 0.128$, $P = 0.99$).

Discussion

In a pooled weighted meta-analysis of 47 studies comparing agreement of four methods for minimally invasive cardiac output measurement with thermodilution, we found that none of the four methods met the criteria for acceptability of agreement suggested by Critchley and Critchley,[89] which is a percentage error of 30% or less.

There are some limitations to our meta-analysis which should be considered. Among the 47 studies that met the criteria for the pooled weighted meta-analysis, 34 (72%) were done in cardiac surgery patients. During development, many devices are tested in patients undergoing cardiac surgery, as this is a readily accessible patient subgroup in whom

Table 2. Agreement between Each of the Four Methods and Thermodilution

Method (*N* Studies)	*n*	Bias *L/min* Mean [±95% CI]	Precision *L/min*	Percentage Error Mean [±95% CI]
Pulse contour (*N* = 24)	714	−0.00 [±0.09]	1.22	41.3 [±2.7]%
Esophageal Doppler (*N* = 2)	57	−0.77 [±0.29]	1.07	42.1 [±9.9]%
P_{CO_2}RB (*N* = 8)	167	−0.05 [±0.17]	1.12	44.5 [±6.0]%
TEB (*N* = 13)	435	−0.10 [±0.11]	1.14	42.9 [±3.6]%

Pooled weighted data, showing agreement between each of the four methods and bolus thermodilution from the studies that met the statistical criteria for inclusion in the meta-analysis, where a single independent measurement from each subject could be identified. 95% CI = 95% confidence intervals; *n* = total number of pooled measurements; P_{CO_2}RB = partial carbon dioxide rebreathing method; Percentage Error = limits of agreement (1.96 SD)/mean cardiac output; Precision = one standard deviation (1 SD) of the difference between paired measurements; TEB = transthoracic electrical bioimpedance.

Table 3. Correlation between the Four Methods and Thermodilution

Method (*N* Studies)	*n*	*r*
Pulse contour (*N* = 12)	359	0.75
Esophageal Doppler (*N* = 2)	57	0.69
P_{CO_2}RB (*N* = 5)	104	0.57
TEB (*N* = 8)	288	0.79

Pooled weighted data, showing correlation between the four methods and bolus thermodilution from the studies that met the statistical criteria for inclusion in the meta-analysis, where a single independent measurement from each subject could be identified.

n = total number of pooled measurements; P_{CO_2}RB = partial carbon dioxide rebreathing method; *r* = correlation coefficient; TEB = transthoracic electrical bioimpedance.

monitoring with pulmonary artery catheters is routine practice in many centers. Subsequent independent testing in the same patient subgroup does not provide information about the performance of the device in wider clinical practice. The potential for this to restrict the generalizability of the analysis was a concern. Figure 2 and Kolmogorov-Smirnov testing revealed no significant differences between the distribution of percentage error among the single measurement studies included in the pooled weighted meta-analysis and the distribution of all sets of data for that method listed in table 1. This suggests that studies included in the pooled weighted meta-analysis provide a representative sample of the total number of studies in the field and that the pooled weighted percentage error for each method is a valid indicator of its precision across the full range of clinical situations in which they have been studied to date. The asymmetric nature of most of these distributions makes it clear that a simple nonparametric estimation (*e.g.*, a median) of overall percentage error would underestimate the pooled weighted percentage error significantly and give an unduly favorable estimate of precision for some of these methods.

Only two studies, incorporating 57 measurements, by esophageal Doppler were eligible for inclusion, which ex-

