Cardiothoracic Anesthesia, Respiration and Airway

Esophageal Doppler and thermodilution are not interchangeable for determination of cardiac output

[Le Doppler œsophagien et la thermodilution ne sont pas interchangeables pour préciser le débit cardiaque]

Sophie Collins MD FRCPC,* François Girard MD FRCPC,* Daniel Boudreault MD FRCPC,*
Philippe Chouinard MD FRCPC,* Louis Normandin MD FRCSC,† Pierre Couture MD FRCPC,‡
Marie-Josée Caron MD,* Monique Ruel RN CCRP*

Purpose: This study compares thermodilution cardiac output (TD-CO) and esophageal Doppler cardiac output (ED-CO) during periods of hemodynamic stability and after heart stabilization during off-pump coronary artery bypass (OPCAB) surgery.

Methods: After Institutional Review Board approval, 58 patients undergoing OPCAB had simultaneous comparison of TD-CO and ED-CO at three time periods. Measurements were recorded, in a blinded manner, after probe insertion (T0), immediately before and after (T1,T2) heart displacement and before starting any pharmacological treatment (if needed) to maintain systolic blood pressure to its value before heart mobilization. Measurements were also taken before sternal closure (Tfinal).

Results: Three hundred and two pairs of data were analyzed using the Bland and Altman method. Bias, standard deviation (SD) of the bias (precision), and degree of agreement (bias $\pm$ 2 SD) were calculated. Based on published literature, we considered that the highest degree of agreement should be < 0.5 L $\cdot$ min $^{-1}$ to consider both methods as interchangeable. At T0, bias and SD of bias between TD-CO and ED-CO were -0.1 ± 1.0 L $\cdot$ min $^{-1}$. Immediately before heart stabilization, bias $\pm$ SD was 0.6 ± 1.0 L $\cdot$ min $^{-1}$ and after heart displacement, 0.5 ± 0.8 L $\cdot$ min $^{-1}$. At Tfinal, bias $\pm$ SD was 0.7 ± 0.7 L $\cdot$ min $^{-1}$.

Conclusion: Because the degree of agreement was > 0.5 L $\cdot$ min $^{-1}$ at all measurement periods except T0, we conclude that TD and ED are not interchangeable at any time during OPCAB surgery.

Objectif : Comparer le débit cardiaque obtenu par thermodilution (DC-TD) à celui du Doppler œsophagien (DC-DO) pendant la stabilité hémodynamique et après la stabilisation cardiaque au cours d'un pontage aortocoronarien à cœur battant (PACCB).

Méthode : Avec l'approbation du Comité de révision, nous avons recruté 58 patients devant subir un PACCB pour une comparaison simultanée du DC-TD et DC-DO à trois moments différents. Les mesures ont été enregistrées à l'aveugle, après l'insertion de la sonde (T0), immédiatement avant et après (T1,T2) le déplacement du cœur et avant de commencer tout traitement pharmacologique, si nécessaire, pour maintenir la tension artérielle systolique à ses valeurs d'avant la mobilisation cardiaque. Des mesures ont aussi été prises avant la fermeture sternale (Tfinal).

Résultats : Trois cent deux paires de données ont été analysées selon la méthode de Bland et Altman. Le biais, l'écart type (ET) du biais (précision) et le degré de concordance (biais $\pm$ 2 ET) ont été calculés. Sur la base des publications consultées, le degré le plus élevé de concordance devrait être $< 0,5$ L $\cdot$ min $^{-1}$ pour conclure que les deux méthodes sont interchangeables. Au T0, le biais et l'ET du biais entre DC-TD et DC-DO ont été de $-0,1 \pm 1,0$ L $\cdot$ min $^{-1}$. Immédiatement avant la stabilisation du cœur, le biais $\pm$ ET était de $0,6 \pm 1,0$ L $\cdot$ min $^{-1}$ et après le déplacement du cœur, de $0,5 \pm 0,8$ L $\cdot$ min $^{-1}$. Au Tfinal, le biais $\pm$ ET était de $0,7 \pm 0,7$ L $\cdot$ min $^{-1}$.

Conclusion : Le degré de concordance étant $> 0,5$ L $\cdot$ min $^{-1}$ pour toutes les mesures, sauf au T0, nous concluons que la TD et le DO ne sont pas interchangeables pendant le PACCB.

