A comparison of the use of transoesophageal Doppler and thermodilution techniques for cardiac output determination

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Summary
Doppler cardiac output (CO) determination is discussed as a non-invasive alternative to CO estimation by thermodilution. This study was designed to compare the accuracy of a new transoesophageal Doppler device with the thermodilution technique. In 24 patients undergoing coronary artery bypass surgery, CO was determined simultaneously by the oesophageal Doppler (OD) and thermodilution (TD) method in triplicate for three sample episodes: after induction of anaesthesia during clinical steady-state conditions (A), after start of surgery (B), and after sternotomy (C). The agreement between ODCO and TDCO estimations was assessed by analysing the mean difference, indicating the systematic error, and analysing the distribution of differences between the two methods. The bias between ODCO and TDCO estimations was 0.38 (−0.06 to +0.81) L min⁻¹ (mean and 95% confidence interval) for sample episode A, 0.48 (−0.11 to +1.1) L min⁻¹ for sample episode B, and 0.69 (+0.08 to +1.3) L min⁻¹ (P<0.05 vs. zero) for sample episode C. Bias analysis of the log-transformed data revealed that 95% of the ODCO values differed from TDCO values by 43% below to 50% above for sample episode A, by 39% below to 95% above for sample episode B, and by 32% below to 96% above for sample episode C. Analysis of the changes in CO from sample episode A to B and from sample episode B to C, expressed as percentage values, showed a non-significant bias between the methods, but the 2 SD limits were ±44% and ±36% respectively. Our findings suggest that CO estimation by OD cannot replace estimation by the TD method.

Keywords: cardiac output; blood flow velocity; doppler effect; thermodilution.

Introduction
The Doppler blood flow measurement technique theoretically offers the possibility of continuous non-invasive cardiac output (CO) monitoring. Several approaches for the estimation of CO have been tested for clinical usefulness: Doppler echocardiography at various intracardiac levels [1–5], the measurement of blood flow in the pulmonary artery [6,7], in the ascending aorta [8,9] or in the descending aorta [10–16]. The transoesophageal Doppler measurement of blood flow in the descending aorta is applicable intra-operatively, minimally invasive, easy to perform, and less expensive compared with the thermodilution technique which currently represents the clinical standard for CO determination. Though the transoesophageal Doppler technique offers an alternative to invasive haemodynamic monitoring previous evaluation of transoesophageal Doppler devices has resulted in conflicting results. Some authors judged the transoesophageal Doppler method to be a possible alternative to the thermodilution technique [10,11,13], and others considered the method to be of minor clinical usefulness [15,17,18]. In view of these differences, we performed a prospective evaluation of a
new oesophageal Doppler (OD) monitoring device in patients undergoing coronary bypass surgery and compared the values of CO and relative CO changes with those obtained using the thermodilution (TD) technique.

**Methods**

Twenty-five patients, 19 male and six female, ranging in age from 30 to 74 yrs (mean age 60 yrs), who were scheduled for coronary bypass surgery were included in the study. The study protocol was approved by the local ethical board and patients gave their written informed consent. All patients had normal myocardial function and did not suffer from valvular heart disease or septal defects. Pre-operative ECG showed sinus rhythm without arrhythmia.

Patients were anaesthetized using sufentanil, etomidate and pancuronium; sufentanil and isoflurane were used for maintenance of anaesthesia. Mechanical ventilation was with 40% oxygen in air without positive end expiratory airway pressure. Normoventilation was controlled using capnography. Standard cardiovascular monitoring (Sirecust 1281 monitor, Siemens, Erlangen, Germany) was performed with a peripheral arterial cannula and a 7.5 FR pulmonary artery catheter (Baxter Healthcare Corporation, Irvine, CA) inserted via the right internal jugular vein. Additionally, a transoesophageal Doppler probe (ODM II, Abbott Laboratories, North Chicago, IL) was introduced. This device emits a 4 MHz continuous wave ultrasound signal at a fixed angle of 45°, and blood velocity was measured using a 300 Hz high-pass filter. The best signal quality was achieved by visual control of the blood flow velocity curve.