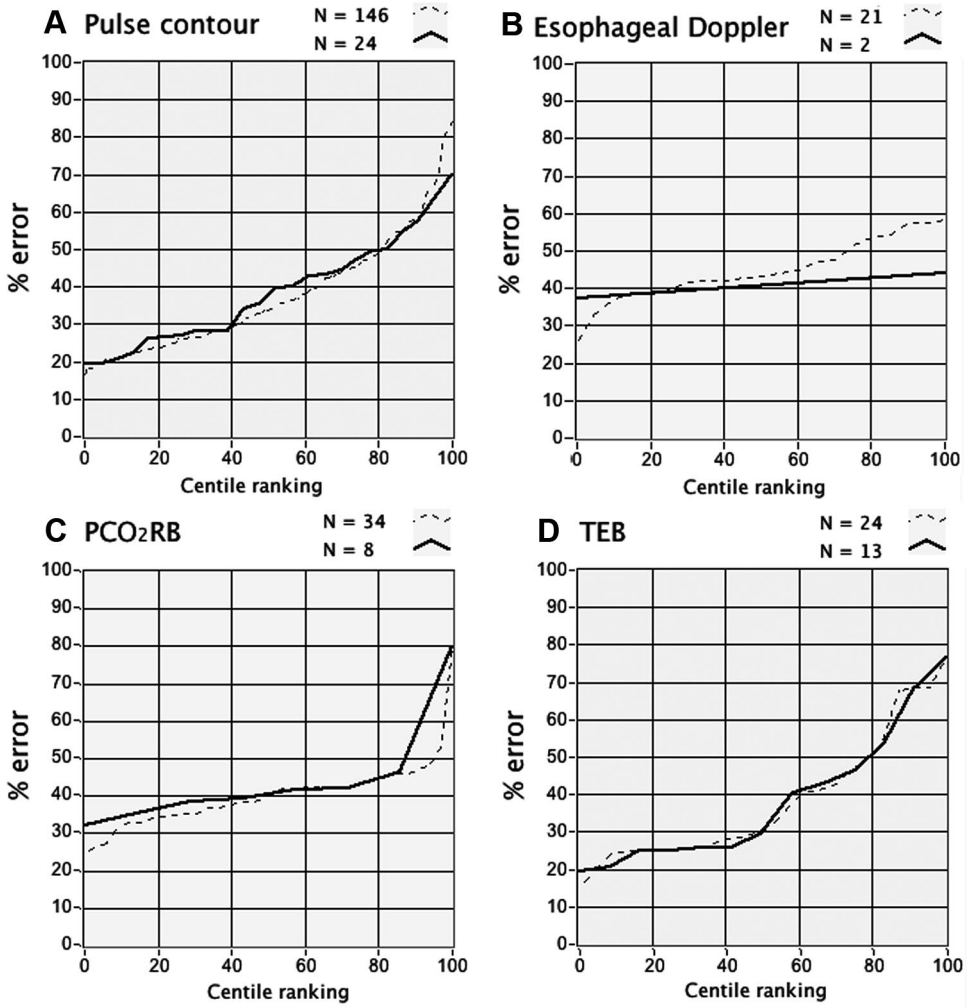

Fig. 2. Distribution of percentage error for each method, from lowest (first centile) to highest (hundredth centile). *A*: Pulse contour; *B*: esophageal Doppler; *C*: partial carbon dioxide rebreathing (P_{CO_2}RB); *D*: transthoracic electrical bioimpedance (TEB). The heavy line represents the single-measurement studies included in the pooled weighted meta-analysis. The broken line represents all sets of measurements among all studies listed in table 1 for that method.

plains the wide confidence intervals for the percentage error and bias, and limited conclusions can be drawn from the pooled weighted data in table 2, although figure 2B suggests that these two studies are consistent with the broader body of published work on this method. Schober *et al.* recently reviewed studies on the accuracy and precision of esophageal Doppler measurement of cardiac output. Applying a nonparametric approach to pooling of their data, they found a median underestimate of 0.37 l/min, and an upper quartile for limits of agreement of 5.0 l/min, relative to a variety of other methods (predominantly thermodilution).[90] However, both their review and our analysis indicate that a negative bias is present for esophageal Doppler measurement, suggesting that the unmeasured proportion of cardiac output to the upper body that is assumed may need to be increased.

A further concern was the 10 yr time span of this review of a rapidly developing field. Improvements in available technologies may mean that our findings do not reflect current performance of these methods. We therefore contrasted data from studies published over the last 5 yr with the findings in table 2. The pooled weighted percentage error for pulse contour (16 studies) was 46.4%, for P_{CO_2}RB (2 studies) was 42.0%, and for TEB (6 studies) was 44.7% (unchanged for esophageal Doppler). Although numbers in this subanalysis are small, there is no evidence that precision of agreement with thermodilution has improved over the interval covered by our review. However, there is ongoing need for repeat review of the performance of all these technologies into the future, to determine whether incremental improvements in precision of agreement are being achieved. Development of newer and more precise "gold standards" for comparison should prompt further validation studies, and more reliable data for future comparisons.

A recent addition to the range of devices available is the Vigileo FloTrac (Edwards Lifesciences, Irvine, CA) pulse contour device. The focus of this review was on the performance of four generic methods in agreement with a common reference standard. We deliberately did not stratify our analysis to examine the performance of individual devices, for simplicity and to avoid either a commercial or proprietary emphasis, or weakening of the statistical power of the analysis. However, our data can be compared with a recent review and meta-analysis of studies on the accuracy and precision of the FloTrac by Mayer *et al.*[91] These authors found a percentage error of 44% for earlier versions of the device and 30% for later versions (v1.07+), but this review excluded studies involving patients with hemodynamic instability or vasodilatory states, thus restricting their analysis to cardiac surgery alone. Subanalysis of our data for studies on the FloTrac found a percentage error of 47.3% for earlier versions and 44.7% for v1.07+, but the latter contained two studies in septic or critically ill patients,[99,100] where high cardiac outputs and hemodynamic instability present greater challenges to the accuracy and precision of a measurement device. Therefore these results for the FloTrac still compared well with the other methods we have surveyed in the current review. The FloTrac system has the advantage of not requiring a calibration maneuver as is required by other commonly used pulse contour devices: PiCCO (Pulsion Medical Systems) which is calibrated by transpulmonary thermodilution, and PulseCO (LiDCO Ltd, Cambridge, United Kingdom) which uses an injected lithium bolus for indicator dilution cardiac output measurement. However, our results do not take into account data from recent case reports questioning the ability of FloTrac to accurately track cardiac output during dramatic intraoperative changes in hemodynamics.[101,102]