From the Department of Anesthesiology* and Cardiac Surgery Division,† CHUM, Hôpital Notre-Dame; and the Department of Anesthesiology,‡ Montreal Heart Institute, Montréal, Québec, Canada.

Address correspondence to: Dr. François Girard, Department of Anesthesiology, CHUM, Hôpital Notre-Dame, 1560 Sherbrooke East, Montréal, Québec H2L 4M1, Canada. Phone: 514-890-8000, ext. 26876; Fax: 514-412-7653; E-mail: francois.girard.chum@ssss.gouv.qc.ca
The Hemosonic™ esophageal Doppler was lent by Arrow International for the duration of the study.

Accepted for publication April 11, 2005.

Revision accepted May 10, 2005.

DURING the past decade, off-pump coronary artery bypass (OPCAB) surgery has been used as an alternative to cardiopulmonary bypass (CPB). Potential advantages of OPCAB include a decrease in neurological injuries, reduction of the inflammatory response, and decreased use of blood products compared with CPB.¹ OPCAB has also been shown to decrease the length of hospital stay, and to be more economical than on-pump coronary artery bypass graft surgery.²

One of the most important roles of the anesthesiologist during OPCAB is to maintain optimal hemodynamic stability during surgical manipulations and stabilization of the heart, and during coronary artery clamping and anastomosis. This implies detecting and treating promptly systemic hypotension, arrhythmias, myocardial ischemia, and especially low cardiac output (CO), which may lead to end-organ injury such as renal failure and neurologic deficits.

Although routine use of the pulmonary artery catheter (PAC) during OPCAB is controversial, its use in selected higher risk patients may be beneficial. Traditionally, thermodilution (TD) CO measurement using a PAC has been accepted as a standard of care, against which other monitoring devices have been compared with varying degrees of correlation.³⁻⁶ Of these alternative technologies, the esophageal Doppler (ED) has been one of the most extensively studied. Its ability to measure descending aortic blood flow (ABF) and to infer CO has been exploited in critical care and perioperatively,^{3,6,7} including coronary artery bypass graft surgery under CPB.^{4,5,8,9} Its value during OPCAB remains to be established. The few studies that have compared ED-CO with TD-CO^{10,11} have done so only during periods of hemodynamic stability. The aim of this study was to compare TD-CO and ED-CO measurements during elective OPCAB, during periods of hemodynamic stability and changing hemodynamic conditions. We hypothesized that TD-CO and ED-CO are interchangeable in this setting, both in absolute values and proportional variations. We also verified whether these variations were in similar direction and/or amplitude compared with end-tidal carbon dioxide (EtCO₂) pressure measurements.

Methods

After Institutional Review Board approval and written informed consent, 59 ASA III-IV patients who were scheduled for elective OPCAB surgery between April 2002 and March 2003 were enrolled in this study. Exclusion criteria were: known esophageal pathology, preoperative use of vasopressive drugs or intra-aortic balloon pump, and significant tricuspid or

pulmonary valvular disease (defined as $\geq 2-4$ severity score on preoperative echocardiogram). Three cardiac surgeons performed all the surgeries in this study, using a similar OPCAB technique. Heart stabilization was achieved with a fork-type compression stabilizer developed at the Montreal Heart Institute (CoroNéo Inc., Montreal, QC, Canada). Briefly, the system consists of four distinct coronary stabilizers, "push" and "pull" types, each optimized for specific artery exposure and immobilization. A bloodless surgical field is ensured by silastic bands (Retract-O-Tape; Quest, Allen, TX, USA), which isolate and occlude the target artery at the arteriotomy site. A "heart-verticalizing" technique, was used to expose the posterior circumflex territory through pericardial traction. Four deep pericardial sutures are placed at the base of the heart, interspersed in a fan-shape arrangement between the left superior pulmonary vein and the inferior vena cava. The "verticalizing" technique enables extraction of the apex, with minimal distortion of the ventricle while preserving hemodynamics. The surgical table, rotated rightward (30°) and set in Trendelenburg position, assists in exposing the posterior coronary territory and helps maintain right ventricular preload. The coronary artery was stabilized using a pull type stabilizer. Exposure of the left anterior descending artery and diagonal coronary arteries used the same setting, except two traction sutures were usually used and the table was positioned in a reverse Trendelenburg position.¹²

Premedication and drugs for induction of general anesthesia were left to the preference of the attending anesthesiologist. Standard monitoring included invasive blood pressure via a radial artery catheter, a five-lead electrocardiogram, and pulse oximetry. After induction, the PAC (Abbott critical care systems, North Chicago, IL, USA) and central venous catheters were inserted using sterile technique. Mechanical ventilation was adjusted for an EtCO₂ pressure between 29 and 35 mmHg during the post-induction period and the ventilator settings were not modified thereafter for the entire study period. Urine output, central temperature (bladder) and airway pressures were monitored for all patients.

