Measurement of cardiac output with a non-invasive continuous wave Doppler device versus the pulmonary artery catheter: a comparative study

Janet S Chan, Davendra Segara and Priya Nair

ABSTRACT

Introduction and aim: Cardiac index remains an important measured variable used to optimise fluid and haemodynamic support in the postoperative cardiac setting. Recent developments in non-invasive continuous wave Doppler devices enable rapid assessment of cardiac index with decreased morbidity. This study aimed to determine the clinical utility of one such device, the USCOM device (USCOM Ltd, Sydney, NSW), in assessing cardiac index compared with invasive continuous measurements of cardiac index using a pulmonary artery (PA) catheter.

Methods: A prospective study was undertaken in patients admitted to an intensive care unit after cardiac revascularisation, open-heart surgery or cardiac or pulmonary transplant, most of whom required haemodynamic support. Cardiac index was measured by a single operator using the USCOM device. Continuous cardiac index measurements using the PA catheter were obtained (blinded to USCOM measurements) within 15 minutes of the USCOM measurement.

Results: 30 patients were enrolled. Adequate Doppler signals were obtained in 26, yielding 34 paired measurements. Comparison of the two methods using a Bland–Altman analysis identified a bias of 0.22 with limits of agreement of –1.17 (–1.53 to –0.82) and 1.62 (1.26 to 1.97), representing limits of agreement for interchangeability of ±52%.

Conclusion: In a heterogeneous population of postoperative cardiac patients, non-invasive determination of cardiac index using USCOM had limited clinical utility. Doppler flow signal quality may have been affected by intrathoracic air, patient position and operator learning curve. Given accepted inherent inaccuracies of continuous cardiac output assessment, further investigation is required to validate the suitability of USCOM in this patient population.

Crit Care Resusc 2006; 8: 309–314

For editorial comment, see page 277

The timely, reliable and repeatable determination of cardiac function is essential for the management of patients in the intensive care unit after cardiac surgery. The recent development of minimally invasive techniques using ultrasound technology has enabled intensivists to monitor cardiac output rapidly and continuously with considerably less morbidity than when traditional invasive methods are used.

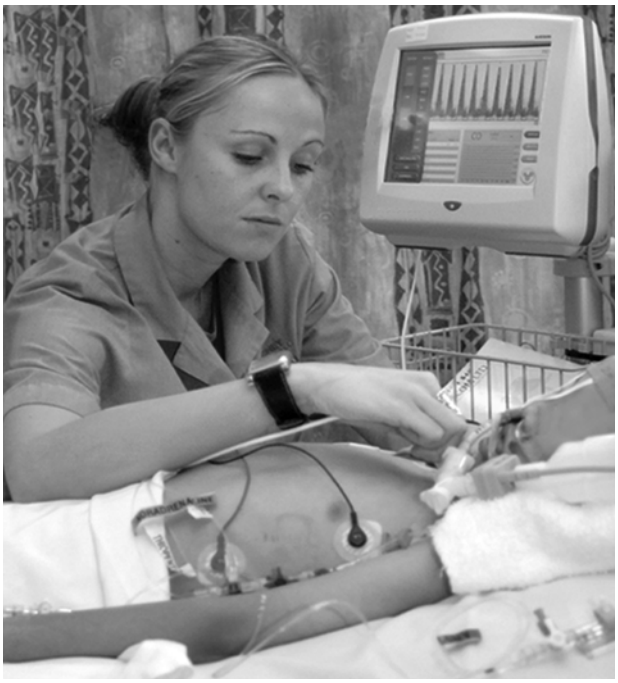
Clinicians make use of multiple indirect clinical variables, including peripheral perfusion and end-organ function such as level of consciousness and urine output, as indicators of cardiac function to make decisions on fluid management. In addition, cardiac function using indices such as pressure, cardiac output and cardiac index, as well as derived indices such as vascular resistance and global oxygen delivery and consumption, are also measured in the ICU to refine and optimise fluid and haemodynamic supports.[1]

Invasive determination of the cardiac output with a pulmonary artery (PA) catheter using the principle of thermodilution remains the mainstay for deriving indices of cardiac function in the modern intensive care setting. Despite the widespread use of the PA catheter, there has been much controversy about its utility and safety. A recent meta-analysis of randomised clinical trials concluded that the use of the PA catheter in critically ill patients neither increased overall mortality or days in hospital nor conferred benefit.[2] While the place of the PA catheter has been called into question, alternative techniques of cardiac output measurement, both invasive and non-invasive, have been compared with the more established thermodilution method.