In 1999, Critchley and Critchley reviewed 25 studies comparing TEB and esophageal Doppler with thermodilution.[89] In an unweighted pooling of the data from these studies, they found a mean percentage error of 37% for TEB and 65% for esophageal Doppler. They went on to suggest a narrower limit of 30% as acceptable, which they derived from the theoretical scatter expected in agreement between two methods whose agreement is each $\pm$ 20% in relation to the true value. In this case, agreement between the two methods will average 28.3%, which they rounded up to 30% for simplicity. Their argument assumed that the precision of thermodilution as the reference method was no worse than $\pm$ 20% in relation to the real cardiac output. This they justified with reference to a review by Stetz *et al.* which examined the accuracy and reproducibility of measurement of cardiac output by thermodilution, and a study by Mackenzie *et al.* which compared three different devices for thermodilution measurement.[103,104]

However, there are significant reasons to question these assumptions in broader clinical practice. The studies included in the review by Stetz *et al.*[103] examined the reproducibility of repeat measurement of cardiac output by thermodilution and were conducted in the cardiac catheterization laboratory or coronary/intensive care unit. They pointed out that measurements were invariably made during intervals of cardiovascular stability, so as to minimize the confounding effect of real variations in cardiac output on assessment of the reproducibility of measurement. The study by MacKenzie *et al.*[104] was carried out *in vitro* on a circulation simulator and was not designed to be a test of accuracy and precision of thermodilution under clinical conditions. In contrast, the majority of the studies in our review were conducted intraoperatively or postoperatively, often in hemodynamically unstable patients, and deliberately sought to test the accuracy and precision of the various methods under sometimes difficult clinical conditions.

Recent studies are more revealing of the accuracy and precision of thermodilution in less tightly controlled perioperative conditions and during hemodynamic instability. Botero *et al.* compared bolus thermodilution in patients undergoing coronary artery surgery against an invasive *in vivo* gold standard technique in the form of an ultrasonic transit time flow probe positioned on the ascending aorta. Percentage error was 41.7% precardiopulmonary bypass and 46.1% postcardiopulmonary bypass.[105] Bajorat *et al.* compared bolus thermodilution with a similar flow probe in a pig model where hemodynamic instability was induced pharmacologically, and found a percentage er-

ror of 48.6% overall.[106] A number of the minimally invasive methods that we have reviewed here were also tested in parallel in these studies. Notably, thermodilution did not perform significantly better than any of them.

This raises questions about the appropriateness of imposing arbitrary limits on the acceptability of accuracy and precision of cardiac output measurement. Feldman, in a recent editorial, proposed a more dynamic approach to assessment of acceptability of agreement, based on receiver operating curve theory, and called Critchley and Critchley's 30% limits "a simplification that makes assumptions about the accuracy of thermodilution and does not consider the impact on decision-making."[4] Indeed, few practicing clinicians would reject thermodilution *via* the pulmonary artery catheter as a valuable monitoring tool in appropriate patients such as in cardiac surgery, despite the evidence cited above of poorer precision than previously assumed. Nevertheless, of the 51 papers listed in table 1 which were published within the last 5 yr, 63% quote Critchley and Critchley's criterion for acceptability in assessing the technique being tested in their study.

The efficacy of a clinical monitor involves many factors other than its absolute accuracy, and includes safety, convenience and adaptability, and cost. Each method reviewed has its practical limitations and advantages. A calibration maneuver is required for some pulse contour techniques but, in common with TEB, they can potentially be used in the awake patient. The P_{CO_2}RB method is entirely noninvasive in the intubated patient, but its use is restricted to this group. Pulse contour and Doppler devices can provide additional indices of volume status based on the shape of the measured waveform. Many of these devices require expensive single-use components (transducers, probes, or valves). The value of the information provided by these methods in influencing management and improving patient outcomes is currently debated,[1–3] and this is an evolving field. Clinicians may in fact be willing to accept lower accuracy in return for monitoring with less invasiveness than traditional methods like thermodilution *via* a pulmonary artery catheter, placement of which causes occasional serious injury to the patient, and which has been associated with poorer outcomes in some studies.[107]

Although often seen as a critical variable in studies in the field, the percentage error of agreement is only one marker of acceptability of a method, and it incorporates multiple components for both the method and the reference method: systematic alinearity of a method, interpatient variability, and intrapatient variability. The last is related to the task of tracking changes in cardiac output. In major surgery, reliable real time tracking of the direction of *changes* in cardiac output is arguably more important than the ability of the monitor to deliver a highly accurate single measurement under stable conditions.[108,109]

In our meta-analysis, the four methods achieved limits of agreement that were very similar. This is significant, as the various methods are based on quite different physical and physiologic principles. This suggests a fundamental limitation exists to the precision of agreement with a given reference standard like thermodilution that can be achieved in clinical practice, and which is independent of the particular method being tested. This level of precision of agreement remains well outside the 30% limits across a range of patient groups and clinical situations. Based on our empirical findings, a percentage error in agreement with thermodilution of $\pm$ 45% represents a more realistic expectation of achievable precision in clinical practice. Using the same mathematical theory as applied by Critchley and Critchley, this is consistent with percentage errors of approximately $\pm$ 30% for both thermodilution and the test method in their agreement with the real cardiac output.