After insertion of invasive central monitoring, an ED probe (Hemosonic™ 100, Arrow International, Everett, MA, USA) covered with a specifically designed disposable sheath was introduced orally, according to the manufacturer's specifications, to the 35 cm mark at the teeth. Adjustments were then made by slight rotations and/or rostral-caudal movements of the probe to obtain a clean signal. This was defined as visualization of both walls of the descending thoracic

aorta in M-mode, coupled with a maximal amplitude of the Doppler waveform.

The TD-CO were performed by an assistant blinded to ED measurements. This was done in triplicate and the average result was noted, provided the three values were within 10% of one another. Otherwise, the measurement was repeated to a maximum of five total values, of which the highest and lowest were excluded. The average value was then calculated. The injectate consisted of 10 mL of room-temperature 5% dextrose in water. As soon as the average TD-CO was obtained, ED-CO was recorded. These recordings, along with arterial systemic pressure, pulse rate and EtCO₂, were documented at the following times: at introduction of the ED (T0) after anesthetic induction, before sternotomy, within five minutes before the surgical stabilization of each coronary artery to be grafted (T1), and after completion of the stabilization (T2) before any pharmacological attempt was made to correct systemic hypotension if it occurred. Once the measurement was completed, but no more than one minute after heart stabilization, the blood pressure was increased if necessary to within the limits of its pre-mobilization value, using an infusion of norepinephrine or dopamine. Patients were systematically tilted to a 15 to 30° Trendelenburg position with a 10 to 15° right-sided tilt before marginal, right and posterior descending coronary artery stabilization, according to surgical OPCAB protocol. Otherwise, the patient was in dorsal position. Invasive pressure transducers were kept at the level of the heart during these mobilizations. A final set of measurements was obtained before the beginning of sternal closure (Tfinal).

The Bland and Altman method¹³ was used to assess the agreement between ED-CO and TD-CO. This method consists of plotting, for a given pair of measurements, the difference of their value against their average. Therefore, agreement is strongest when the average difference between the two measurement techniques (the bias) is close to zero and the scatter of differences (inversely proportional to the precision) is minimal. Based on this principle and on previously published literature,⁹ we determined that ± 0.5 L·min⁻¹ would be the highest limit of agreement [the value of 2 standard deviations (SD)] that would be acceptable in order to consider ED and TD clinically interchangeable. Assuming a normal distribution of values, this implies that 95% of differences should be within these limits (± 0.5 L·min⁻¹), if these methods of measurements are considered interchangeable. This margin of error should normally correspond to 10–15% of the measured CO under physiological circumstances. Percentages of variation of hemodynamic

TABLE Patient demographics

<i>Number of patients</i>	<i>50</i>
Sex (F/M)	10/40
Age (yr)	65 $\pm$ 9
Weight (kg)	77 $\pm$ 13
Height (cm)	167 $\pm$ 6
Hypertension	36 (72)
Dyslipidemia	34 (68)
Smoking history	24 (48)
Diabetes	16 (32)
Renal failure	7 (14)
LVEF above 50 %30-50 %	40 (80)10 (20)
No. of bypasses	Median 3 (range 1-6)

Values are mean $\pm$ standard deviation, *n* (%) or *n*. LVEF= left ventricular ejection fraction.

variables (CO), EtCO₂ and mean arterial pressure (MAP), were calculated with the following formula: $100 (X \text{ after heart positioning} - X \text{ before heart positioning}) / X \text{ before heart positioning}$, where X is the value of CO, ET_{CO}₂ and MAP successively. All statistics were handled with Microsoft Excel for Windows XP (Microsoft Corporation, Redmond, WA, USA).

Results

Of the 59 eligible patients, nine were excluded on the following basis: one had esophageal varices, six were converted to CPB for surgical reasons and we failed to obtain a interpretable ED signal in two patients. Therefore, results were analyzed for a total of 50 subjects. The Table summarizes patient characteristics. All patients had a left anterior descending artery intervention and this was the first vessel to be grafted in all 50 patients. No complications occurred due to either ED or PAC insertion.