CO was determined at three sample times: 15–30 min after induction of anaesthesia under clinical steady-state conditions before surgical preparation (sample episode A), after start of operation when dissection of the saphenous vein was performed (sample episode B), and immediately after sternotomy before chest retraction (sample episode C). Only CO measurements performed during sinus rhythm without ectopic beats were accepted for analysis.

### Table 1.  Thermodilution- and oesophageal Doppler-determined cardiac output (CO), mean CO differences between oesophageal Doppler and thermodilution (bias), and upper and lower limits of agreement (bias ± 2 SD). ODCO and TDCO are expressed as mean ± SD; 95% CI are reported for the bias and the limits of agreement

<table>
<thead>
<tr>
<th>Sample episode</th>
<th>TDCO (L min⁻¹)</th>
<th>ODCO (L min⁻¹)</th>
<th>Bias (95% CI)</th>
<th>Upper limit of agreement (95% CI) (L min⁻¹)</th>
<th>Lower limit of agreement (95% CI) (L min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.0 ± 1.1</td>
<td>4.3 ± 1.5</td>
<td>0.38 (-0.06 to +0.81)</td>
<td>2.5 (+1.7 to 3.2)</td>
<td>-1.7 (-2.5 to -0.97)</td>
</tr>
<tr>
<td>B</td>
<td>4.5 ± 1.2</td>
<td>5.0 ± 1.6</td>
<td>0.48 (-0.11 to +1.1)</td>
<td>3.3 (+2.2 to +4.3)</td>
<td>-2.3 (-3.3 to -1.3)</td>
</tr>
<tr>
<td>C</td>
<td>4.6 ± 1.3</td>
<td>5.3 ± 1.5</td>
<td>0.69 (+0.08 to +1.3)∗</td>
<td>3.6 (+2.5 to +4.6)</td>
<td>-2.2 (-3.2 to -1.1)</td>
</tr>
</tbody>
</table>

A = after anaesthesia induction; B = after start of surgery; C = after sternotomy; OD = oesophageal Doppler; TD = thermodilution; 95% CI = 95% confidence interval.

### Table 2. Absolute and percentage changes in ODCO and TDCO, expressed as mean ± SD, and bias analysis. The bias is calculated as mean difference between oesophageal Doppler and thermodilution CO measurements, upper and lower limits of agreement = bias ± 2 SD

<table>
<thead>
<tr>
<th>Changes between sample episodes</th>
<th>TDCO (L min⁻¹)</th>
<th>ODCO (L min⁻¹)</th>
<th>Bias (95% CI)</th>
<th>Upper limit of agreement (95% CI)</th>
<th>Lower limit of agreement (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A→B absolute value (L min⁻¹)</td>
<td>0.57 ± 0.67</td>
<td>0.68 ± 1.0</td>
<td>0.10 (-0.27 to +0.48)</td>
<td>1.9 (+1.2 to +2.5)</td>
<td>-1.7 (-2.3 to -1.0)</td>
</tr>
<tr>
<td>percentage change</td>
<td>17±19</td>
<td>19±27</td>
<td>2.3 (-7.2 to +11.7)</td>
<td>47 (+31 to +63)</td>
<td>-42 (-59 to -26)</td>
</tr>
<tr>
<td>B→C absolute value (L min⁻¹)</td>
<td>0.09 ± 0.73</td>
<td>0.30 ± 1.1</td>
<td>0.21 (-0.19 to +0.60)</td>
<td>2.2 (+1.5 to +2.9)</td>
<td>-1.8 (-2.5 to -1.1)</td>
</tr>
<tr>
<td>percentage change</td>
<td>2.9±17</td>
<td>10±22</td>
<td>6.8 (-0.80 to +14.5)</td>
<td>43 (+30 to +56)</td>
<td>-29 (-43 to -16)</td>
</tr>
</tbody>
</table>

A = after anaesthesia induction; B = after start of surgery; C = after sternotomy; OD = oesophageal Doppler; TD = thermodilution; 95% CI = 95% confidence interval.