References

1. Abbas SM, Hill AG: Systematic review of the literature for the use of oesophageal Doppler monitor for fluid replacement in major abdominal surgery. Anaesthesia 2008; 63: 44–51
2. Bundgaard-Nielsen M, Holte K, Secher NH, Kehlet H: Monitoring of peri-operative fluid administration by individualized goal-directed therapy. Acta Anaesthesiol Scand 2007; 51:331–40
3. Funk DJ, Moretti EW, Gan TJ: Minimally invasive cardiac output monitoring in the perioperative setting. Anesth Analg 2009; 108:887–97
4. Feldman JM: Is it a bird? Is it a plane? The role of patient monitors in medical decision making. Anesth Analg 2009; 108:707–10
5. Mayer J, Boldt J, Beschmann R, Stephan A, Suttner S: Uncalibrated arterial pressure waveform analysis for less-invasive cardiac output determination in obese patients undergoing cardiac surgery. Br J Anaesth 2009; 103:185–90
6. Senn A, Button D, Zollinger A, Hofer CK: Assessment of cardiac output changes using a modified FloTrac/Vigileo algorithm in cardiac surgery patients. Crit Care 2009; 13:R32
7. Biancofiore G, Critchley LA, Lee A, Bindi L, Bisà M, Esposito M, Meacci L, Mozzo R, DeSimone P, Urbani L, Filipponi F: Evaluation of an uncalibrated arterial pulse contour cardiac output monitoring system in cirrhotic patients undergoing liver surgery. Br J Anaesth 2009; 102:47–54
8. Østergaard M, Nielsen J, Nygaard E: Pulse contour cardiac output: An evaluation of the FloTrac method. Eur J Anaesthesiol 2009; 26:484–9
9. Mutoh T, Ishikawa T, Nishino K, Yasui N: Evaluation of the FloTrac uncalibrated continuous cardiac output system for perioperative hemodynamic monitoring after subarachnoid hemorrhage. J Neurosurg Anesthesiol 2009; 21:218–25
10. Della Rocca G, Costa MG, Chiarandini P, Bertossi G, Lugano M, Pompei L, Coccia C, Sainz-Barriga M, Pietropaoli P: Arterial pulse cardiac output agreement with thermodilution in patients in hyperdynamic conditions. J Cardiothorac Vasc Anesth 2008; 22:681–7
11. Mayer J, Boldt J, Wolf MW, Lang J, Suttner S: Cardiac output derived from arterial pressure waveform analysis in patients undergoing cardiac surgery: Validity of a second generation device. Anesth Analg 2008; 106:867–72
12. Mehta Y, Chand RK, Sawhney R, Bhise M, Singh A, Trehan N: Cardiac output monitoring: Comparison of a new arterial pressure waveform analysis to the bolus thermodilution technique in patients undergoing off-pump coronary artery bypass surgery. J Cardiothorac Vasc Anesth 2008; 22:394–9
13. Zimmermann A, Kufner C, Hofbauer S, Steinwendner J, Hitzl W, Fritsch G, Schistek R, Kirnbauer M, Pauser G: The accuracy of the Vigileo/FloTrac continuous cardiac