A total of 342 pairs of CO measurements were made during the course of the study; ED-CO values ranged from 1.0 to 10.0 L·min⁻¹, whereas TD-CO measurements went from 0.8 to 8.4 L·min⁻¹. Of these 342 pairs, 40 were incomplete or invalid either because of temporary loss of ED signal, or TD values for which we failed to obtain triplicate measures before pharmacological support to maintain systolic pressure became necessary. By protocol, the 302 pairs of CO values were analyzed in four distinct groups according to the four time periods: after anesthetic induction (T0), before heart stabilization for exposure of each coronary vessel (T1), after heart stabilization (T2) and before Tfinal. From these four Bland-Altman plots (Figures 1, panels A–D), bias and SD of bias between TD-CO and ED-CO during four measurement peri-

FIGURE 1 Bland-Altman comparison between thermolulution (TD) and esophageal Doppler (ED) estimations of cardiac output (CO). The solid line represents the mean difference between measurements (bias) and the dotted lines represent the 95% limits of agreement (± 2 standard deviation). A) at the time of insertion of the probe; B) before heart displacement; C) after heart displacement; D) before sternal closure.

ods are as follows: after anesthetic induction (T0), -0.1 ± 1.0 L $\cdot$ min $^{-1}$ (panel A) with 95% limits of agreement (bias ± 2 SD) of -2.1 to 1.9 L $\cdot$ min $^{-1}$; before heart positioning (T1), 0.6 ± 1.0 L $\cdot$ min $^{-1}$ (panel B) with limits of agreement of -1.4 to 2.6 L $\cdot$ min $^{-1}$; after heart positioning (T2), 0.5 ± 0.8 L $\cdot$ min $^{-1}$ (panel C) with limits of agreement of -1.1 to 2.1 L $\cdot$ min $^{-1}$ and before Tfinal, 0.7 ± 0.7 L $\cdot$ min $^{-1}$ (panel D) with limits of agreement of -0.7 to 2.1 L $\cdot$ min $^{-1}$. Except at T0, TD-CO systematically overestimated ED-CO by 0.5 to 0.7 L $\cdot$ min $^{-1}$ on average. The bias was least at T0 (-0.1 L $\cdot$ min $^{-1}$) and greatest before chest closure ($+0.7$ L $\cdot$ min $^{-1}$). However, the precision (reflected by the SD) was poor for each measurement period. The limit of agreement (bias ± 2

SD) was much higher than the predetermined value of 0.5 L $\cdot$ min $^{-1}$ which was considered the highest limit of agreement for clinical interchangeability.

Thirty patients needed vasoactive drugs for at least one heart manipulation. The average variations for the four hemodynamic parameters (Δ ED-CO, Δ TD-CO, Δ EtCO $_2$ and Δ MAP) following heart stabilization are presented in Figure 2. Each variation is expressed as a percentage of the initial measurement, i.e., before cardiac manipulation. Correlation coefficients between these variations were established for each of the coronary vessels (with the exception of the right coronary artery, for which we only had three sets of parameters). Depending on the coronary artery grafted, the

FIGURE 2 Percentages of variation (post-stabilization - pre-stabilization) of thermodilution (TD)- and esophageal Doppler (ED)-derived cardiac output (CO), end-tidal carbon dioxide pressure (EtCO₂) and mean arterial pressure (MAP), following heart displacement for bypass of four coronary vessels. LAD = left anterior descending artery; Diag = diagonal branch of the LAD; Marg = marginal branch of the circumflex artery; PDA = posterior descending artery. Values are presented in mean $\pm$ standard deviation intervals.

$\Delta\%$ ED-CO *vs* $\Delta\%$ TD-CO, r^2 ranged from 0.353 to 0.568; for $\Delta\%$ ED-CO *vs* $\Delta\%$ EtCO₂, r^2 ranged from 0.190 to 0.543. As for $\Delta\%$ TD-CO *vs* $\Delta\%$ EtCO₂, correlation proved equally poor (r^2 ranged from 0.308 to 0.670), with the exception of the posterior descending artery: during heart manipulation for its exposure, $r^2 = 0.848$.