Continuous wave Doppler is a well described method of evaluating cardiac function[3] and is the basis of echocardiographic measurement of cardiac output. However, its use in conventional echocardiography, either transthoracic or transoesophageal, requires considerable training and experience in ultrasonography.[4] The recent availability of the Ultra Sonic Cardiac Output Monitor (USCOM) continuous wave Doppler machine (USCOM Ltd, Sydney, NSW; Figure 1) promises to allow intensivists to acquire cardiac output data without the need for extensive formal training in ultrasonography. It provides information about beat-to-beat cardiac output and, as it is non-invasive, avoids the possible complications associated with the invasive PA catheter.[5,6] This device has been evaluated in other branches of acute medicine, including emergency and retrieval medicine.[7]

The USCOM machine is a portable bedside device based on a 2.0 or 3.3 MHz acoustic transducer, which uses

Figure 1. Ultra Sonic Cardiac Output Monitor (USCOM) continuous wave Doppler device



(Image courtesy of USCOM Ltd, Sydney, NSW.)

validated proprietary algorithms (USCOM) to determine cardiac output and cardiac index from pulmonary flow Doppler and pulmonary valve area.

We compared non-invasive measurement of cardiac index using the continuous wave Doppler USCOM device with invasive PA catheter continuous cardiac output measurements in a cohort of postoperative cardiac patients.

Methods

Patient population

We identified a cohort of patients who were considered to require invasive cardiac output monitoring with a PA catheter as an essential part of their perioperative management and were admitted to the intensive therapy unit across the St Vincent's Hospital campus in Sydney, NSW. At this institution, routine continuous cardiac output monitoring is not standard practice, but selected patients undergoing cardiothoracic surgery have PA catheters inserted after anaesthetic induction at the discretion of the treating cardiac anaesthetist. These include high-risk patients (poor ventricular function, emergency or re-do cardiac surgery) and those undergoing cardiac revascularisation, valve replacement surgery, thoracic aneurysm surgery, pulmonary thromboendarterectomy and orthotopic cardiac and pulmonary transplants.

The study received full Human Research and Ethics Committee approval. Post-cardiothoracic surgical patients admitted to the intensive therapy unit with a PA catheter already in place were eligible for the study. Written consent was not required as the USCOM device is a non-invasive probe, and the measurements obtained were not used to alter patient management. Verbal consent was sought from either the patients or their immediate relatives.

We prospectively studied cardiac output and cardiac index in this cohort of patients returning to the unit with PA catheters (8.5 Fr, Edwards Lifesciences, Irvine, Calif, USA) connected to pre-calibrated Continuous Cardiac Output monitors (Edwards Lifesciences). All patients were mechanically ventilated and in a supine reversed Trendelenburg position with a maximum angle of 30°.

Cardiac index measurements

Paired measurements of cardiac index were obtained using the PA catheter and continuous cardiac output monitor (CI_{PA}) and the USCOM device (CI_{USCOM}) within 15 minutes of each other. All measurements were made in the 24- to 48-hour period after cardiac surgery.

A single operator (JSC) with no previous ultrasound experience performed all CI_{USCOM} measurements as per the manufacturer's instructions and training. Measurements were made by placing a transducer on the left anterior surface of the patient's chest in the third or fourth parasternal intercostal space, aligned along the pulmonary outflow tract. The position and angle of the probe was adjusted until acoustic and Doppler signals demonstrated an optimal transpulmonary flow profile. Once graphical representation of flow versus time was captured, the area under the curve to be included for calculation of velocity time integral was refined using a stylus. Cardiac output was determined using pulmonary valve cross-sectional area derived from a proprietary height-indexed algorithm. CI_{USCOM} was then obtained after correcting for body surface area.

Immediately after completion of USCOM measurements, intensive care staff recorded cardiac output and CI_{PA} readings from the Continuous Cardiac Output monitor.

One to three sets of paired measurements were taken from each patient, with measurements ceasing when the patient was weaned from mechanical ventilation, or the PA catheter was removed.

All CI_{USCOM} measurements were performed by a single observer who was blinded to the measurements determined with the PA catheter. Similarly, the intensive care staff acquiring CI_{PA} were blinded to the USCOM readings.