output monitor. J Cardiothorac Vasc Anesth 2008; 22: 388–93

14. Staier K, Wiesenack C, Günkel L, Keyl C: Cardiac output determination by thermodilution and arterial pulse waveform analysis in patients undergoing aortic valve replacement. Can J Anaesth 2008; 55:22–8
15. McGee WT, Horswell JL, Calderon J, Janvier G, Van Severen T, Van den Berghe G, Kozikowski L: Validation of a continuous, arterial pressure-based cardiac output measurement: A multicenter, prospective clinical trial. Crit Care 2007; 11:R105
16. Cannesson M, Attof Y, Rosamel P, Joseph P, Bastien O, Lehot JJ: Comparison of FloTrac cardiac output monitoring system in patients undergoing coronary artery bypass grafting with pulmonary artery cardiac output measurements. Eur J Anaesthesiol 2007; 24:832–9
17. de Waal EE, Kalkman CJ, Rex S, Buhre WF: Validation of a new arterial pulse contour-based cardiac output device. Crit Care Med 2007; 35:1904–9
18. Prasser C, Bele S, Keyl C, Schweiger S, Trabold B, Amann M, Welnhofer J, Wiesenack C: Evaluation of a new arterial pressure-based cardiac output device requiring no external calibration. BMC Anesthesiology 2007; 7:9
19. Mayer J, Boldt J, Schöllhorn T, Röhm KD, Mengistu AM, Suttner S: Semi-invasive monitoring of cardiac output by a new device using arterial pressure waveform analysis: A comparison with intermittent pulmonary artery thermodilution in patients undergoing cardiac surgery. Br J Anaesth 2007; 98:176–82
20. Manecke GR, Jr., Auger WR: Cardiac output determination from the arterial pressure wave: Clinical testing of a novel algorithm that does not require calibration. J Cardiothorac Vasc Anesth 2007; 21:3–7
21. Breukers RM, Sepehrkhouy S, Spiegelenberg SR, Groeneveld AB: Cardiac output measured by a new arterial pressure waveform analysis method without calibration compared with thermodilution after cardiac surgery. J Cardiothorac Vasc Anesth 2007; 21:632–5
22. Button D, Weibel L, Reuthebuch O, Genoni M, Zollinger A, Hofer CK: Clinical evaluation of the FloTrac/Vigileo system and two established continuous cardiac output monitoring devices in patients undergoing cardiac surgery. Br J Anaesth 2007; 99:329–36
23. Chakravarthy M, Patil TA, Jayaprakash K, Kalligudd P, Prabhakumar D, Jawali V: Comparison of simultaneous estimation of cardiac output by four techniques in patients undergoing off-pump coronary artery bypass surgery—a prospective observational study. Ann Card Anaesth 2007; 10:121–6
24. Opdam HI, Wan L, Bellomo R: A pilot assessment of the FloTrac cardiac output monitoring system. Intensive Care Med 2007; 33:344–9
25. Sander M, Spies CD, Grubitzsch H, Foer A, Muller M, von Heymann C: Comparison of uncalibrated arterial waveform analysis in cardiac surgery patients with thermodilution cardiac output measurements. Crit Care 2006; 10: R164
26. Breukers RM, Willems JH, de Wilde R, Jansen JR, Groeneveld AJ: Less invasive indicators of changes in thermodilution cardiac output by ventilatory changes after cardiac surgery. Eur J Anaesthesiol 2009; 26:863–7
27. Compton F, Wittrock M, Schaefer JH, Zidek W, Tepel M, Scholze A: Noninvasive cardiac output determination using applanation tonometry-derived radial artery pulse contour analysis in critically ill patients. Anesth Analg 2008; 106:171–4
28. Yamashita K, Nishiyama T, Yokoyama T, Abe H, Manabe M: The effects of vasodilation on cardiac output measured by PiCCO. J Cardiothorac Vasc Anesth 2008; 22: 688–92
29. de Wilde RB, Schreuder JJ, van den Berg PC, Jansen JR: An evaluation of cardiac output by five arterial pulse contour techniques during cardiac surgery. Anaesthesia 2007; 62:760–8
30. Ostergaard M, Nielsen J, Rasmussen JP, Berthelsen PG: Cardiac output—pulse contour analysis *versus* pulmonary artery thermodilution. Acta Anaesthesiol Scand 2006; 50:1044–9
31. Felbinger TW, Reuter DA, Eltzschig HK, Bayerlein J, Goetz AE: Cardiac index measurements during rapid preload changes: A comparison of pulmonary artery thermodilution with arterial pulse contour analysis. J Clin Anesth 2005; 17:241–8
32. Sander M, von Heymann C, Foer A, von Dossow V, Grosse J, Dushe S, Konertz WF, Spies CD: Pulse contour analysis after normothermic cardiopulmonary bypass in cardiac surgery patients. Crit Care 2005; 9:R729–34
33. Wouters PF, Quaghebeur B, Sergeant P, Van Hemelrijck J, Vandermeersch E: Cardiac output monitoring using a brachial arterial catheter during off-pump coronary artery bypass grafting. J Cardiothorac Vasc Anesth 2005; 19:160–4
34. de Vaal JB, de Wilde RB, van den Berg PC, Schreuder JJ, Jansen JR: Less invasive determination of cardiac output from the arterial pressure by aortic diameter-calibrated pulse contour. Br J Anaesth 2005; 95:326–31
35. Della Rocca G, Costa MG, Coccia C, Pompei L, Di Marco P, Vilardi V, Pietropaoli P: Cardiac output monitoring: Aortic transpulmonary thermodilution and pulse contour analysis agree with standard thermodilution methods in patients undergoing lung transplantation. Can J Anaesth 2003; 50:707–11
36. Grigorov Tzenkov I, Arnal Velasco D, Perez Peña JM, Olmedilla Arnal L, Garutti Martínez I, Sanz Fernández J: Cardiac output by femoral arterial thermodilution-calibrated pulse contour analysis during liver transplantation: Comparison with pulmonary artery thermodilution. Transplant Proc 2003; 35:1920–2
37. Mielck F, Buhre W, Hanekop G, Tirilomis T, Hilgers R, Sonntag H: Comparison of continuous cardiac output measurements in patients after cardiac surgery. J Cardiothorac Vasc Anesth 2003; 17:211–6
38. Della Rocca G, Costa MG, Pompei L, Coccia C, Pietropaoli P: Continuous and intermittent cardiac output measurement: Pulmonary artery catheter *versus* aortic transpulmonary technique. Br J Anaesth 2002; 88:350–6
39. Romano SM, Pistolesi M: Assessment of cardiac output from systemic arterial pressure in humans. Crit Care Med 2002; 30:1834–41
40. Felbinger TW, Reuter DA, Eltzschig HK, Moerstedt K, Goedje O, Goetz AE: Comparison of pulmonary arterial thermodilution and arterial pulse contour analysis: Evaluation of a new algorithm. J Clin Anesth 2002; 14:296–301
41. Rauch H, Müller M, Fleischer F, Bauer H, Martin E, Böttiger BW: Pulse contour analysis *versus* thermodilution in cardiac surgery patients. Acta Anaesthesiol Scand 2002; 46:424–9
42. Segal E, Katzenelson R, Berkenstadt H, Perel A: Transpulmonary thermodilution cardiac output measurement using the axillary artery in critically ill patients. J Clin Anesth 2002; 14:210–3
43. Jansen JR, Schreuder JJ, Mulier JP, Smith NT, Settels JJ, Wesseling KH: A comparison of cardiac output derived from the arterial pressure wave against thermodilution in cardiac surgery patients. Br J Anaesth 2001; 87:212–22
44. Hirschl MM, Kittler H, Woisetschläger C, Siostrzonek P, Staudinger T, Kofler J, Oschatz E, Bur A, Gwechenberger M, Laggner AN: Simultaneous comparison of thoracic bioimpedance and arterial pulse waveform-derived cardiac output with thermodilution measurement. Crit Care Med 2000; 28:1798–802
45. Zöllner C, Haller M, Weis M, Mörstedt K, Lamm P, Kilger