Discussion

In this study, we have demonstrated that during non-emergent OPCAB surgery using a compression-type stabilizer, the measurements of CO with bolus TD technique and ED are not interchangeable at any time period. Except for T0 (bias = -0.1 L·min⁻¹), the bias remained high (0.5 to 0.7 L·min⁻¹). The large 95% limits of agreement during the four measurement periods are translated to poor clinical precision, well above our established acceptable limit of ± 0.5 L·min⁻¹,

meaning that the methods are not interchangeable. These findings lead us to question the value not only of ED-CO measurement, the device we studied as an alternative, but also that of TD, which has often been considered a standard for CO quantification to which other techniques have been compared.⁶⁻¹¹ To compare the two measurement techniques used in this study, we chose the Bland and Altman method to avoid using TD as a reference; therefore, any significant divergence between ED and TD may be explained by errors of either or both measurement techniques. If we had chosen TD as a standard, then biases and scatter would have been attributed solely to ED, quite possibly in a false manner.

The mean difference between TD-CO and ED-CO at T0 (-0.1 L·min⁻¹, Figure 1, panel A) was small, perhaps reflecting the only period of relative hemodynamic normality: the sternum was not yet open, thus

normal anatomical proportions between descending aorta, esophagus and the heart itself were preserved. On the other hand, precision of this difference ($SD = 1.0 \text{ L}\cdot\text{min}^{-1}$) remains poor for other measurement times, which leads us to think that mechanisms other than sternal opening are responsible for this wide scatter of CO values.

Reproducibility of measurements could not be evaluated in this series, as only one pair of values was recorded for a given patient at a given surgical time. We ensured that the observers were familiar with their respective study technique: as Lefrant had previously suggested,¹⁴ ED manipulation was practiced on ten patients under general anesthesia before the beginning of the study period. Bolus TD technique has been used on a regular basis for cardiac surgery patients in our institution for several years. The 40 data pairs which contained invalid CO measurements were equally spread throughout the duration of the study period. Accordingly, we believe that, in the condition of this study, our conclusion of non-interchangeability of the two methods is valid.

Several conditions are necessary to successfully obtain a CO determination by ED.¹⁴ The angle of the probe determines the incidence of the Doppler beam in relation to axial flow. Ideally, this angle should be between 0 and 20° to ensure maximal recorded blood velocity. The T6 level is recommended for positioning the tip of the probe, because at this level the descending ABF and esophagus are usually parallel. However, with sternal opening and retraction, a slight movement was often required to reposition the probe, possibly changing the Doppler angle. This need for frequent readjustment, with temporary loss of more than 20 signals during heart manipulation and exclusion of two patients for a complete lack of Doppler signal, is in itself a problem. We do not believe this was operator-related though, because other authors have reported similar difficulties.^{8,11}

Also, the nomogram of the Hemosonic device assumes that the cross-sectional area of the descending thoracic aorta is always circular, when in fact it is rather dependent on pulse pressure and aortic compliance.¹⁵ Furthermore, axial flow is not always laminar: anemia, tachycardia, aortic valve disease¹⁵ and atheroma, which are probably quite common in the population of OPCAB surgical patients, may all affect blood velocity measurements by causing turbulent flow. Finally, calculation of CO from ABF is made with the assumption that ABF represents 70% of total CO, the remaining 30% corresponding to upper body flow. However, this is based upon physiological distribution of total CO, which is presumably disturbed under hemodynamic

stress such as heart manipulation, myocardial ischemia, low CO and systemic hypotension. These conditions being fairly common during OPCAB surgery,¹⁶ we hypothesized that upper body blood flow is probably higher than 30% of total CO during a significant part of the surgical intervention. This would be due to compensatory redistribution of CO towards the brain and the heart. Under these circumstances, ED-CO measurements could be underestimated. In fact, with similar reasoning, Leather *et al.*¹⁷ showed that lower body vasodilation, mediated by lumbar epidural anesthesia, led to overestimation of CO by ED.

Thermodilution is also a source of error for CO measurement. In this series, the most significant problem remained the inability, in about 20 cases, to obtain a timely measurement during periods of hemodynamic changes. This is due to the design of our study: we allowed ourselves no more than one minute to take measurements before a vasopressive treatment was initiated. For obvious ethical reasons, this period could not be prolonged merely for the sake of collecting data. The choice of bolus TD technique was due both to the current method of its utilization in our institution, and to the relatively short delay of measurement it allows. We are aware that many practitioners now routinely insert continuous CO PACs for cardiac anesthesia, and it has been suggested that its correlation with ED-CO is better.⁸ Nonetheless, its slow response time, which has been demonstrated *in vitro* to range from five to 15 min,¹⁸ made it inappropriate for the purpose of this study.