Statistical analyses

Statistical analyses were performed with Statview 5.0 software (Abacus Systems, Berkeley, Cal, USA). CI_{USCOM} and CI_{PA} measurements were compared by paired *t* test, with a

Table 1. Characteristics of the patient cohort

Procedure	Number of patients ($n = 30$)
Coronary artery bypass grafting (CABG)	6
CABG plus aortic valve replacement	8 (2*)
Aortic valve replacement	1
CABG plus mitral valve replacement	1
Mitral valve replacement	1
Cardiac transplantation	7 (1*)
Bilateral sequential lung transplantation	3
Thoracic aneurysm dissection	1
Pulmonary endarterectomy	2 (1*)
Re-do sternotomy	2 (2*)†

* Numbers in parentheses are patients in whom a suitable Doppler signal could not be obtained.
† For the two re-do sternotomy patients, suitable signals were not obtained after either the first or re-do operations. ◆

P value < 0.05 considered statistically significant. Correlation between the two methods was assessed using the Pearson correlation coefficient.

Following the approach of Bland and Altman,[8] we calculated the mean bias between the two methods of cardiac index determination (PA catheter and USCOM), the standard deviation of the difference between paired measurements, the limits of agreement (mean bias ± 1.96 standard deviations), and the standard errors of bias and agreement. The difference between measurements by the two methods was graphed against the mean of the paired measurements, incorporating the limits of agreement.

The limits of agreement for interchangeability were calculated as the ratio between these limits and the mean of cardiac index for both methods (1.96 SD of the bias/mean). [9]

Results

Patient characteristics

The cohort comprised 30 patients (21 males; age [mean ±SD], 60.6 ±16.1 years; body surface area, 1.87 ±0.21 m^2) in whom suitable cardiac index measurements could be undertaken. Four of these were excluded as adequate acoustic or flow signals were not obtained.

The cohort included a wide variety of tertiary cardiothoracic patients (Table 1), with most (22 out of 30) requiring haemodynamic support, including various combinations of inotropes, vasopressors, vasodilators and mechanical supports, such as cardiac pacing (Table 2). One patient required intra-aortic balloon pump support. Three patients had atrial fibrillation. No adverse events or complications of the USCOM device were identified during the study.

Cardiac index measurements

Thirty four suitable paired measurements of cardiac output and cardiac index were obtained from the 26 patients. Invasive cardiac index (mean ±SD) assessed by the PA catheter was 2.78 ±0.73 L/min/m^2 (95% CI, 2.53–3.04 L/min/m^2), and assessed by the USCOM system was 2.56 ±0.63 L/min/m^2 (95% CI, 2.34–2.78 L/min/m^2). The Pearson correlation coefficient was 0.46 ($P = 0.006$). The cardiac index values obtained with the two methods are shown in Figure 2.

Using the methods of Bland and Altman, the mean of the differences (estimate of bias) between the two techniques was 0.22 L/min/m^2 (95% CI, 0.01–0.42 L/min/m^2; SD, 0.71; SE, 0.12). The limits of agreement for the two techniques were –1.17 L/min/m^2 (–1.53 to –0.82 L/min/m^2) and 1.62 L/min/m^2 (1.26 to 1.97 L/min/m^2) (Figure 3). The limits of agreement for interchangeability between the two methods were ± 52%.

Discussion

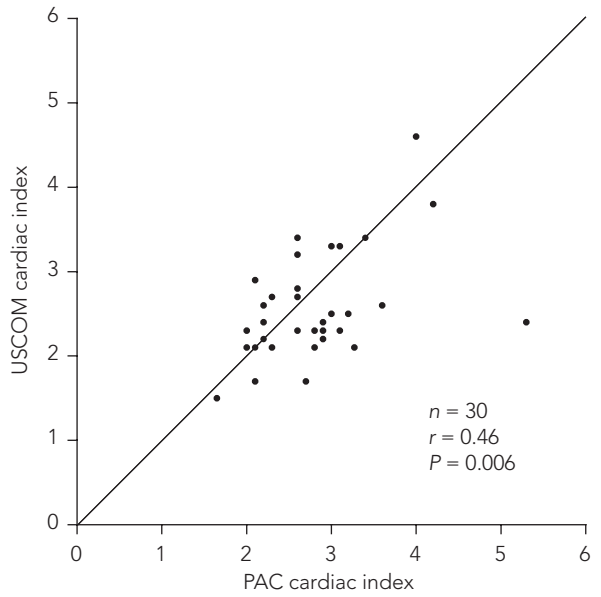
The recent development of portable continuous wave Doppler technology has facilitated the acquisition of beat-to-beat cardiac output data to aid in the management of the critically ill patient. The USCOM device has promise as a repeatable, cost-effective and non-invasive method of assessing cardiac function in the postoperative cardiac surgery intensive care setting.