E, Goetz AE: Beat-to-beat measurement of cardiac output by intravascular pulse contour analysis: A prospective criterion standard study in patients after cardiac surgery. J Cardiothorac Vasc Anesth 2000; 14:125–9

46. Missant C, Rex S, Wouters PF: Accuracy of cardiac output measurements with pulse contour analysis (PulseCO) and Doppler echocardiography during off-pump coronary artery bypass grafting. Eur J Anaesthesiol 2008; 25:243–8
47. Costa MG, Della Rocca G, Chiarandini P, Mattelig S, Pompei L, Barriga MS, Reynolds T, Cecconi M, Pietropaoli P: Continuous and intermittent cardiac output measurement in hyperdynamic conditions: Pulmonary artery catheter vs. lithium dilution technique. Intensive Care Med 2008; 34:257–63
48. Garcia-Rodriguez C, Pittman J, Cassell CH, Sum-Ping J, El-Moalem H, Young C, Mark JB: Lithium dilution cardiac output measurement: A clinical assessment of central venous and peripheral venous indicator injection. Crit Care Med 2002; 30:2199–204
49. Kotake Y, Yamada T, Nagata H, Suzuki T, Serita R, Katori N, Takeda J, Shimizu H: Improved accuracy of cardiac output estimation by the partial CO2 rebreathing method. J Clin Monit Comput 2009; 23:149–55
50. Killick CJ, Parkin WG: Non-invasive cardiac output measurement using a fast mixing box to measure carbon dioxide elimination. Anaesth Intensive Care 2008; 36: 665–73
51. Peyton PJ, Thompson D, Junor P: Non-invasive automated measurement of cardiac output during stable cardiac surgery using a fully integrated differential CO(2) Fick method. J Clin Monit Comput 2008; 22:285–92
52. Ng JM, Chow MY, Ip-Yam PC, Goh MH, Agasthian T: Evaluation of partial carbon dioxide rebreathing cardiac output measurement during thoracic surgery. J Cardiothorac Vasc Anesth 2007; 21:655–8
53. Tachibana K, Imanaka H, Takeuchi M, Nishida T, Takauchi Y, Nishimura M: Effects of reduced rebreathing time, in spontaneously breathing patients, on respiratory effort and accuracy in cardiac output measurement when using a partial carbon dioxide rebreathing technique: A prospective observational study. Crit Care 2005; 9:R569–74
54. Rocco M, Spadetta G, Morelli A, Dell'Utri D, Porzi P, Conti G, Pietropaoli P: A comparative evaluation of thermodilution and partial CO2 rebreathing techniques for cardiac output assessment in critically ill patients during assisted ventilation. Intensive Care Med 2004; 30:82–7
55. Tachibana K, Imanaka H, Takeuchi M, Takauchi Y, Miyano H, Nishimura M: Noninvasive cardiac output measurement using partial carbon dioxide rebreathing is less accurate at settings of reduced minute ventilation and when spontaneous breathing is present. ANESTHESIOLOGY 2003; 98:830–7
56. Kotake Y, Moriyama K, Innami Y, Shimizu H, Ueda T, Morisaki H, Takeda J: Performance of noninvasive partial CO2 rebreathing cardiac output and continuous thermodilution cardiac output in patients undergoing aortic reconstruction surgery. ANESTHESIOLOGY 2003; 99:283–8
57. Tachibana K, Imanaka H, Miyano H, Takeuchi M, Kumon K, Nishimura M: Effect of ventilatory settings on accuracy of cardiac output measurement using partial CO(2) rebreathing. ANESTHESIOLOGY 2002; 96:96–102
58. Murias GE, Villagrá A, Vatua S, del Mar Fernandez M, Solar H, Ochagavía A, Fernández R, López Aguilar J, Romero PV, Blanch L: Evaluation of a noninvasive method for cardiac output measurement in critical care patients. Intensive Care Med 2002; 28:1470–4
59. Odenstedt H, Stenqvist O, Lundin S: Clinical evaluation of a partial CO2 rebreathing technique for cardiac output monitoring in critically ill patients. Acta Anaesthesiol Scand 2002; 46:152–9