In three of the four Bland-Altman plots, bias was significantly above zero in favour of TD-CO. This may be a result of ED underestimation as discussed above, but also suggests a possible overestimation of true CO. Several authors have noted a tendency for TD to yield higher CO values compared with a variety of other measurement devices, such as the Fick method, dye dilution, ultrasonic aortic flow probe, electromagnetic pulmonary flow probe and ED.^{3,4,6,9-11,19-21} This overestimation seems even higher in low CO states^{19,21} and may be exaggerated by the use of room-temperature TD injectate (as opposed to cold injectate).²¹

Heerdt *et al.* showed that acute tricuspid regurgitation (TR) may produce TD overestimation of CO in low-flow states.²² In this study, because of the presence of the ED probe, we could not use intraoperative transesophageal echocardiography to document the presence of TR. While right heart compression and/or diastolic dysfunction have been documented in OPCAB,^{23,24} acute TR has never been demonstrated during this type of surgery. The loss of contact between heart and esophagus during ante-

rior 90° cardiac displacement, which could very well be associated with TR, makes this diagnosis hard to prove. Through three-dimensional reconstruction of transesophageal echocardiography images, George *et al.*²⁵ have reported significant mitral annulus distortion during heart displacement, associated with both acute mitral stenosis and regurgitation. This distortion was greatest with positioning to access the posterior wall. As intracardiac structures are then folded at the atrioventricular groove,²⁵ it is reasonable to think of acute TR as a definite possibility. Epicardial echography could be used to assess this hypothesis in a future study, because transesophageal echocardiography is not useful (lack of imaging) during heart positioning.

Correlation between Δ ED-CO, Δ TD-CO and Δ EtCO₂ following each heart stabilization (except that for proximal right coronary artery, for which insufficient data was available) was poor. We chose to assess the correlation between CO and EtCO₂ because acute modifications of the latter are presumably secondary to changes in alveolar perfusion, pending that ventilation and metabolic CO₂ production are stable.²⁶ Out of twelve correlation coefficients (three parameters times four coronary vessels), merely one is significant. This obviously has little clinical impact. Figure 2 outlines a tendency for variations of ED-CO, TD-CO and EtCO₂ to follow similar directions. The small number of data, combined with several wide SDs, precludes determination of any significant relationship.

There are limitations in this study. First, as discussed above, no CO measurement methodology can be considered the gold standard, and many factors can affect their performances. Secondly, we have measured hemodynamic changes before and after heart stabilization, but did not measure hemodynamic changes after coronary artery clamping, where additional hemodynamic changes may occur. However, this does not change our conclusion that TD-CO and ED-CO are not interchangeable during the measurement periods performed in this study. Finally, many of the hemodynamic measurements were made during head down positioning. It is difficult to standardize the level of the transducer to the heart for pressure measurements. However, this should not affect the CO measurements, which was the main objective of this study.

In conclusion, this study shows that during elective OPCAB surgery using a compression-type epicardial stabilizer, ED and bolus TD of CO are not interchangeable. Even if the bias between both methods was small after anesthetic induction and before chest opening, the precision and degree of agreement was too poor to be clinically useful.