Table 2. Types of haemodynamic support required

Haemodynamic support	Number of patients ($n = 30$)*
No haemodynamic support	8
Noradrenaline	8 (1†)
Adrenaline	1
Vasopressin	1 (1†)
Isoprenaline	5 (1†)
Dobutamine	5
Milrinone	3
Glyceryl trinitrate/sodium nitroprusside	10 (1†)
Inhaled nitric oxide	3 (1†)
Amiodarone	1
Pacing	5 (1†)
Intra-aortic balloon pump	1

* As patients had a combination of supports, numbers do not sum to 30.
† Numbers in parentheses are patients in whom a suitable Doppler signal could not be obtained. ◆

Figure 2. Cardiac index determined with the USCOM device versus the pulmonary artery catheter (PAC)



The line of agreement is superimposed for reference.

The purpose of this study was to determine the clinical utility of the USCOM continuous wave Doppler device by comparing USCOM measurements of cardiac index with those acquired from conventional continuous cardiac output measurement using a PA catheter. We chose to compare cardiac index instead of cardiac output, as indexing cardiac haemodynamics to body surface area removes uncertainty about the interpretation of cardiac output at the extremes of body size, making it more clinically useful as an end-point for therapy titration.

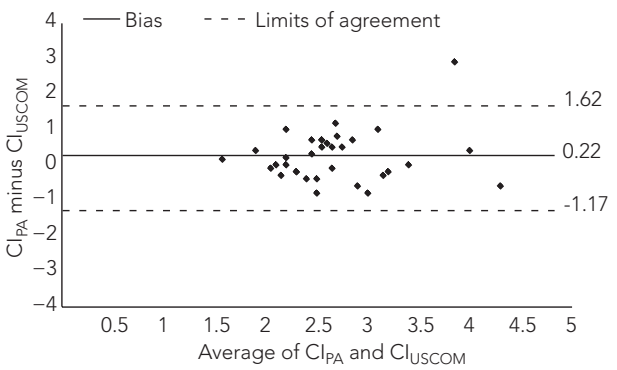
In this cohort of high-risk postoperative cardiac patients, we found poor correlation between the USCOM-derived cardiac index and the cardiac index derived from continuous measurements with a PA catheter. We identified a statistically significant poor correlation coefficient of 0.46.

In addition, we used the Bland–Altman method to determine agreement between the two methods, as correlation assesses only the strength of relation between the two methods and not agreement. This may confound interpretation, as data in poor agreement can show high correlation.[10] Thus, assessing agreement between the two methods reveals how much USCOM results differ from results of the PA catheter thermodilution method. How far apart paired measurements can be while maintaining clinical significance is a question of clinical judgement,[10] leaving the intensivist to decide if the limits of agreement are clinically acceptable. The data presented suggest that a cardiac index measurement acquired from the USCOM device is unlikely to exceed a measurement using the PA catheter by 1.62 L/min/m^2 or to be more than 1.17 L/min/m^2 below it. Furthermore, our data identified that our limits of agreement for interchangeability between the two methods was 52%. Critchley et al have proposed that when comparing a newer technique for cardiac output measurement to thermodilution, acceptable limits should be about 14%–28%.[11,12] Hence, in this population of high-risk postoperative cardiac patients with borderline cardiac function, the cardiac index derived by the USCOM device had poor correlation, wide limits of agreement and was not interchangeable with measurements derived from a PA catheter. Thus the device had limited clinical utility in this subset of intensive care patients.

Moreover, the PA catheter retains a place in cardiac intensive care as it provides measures of other important parameters besides cardiac output, such as pulmonary occlusion pressure and mixed venous oxygen saturation, as well as additional ports for central venous access.