60. Binder JC, Parkin WG: Non-invasive cardiac output determination: Comparison of a new partial-rebreathing technique with thermodilution. Anaesth Intensive Care 2001; 29:19–23
61. Nilsson LB, Eldrup N, Berthelsen PG: Lack of agreement between thermodilution and carbon dioxide-rebreathing cardiac output. Acta Anaesthesiol Scand 2001; 45:680–5
62. van Heerden PV, Baker S, Lim SI, Weidman C, Bulsara M: Clinical evaluation of the non-invasive cardiac output (NICO) monitor in the intensive care unit. Anaesth Intensive Care 2000; 28:427–30
63. Raue W, Swierzy M, Koplin G, Schwenk W: Comparison of electrical velocimetry and transthoracic thermodilution technique for cardiac output assessment in critically ill patients. Eur J Anaesthesiol 2009; 26:1067–71
64. Mekis D, Kamenik M, Starc V, Jeretin S: Cardiac output measurements with electrical velocimetry in patients undergoing CABG surgery: A comparison with intermittent thermodilution. Eur J Anaesthesiol 2008; 25:237–42
65. Gujjar AR, Muralidhar K, Banakal S, Gupta R, Sathyaprabha TN, Jairaj PS: Non-invasive cardiac output by transthoracic electrical bioimpedence in post-cardiac surgery patients: Comparison with thermodilution method. J Clin Monit Comput 2008; 22:175–80
66. Zoremba N, Bickenbach J, Krauss B, Rossaint R, Kuhlen R, Schälte G: Comparison of electrical velocimetry and thermodilution techniques for the measurement of cardiac output. Acta Anaesthesiol Scand 2007; 51:1314–9
67. Heringlake M, Handke U, Hanke T, Eberhardt F, Schumacher J, Gehring H, Heinze H: Lack of agreement between thermodilution and electrical velocimetry cardiac output measurements. Intensive Care Med 2007; 33:2168–72
68. Shoemaker WC, Wo CC, Chien LC, Lu K, Ahmadpour N, Belzberg H, Demetriades D: Evaluation of invasive and noninvasive hemodynamic monitoring in trauma patients. J Trauma 2006; 61:844–53; discussion 853–4
69. Suttner S, Schöllhorn T, Boldt J, Mayer J, Röhm KD, Lang K, Piper SN: Noninvasive assessment of cardiac output using thoracic electrical bioimpedance in hemodynamically stable and unstable patients after cardiac surgery: A comparison with pulmonary artery thermodilution. Intensive Care Med 2006; 32:2053–8
70. Engoren M, Barbee D: Comparison of cardiac output determined by bioimpedance, thermodilution, and the Fick method. Am J Crit Care 2005; 14:40–5
71. Albert NM, Hail MD, Li J, Young JB: Equivalence of the bioimpedance and thermodilution methods in measuring cardiac output in hospitalized patients with advanced, decompensated chronic heart failure. Am J Crit Care 2004; 13:469–79
72. Cotter G, Moshkovitz Y, Kaluski E, Cohen AJ, Miller H, Goor D, Vered Z: Accurate, noninvasive continuous monitoring of cardiac output by whole-body electrical bioimpedance. Chest 2004; 125:1431–40
73. Drazner MH, Thompson B, Rosenberg PB, Kaiser PA, Boehrer JD, Baldwin BJ, Dries DL, Yancy CW: Comparison of impedance cardiography with invasive hemodynamic measurements in patients with heart failure secondary to ischemic or nonischemic cardiomyopathy. Am J Cardiol 2002; 89:993–5
74. Sageman WS, Riffenburgh RH, Spiess BD: Equivalence of bioimpedance and thermodilution in measuring cardiac index after cardiac surgery. J Cardiothorac Vasc Anesth 2002; 16:8–14
75. Spiess BD, Patel MA, Soltow LO, Wright IH: Comparison of bioimpedance *versus* thermodilution cardiac output during cardiac surgery: Evaluation of a second-generation bioimpedance device. J Cardiothorac Vasc Anesth 2001; 15:567–73
76. Imhoff M, Lehner JH, Löhlein D: Noninvasive whole-body electrical bioimpedance cardiac output and invasive ther-