References

- 1 Heames RM, Gill RS, Ohri SK, Hett DA. Off-pump coronary artery surgery. *Anaesthesia* 2002; 57: 676–85.
- 2 Nathoe HM, van Dijk D, Jansen EW, *et al.* A comparison of on-pump and off-pump coronary bypass surgery in low risk patients. *N Engl J Med* 2003; 348: 394–402.
- 3 Castor G, Klocke RK, Stoll M, Helms J, Niedermark I. Simultaneous measurement of cardiac output by thermodilution, thoracic electrical bioimpedance and Doppler ultrasound. *Br J Anaesth* 1994; 72: 133–8.
- 4 Blas ML, Nene S, Bonome A, Lobato EB. Comparison of the HemoSonic 100® esophageal Doppler cardiac output system, pulmonary artery catheterization and ultrasonic aortic flow probe in cardiac surgical patients. *Anesth Analg* 2002; 94: S-76 (abstract).
- 5 DiCorte CJ, Latham P, Greilich PE, Cooley MV, Grayburn PA, Jessen ME. Esophageal Doppler monitor determinations of cardiac output and preload during cardiac operations. *Ann Thorac Surg* 2000; 69: 1782–6.
- 6 Valtier B, Cholley BJ, Belot JP, de la Coussaye JE, Mateo J, Payen DM. Noninvasive monitoring of cardiac output in critically ill patients using transesophageal Doppler. *Am J Respir Crit Care Med* 1998; 158: 77–83.
- 7 Schmid ER, Spahn DR, Tornic M. Reliability of a new generation transesophageal Doppler device for cardiac output monitoring. *Anesth Analg* 1993; 77: 971–9.
- 8 Keyl C, Rödig G, Lemberger P, Hobbhahn J. A comparison of the use of transesophageal Doppler and thermodilution techniques for cardiac output determination. *Eur J Anaesthesiol* 1996; 13: 136–42.
- 9 Su NY, Huang CJ, Tsai P, Hsu YW, Hung YC, Cheng CR. Cardiac output measurement during cardiac surgery: esophageal Doppler versus pulmonary artery catheter. *Acta Anaesthesiol Sin* 2002; 40: 127–33.
- 10 Decoene C, Modine T, Al-Ruzzeh S, *et al.* Analysis of thoracic aortic blood flow during off-pump coronary artery bypass surgery. *Eur J Cardiothorac Surg* 2004; 25: 26–34.
- 11 Cartier R, Blain R. Off-pump revascularization of the circumflex artery: technical aspect and short-term results. *Ann Thorac Surg* 1999; 68: 94–9.
- 12 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.
- 13 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 327: 307–10.
- 14 Lefrant JY, Bruelle P, Aya AG, *et al.* Training is required to improve the reliability of esophageal

- Doppler to measure cardiac output in critically ill patients. *Intensive Care Med* 1998; 24: 347–52.
- 15 Chaney JC, Derdak S. Minimally invasive hemodynamic monitoring for the intensivist: current and emerging technology. *Crit Care Med* 2002; 30: 2338–45.
 - 16 Couture P, Denault A, Limoges P, Sheridan P, Babin D, Cartier R. Mechanisms of hemodynamic changes during off-pump coronary artery bypass surgery. *Can J Anesth* 2002; 49: 835–49.
 - 17 Leather HA, Wouters PF. Oesophageal Doppler monitoring overestimates cardiac output during lumbar epidural anaesthesia. *Br J Anaesth* 2001; 86: 794–7.
 - 18 Aranda M, Mihm FG, Garrett S, Mihm MN, Pearl RG. Continuous cardiac output catheters: delay in in vitro response time after controlled flow changes. *Anesthesiology* 1998; 89: 1592–5.
 - 19 Tournadre JP, Chassard D, Muchada R. Overestimation of low cardiac output measured by thermodilution. *Br J Anaesth* 1997; 79: 514–6.
 - 20 Espersen K, Jensen EW, Rosenborg D, *et al.* Comparison of cardiac output measurement techniques: thermodilution, Doppler, CO₂-rebreathing and the direct Fick method. *Acta Anaesthesiol Scand* 1995; 39: 245–51.
 - 21 Woog RH, McWilliam DB. A comparison of methods of cardiac output measurement. *Anaesth Intensive Care* 1983; 11: 141–6.
 - 22 Heerdt PM, Blessios GA, Beach ML, Hogue CW. Flow dependency of error in thermodilution measurement of cardiac output during acute tricuspid regurgitation. *J Cardiothorac Vasc Anesth* 2001; 15: 183–7.
 - 23 Gründeman PE, Borst C, van Herwaarden JA, Verlaan CW, Jansen EW. Vertical displacement of the beating heart by the Octopus tissue stabilizer: influence on coronary flow. *Ann Thorac Surg* 1998; 65: 1348–52.
 - 24 Mathison M, Edgerton JR, Horswell JL, Akin JJ, Mack MJ. Analysis of hemodynamic changes during beating heart surgical procedures. *Ann Thorac Surg* 2000; 70: 1355–61.
 - 25 George SJ, Al-Ruzzeh S, Amrani M. Mitral annulus distortion during beating heart surgery: a potential cause for hemodynamic disturbance—a three-dimensional echocardiography reconstruction study. *Ann Thorac Surg* 2002; 73: 1424–30.
 - 26 Tournadre JP, Moulaire V, Barreiro G, Brunfl D, van Straten V, Muchada R. Simultaneous monitoring of noninvasive hemodynamic profile and capnography for tissue perfusion evaluation. *J Anesth* 1994; 8: 400–5.