Although recent studies have identified good agreement between the USCOM device and thermodilution techniques,[13–15] most of these studies were performed in cohorts of patients who underwent coronary revascularisation. Our study included a heterogeneous population of postoperative cardiac patients representative of patients encountered in our tertiary ICU. They included patients undergoing complex revascularisation, valve replacement and transplantation, most of whom had borderline cardiac function with low cardiac output states necessitating haemodynamic support. These patients were "preselected" for continuous cardiac monitoring, based either on their preoperative cardiac function or operative intervention. This

Figure 3. Bland–Altman plot of difference versus mean of cardiac index measurements by the two methods



CI_{PA} = cardiac index determined by pulmonary artery catheter.
CI_{USCOM} = cardiac index determined by USCOM device.

confounding by indication suggests that additional risk factors cannot all be known, measured or controlled.[10]

These significant differences in patient profile may account for the disparity observed in our study. Low cardiac output states are generally more difficult to measure by most direct and indirect methods and have been associated with more measurement error.[16, 17] Furthermore, measurement with the USCOM device depends on accurate estimation of the pulmonary velocity time integral and pulmonary valve cross-sectional area to derive cardiac indices. Postoperative alterations in flow characteristics distal to the pulmonary outflow tract caused by anatomic changes from the surgical anastomoses required for cardiac and pulmonary transplantation and prosthetic implantation may account for some of the observed discrepancies between the USCOM and PA catheter-derived measurements. In addition, lung transplant and pulmonary endarterectomy patients often have residual intrathoracic air, as do patients with ongoing air leaks, both of which may have attenuated the quality of the Doppler flow signal. Mechanical ventilation and excessive end expiratory pressure are known to alter cardiac output and may contribute to measurement variability.[18, 19]

Patient position is often a cause for suboptimal ultrasound and Doppler signal acquisition. A 10°–15° left lateral tilt is reported to improve Doppler signal using the USCOM device.[13] Because of their clinical status, patients in our cohort were not able to tolerate this tilt.

Although the operator learning curve for the USCOM device has been described as short and reproducible,[20] it may also have accounted for variability in flow signal. Analysis of this possibility was precluded by the blinding associated with the prospective methodology. The use of continuous wave Doppler with conventional echocardiography to determine cardiac output can be technically challenging and provide inconsistent measurements,[21, 22] even in the absence of the clinical confounders associated with our cohort. Acoustic and flow windows may well be more easily accessible from the suprasternal notch for transaortic flow in the presence of excess intrathoracic air or mechanical ventilation.

The use of continuous cardiac output monitoring as the reference method in this study introduces some inaccuracies. This type of monitoring uses the principle of thermodilution for assessing cardiac output. It uses PA catheters equipped with thermal heating filaments that are activated every 1–4 seconds, providing continuous measurements of cardiac output using an averaging technique. Potential advantages of continuous measurements over the bolus intermittent method are greater resistance to thermal noise and higher accuracy in low cardiac output states.[23] More significantly, it provides continuous rather than sequential information on cardiac output.[24]

Measuring physiological variables that may be rapidly changing is imprecise, and the clinical reference standard of thermodilution has an inherent error of ±10%–20%.[12] Hence, it is against this level of error that the USCOM device is being compared.

The multiple limitations of our study described above suggest that our results cannot be generalised to patients with normal cardiac function and uncomplicated cardiac surgery.

Conclusion

The USCOM device shows promising clinical utility in various fields of acute medicine because of its non-invasive nature. This is a great advantage when information on cardiac function is required, but the risks associated with more invasive methods outweigh the benefits. Roles are being established for this device in paediatrics, neonatology, emergency room and retrieval medicine.

However, in a cohort of high-risk patients with borderline cardiac function after cardiac surgery, we found poor agreement between cardiac index determined with the USCOM device and with the reference method of continuous cardiac output monitoring using a PA catheter.

While this study identified limited clinical utility of the USCOM device in this patient cohort, further studies in larger independent cohorts, including patients with both high and low cardiac output, perhaps utilising a suprasternal Doppler signal acquisition technique, is warranted to evaluate fully the role of the USCOM device after cardiac surgery.

Acknowlegements

We thank USCOM Ltd Sydney, NSW, for the loan of the USCOM device and technical support.

Author details

Janet S Chan, Intensivist[1]
Davendra Segara, Surgeon[2]
Priya Nair, Intensivist[1]
1 Intensive Therapy Unit, St Vincent's Hospital, Sydney, NSW.
2 Division of Surgery, St Vincent's Hospital, Sydney, NSW.
Correspondence: jsachan@hotmail.com

References

1 Bendjelid K, Schutz N, Suter P, Romand JA. Continuous cardiac output monitoring after cardiopulmonary bypass: a comparison

with bolus thermodilution measurement. *Intensive Care Med* 2006; 32: 919-22.