modilution cardiac output in high-risk surgical patients. Crit Care Med 2000; 28:2812–8

77. Barin E, Haryadi DG, Schookin SI, Westenskow DR, Zubenko VG, Beliaev KR, Morozov AA: Evaluation of a thoracic bioimpedance cardiac output monitor during cardiac catheterization. Crit Care Med 2000; 28:698–702
78. Critchley LA, Calcroft RM, Tan PY, Kew J, Critchley JA: The effect of lung injury and excessive lung fluid, on impedance cardiac output measurements, in the critically ill. Intensive Care Med 2000; 26:679–85
79. Lafanechère A, Albaladejo P, Raux M, Geeraerts T, Bocquet R, Wernet A, Castier Y, Marty J: Cardiac output measurement during infrarenal aortic surgery: Echoesophageal Doppler *versus* thermodilution catheter. J Cardiothorac Vasc Anesth 2006; 20:26–30
80. Sharma J, Bhise M, Singh A, Mehta Y, Trehan N: Hemodynamic measurements after cardiac surgery: Transesophageal Doppler *versus* pulmonary artery catheter. J Cardiothorac Vasc Anesth 2005; 19:746–50
81. Collins S, Girard F, Boudreault D, Chouinard P, Normandin L, Couture P, Caron MJ, Ruel M: Esophageal Doppler and thermodilution are not interchangeable for determination of cardiac output. Can J Anaesth 2005; 52:978–85
82. Kim K, Kwok I, Chang H, Han T: Comparison of cardiac outputs of major burn patients undergoing extensive early escharectomy: Esophageal Doppler monitor *versus* thermodilution pulmonary artery catheter. J Trauma 2004; 57:1013–7
83. Hullett B, Gibbs N, Weightman W, Thackray M, Newman M: A comparison of CardioQ and thermodilution cardiac output during off-pump coronary artery surgery. J Cardiothorac Vasc Anesth 2003; 17:728–32
84. Jaeggi P, Hofer CK, Klaghofer R, Fodor P, Genoni M, Zollinger A: Measurement of cardiac output after cardiac surgery by a new transesophageal Doppler device. J Cardiothorac Vasc Anesth 2003; 17:217–20
85. Moxon D, Pinder M, van Heerden PV, Parsons RW: Clinical evaluation of the HemoSonic monitor in cardiac surgical patients in the ICU. Anaesth Intensive Care 2003; 31:408–11
86. Leather HA, Wouters PF: Oesophageal Doppler monitoring overestimates cardiac output during lumbar epidural anaesthesia. Br J Anaesth 2001; 86:794–7
87. Penny JA, Anthony J, Shennan AH, De Swiet M, Singer M: A comparison of hemodynamic data derived by pulmonary artery flotation catheter and the esophageal Doppler monitor in preeclampsia. Am J Obstet Gynecol 2000; 183:658–61
88. Bland JM, Altman DG: Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; i:307–10
89. Critchley LA, Critchley JA: A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. J Clin Monit Comput 1999; 15:85–91
90. Schober P, Loer SA, Schwarte LA: Perioperative hemodynamic monitoring with transesophageal Doppler technology. Anesth Analg 2009; 109:340–53
91. Mayer J, Boldt J, Poland R, Peterson A, Manecke GR Jr: Continuous arterial pressure waveform-based cardiac output using the FloTrac/Vigileo: A review and meta-analysis. J Cardiothorac Vasc Anesth 2009; 23:401–6
92. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group: Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Ann Intern Med 2009; 151:264–9
93. Altman DG, Schulz KF, Moher D, Egger M, Davidoff F, Elbourne D, Gøtzsche PC, Lang T, CONSORT GROUP (Consolidated Standards of Reporting Trials): The revised CONSORT statement for reporting randomized trials: Explanation and elaboration. Ann Intern Med 2001; 134:663–94
94. Moher D, Schulz KF, Altman DG: The CONSORT statement: Revised recommendations for improving the quality of reports of parallel-group randomised trials. Lancet 2001; 357:1191–4
95. Bland JM, Altman DG: Measuring agreement in method comparison studies. Stat Methods Med Res 1999; 8:135–60
96. Bland JM, Altman DG: Agreement between methods of measurement with multiple observations per individual. J Biopharm Stat 2007; 17:571–82
97. Myles PS, Cui J: Using the Bland-Altman method to measure agreement with repeated measures. Br J Anaesth 2007; 99:309–11
98. Hunter JE, Schmidt FL: Methods of Meta-analysis: Correcting Error and Bias in Research Findings, 2nd Edition. Newbury Park, CA, Sage, 2004, pp 89
99. Compton FD, Zukunft B, Hoffmann C, Zidek W, Schaefer JH: Performance of a minimally invasive uncalibrated cardiac output monitoring system (Flotrac/Vigileo) in haemodynamically unstable patients. Br J Anaesth 2008; 100:451–6
100. Sakka SG, Kozieras J, Thuemer O, van Hout N: Measurement of cardiac output: A comparison between transpulmonary thermodilution and uncalibrated pulse contour analysis. Br J Anaesth 2007; 99:337–42
101. Collange O, Xavier L, Kuntzman H, Calon B, Schaeffer R, Pottecher T, Diemunsch P, Pessaux P: FloTrac for monitoring arterial pressure and cardiac output during phaeochromocytoma surgery. Eur J Anaesthesiol 2008; 25: 779–80
102. Vannucci A, Krejci V, Kangrga I: Performance of Vigileo and LiDCOplus cardiac output monitors during a prolonged cardiac arrest and resuscitation. Eur J Anaesthesiol 2009; 26:885–7
103. Stetz CW, Miller RG, Kelly GE, Raffin TA: Reliability of the thermodilution method in the determination of cardiac output in clinical practice. Am Rev Resp Dis 1982; 126: 1001–4
104. Mackenzie JD, Haites NE, Rawles JM: Method of assessing the reproducibility of blood flow measurement: Factors influencing the performance of thermodilution cardiac output computers. Br Heart J 1986; 55:14–24
105. Botero M, Kirby D, Lobato EB, Staples ED, Gravenstein N: Measurement of cardiac output before and after cardiopulmonary bypass: Comparison among aortic transit-time ultrasound, thermodilution, and noninvasive partial CO2 rebreathing. J Cardiothorac Vasc Anesth 2004; 18:563–72
106. Bajorat J, Hofmockel R, Vagts DA, Janda M, Pohl B, Beck C, Noeldge-Schomburg G: Comparison of invasive and less-invasive techniques of cardiac output measurement under different haemodynamic conditions in a pig model. Eur J Anaesthesiol 2006; 23:23–30
107. Vender JS: Pulmonary artery catheter utilization: The use, misuse, or abuse. J Cardiothorac Vasc Anesth 2006; 20:295–9
108. Bein B, Renner J, Scholz J, Tonner PH: Comparing different methods of cardiac output determination: A call for consensus. Eur J Anaesthesiol 2006; 23:710
109. Linton NW, Linton RA: Is comparison of changes in cardiac output, assessed by different methods, better than only comparing cardiac output to the reference method? Br J Anaesth 2002; 89:336–7