2 Shah MR, Hasselblad V, Stevenson LW, et al. Impact of the pulmonary artery catheter in critically ill patients: meta-analysis of randomized clinical trials. *JAMA* 2005; 294: 1664-70.

3 Donovan KD, Colreavy F. Echocardiography in intensive care: the basics. Part II. *Crit Care Resusc* 1999; 1: 296-310.

4 Brown JM. Use of echocardiography for hemodynamic monitoring. *Crit Care Med* 2002; 30: 1361-4.

5 Bernard GR, Sopko G, Cerra F, et al. Pulmonary artery catheterization and clinical outcomes: National Heart, Lung, and Blood Institute and Food and Drug Administration Workshop Report. Consensus Statement. *JAMA* 2000; 283: 2568-72.

6 Cholley BP. Benefits, risks and alternatives of pulmonary artery catheterization. *Curr Opin Anaesthesiol* 1998; 11: 645-50.

7 Knobloch K, Hubrich V, Rohmann P, et al. [Non-invasive determination of cardiac output by continuous wave Doppler in air rescue service]. *Anasthesiol Intensivmed Notfallmed Schmerzther* 2005; 40: 750-5.

8 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1: 307-10.

9 Lee A, Critchley LA. Acceptable limits of agreement need to be defined a priori [eletter]. *Br J Anaesth* 2005; 94: 287-91.

10 Altman DG, Bland JM. Measurement in medicine: the analysis of method comparison studies. *Statistician* 1983; 32: 307-17.

11 Critchley LA, Peng ZY, Fok BS, et al. Testing the reliability of a new ultrasonic cardiac output monitor, the USCOM, by using aortic flowprobes in anesthetized dogs. *Anesth Analg* 2005; 100: 748-53.

12 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.

13 Tan HL, Pinder M, Parsons R, et al. Clinical evaluation of USCOM ultrasonic cardiac output monitor in cardiac surgical patients in intensive care unit. *Br J Anaesth* 2005; 94: 287-91.

14 Knobloch K, Lichtenberg A, Winterhalter M, et al. Non-invasive cardiac output determination by two-dimensional independent Doppler during and after cardiac surgery. *Ann Thorac Surg* 2005; 80: 1479-83.

15 Chand R, Mehta Y, Trehan N. Cardiac output estimation with a new Doppler device after off-pump coronary artery bypass surgery. *J Cardiothorac Vasc Anesth* 2006; 20: 315-9.

16 van Grondelle A, Ditchey RV, Groves BM, et al. Thermodilution method overestimates low cardiac output in humans. *Am J Physiol* 1983; 245: H690-2.

17 Nishikawa T, Dohi S. Errors in the measurement of cardiac output by thermodilution. *Can J Anaesth* 1993; 40: 142-53.

18 Cheatham ML, Nelson LD, Chang M, Safcsak K. Right ventricular end-diastolic volume index as a predictor of preload status in patients on positive end-expiratory pressure. *Crit Care Med* 1998; 26: 1801-6.

19 Latson TW, Whitten CW, OíFlaherty . Ventilation, thermal noise, and errors in cardiac output measurements after cardiopulmonary bypass. *Anesthesiology* 1993; 79: 1233-43.D

20 Dey I, Sprivulis P. Emergency physicians can reliably assess emergency department patient cardiac output using the USCOM continuous wave Doppler cardiac output monitor. *Emerg Med Australas* 2005; 17: 193-9.

21 Donovan KD, Colreavy F. Echocardiography in intensive care: the basics. Part I. *Crit Care Resusc* 1999; 1: 291-5.

22 Cook CH, Praba AC, Beery PR, Martin LC. Transthoracic echocardiography is not cost-effective in critically ill surgical patients. *J Trauma* 2002; 52: 280-4.

23 Burchell SA, Yu M, Takiguchi SA, et al. Evaluation of a continuous cardiac output and mixed venous oxygen saturation catheter in critically ill surgical patients. *Crit Care Med* 1997; 25: 388-91.

24 Mihaljevic T, von Segesser LK, Tonz M, et al. Continuous versus bolus thermodilution cardiac output measurements — a comparative study. *Crit Care Med* 1995; 23: 944-.9 ❑