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Fig. 1. Bias analysis of cardiac output (CO) measurements performed by oesophageal Doppler (OD) and by thermodilution (TD). The bias is calculated as the mean difference between the methods; the limits of agreement are indicated by the mean difference ± 2 SD. (a) = after induction of anaesthesia. (b) = after start of surgery. (c) = after sternotomy.

TDCO measurements were performed by manual injection of 10 mL of ice-cooled 0.9% sodium chloride solution. The average of three measurements randomly distributed over the respiratory cycle was calculated. If there was more than a 15% variation between the values, five measurements were performed, the highest and lowest values from CO calculation were excluded, and the remaining three values averaged.

ODCO measurements were performed simultaneously with TDCO measurements, and the CO was also calculated as the mean of three CO determinations, each averaged over five consecutive heart beats.

Statistical analysis was performed using the method described by Bland and Altman [19]. The bias between the methods was calculated as the mean difference between ODCO and TDCO measurements. Student’s t-test was used to test whether the bias was different from zero (the ideal difference between methods). The upper and lower limits of agreement were calculated as bias ± 2 SD and defined the range in which 95% of the differences between methods were expected to lie. The precision of the bias analysis and the limits of the agreement were assessed using 95% confidence intervals (CI). Differences between ODCO and TDCO were plotted against the means of the two methods. As there was a trend towards increased scattering of
Transoesophageal Doppler vs. Thermodilution

As the differences between ODCO and TDCO tended to increase with increasing CO (Fig. 1), bias analysis was also performed for the log-transformed data, as suggested by Bland and Altman [19]. The plots of the log-transformed data showed less proportionality of the bias (Fig. 2). The antilog values of the limits of agreement indicated that in 95% of measurements the ODCO values differed from the TDCO values by 43% below to 50% above for sample episode A, from 39% below to 95% above for sample episode B, and from 32% below to 96% above for sample episode C.

When analysing the changes in CO from sample episode A to B and from sample episode B to C, the bias was small and not significantly different from zero (Table 2). The 2 SD limits of the differences between OD and TD measurements, however, were 1.8 L min$^{-1}$ (A to B) and 2.0 L min$^{-1}$ (B to C). When analysing the differences of the changes, expressed as percentage values, the 2 SD limits were 44% and 36% respectively (Fig. 3).

In two of 22 cases (9%), when TDCO changed more than 15%, ODCO changed 15% and 8% respectively in the opposite direction.

The estimation of CO by TD has become the clinical standard, despite the fact that the method is expensive, needs trained personnel, and is associated with considerable risks [20-22]. Furthermore, CO measurement by TD has limited accuracy and may be affected by many factors such as ventilation, volume and temperature of injectate, and technique of indicator injection [23,24]. Whereas under experimental conditions an accuracy rate of 5-10% for TDCO measurements can be obtained [25], differences of at least 15% in CO must be achieved under clinical conditions for clinical relevance when using the triplicate technique [23,26].

We observed, as have other authors [13], a significantly higher coefficient of variation for the TD technique than for the OD technique. This phenomenon may be caused by respiratory-dependent variations in ventricular filling and output, which are more pronounced in the right ventricle than in the left. The coefficients of variation for the OD and TD methods are slightly higher than those reported by...
Singer [13], but are, in the case of TD, comparable with those reported by other investigators for critically ill patients [27].

Several investigators tried to reduce the influences of ventilation on TDCO by injecting the indicator at fixed points in the breathing cycle, usually at end-exhalation [10,16]. On the other hand, a study carried out by Stevens et al. revealed that mean TDCO was not significantly different in mechanically ventilated patients when the indicator was injected randomly, as in the present study, or at end-exhalation [28].

Temperature and volume of injectate may also affect accuracy of TDCO measurements [24]. We performed CO determination with 10 mL iced injectate, several other studies reported no differences in the accuracy or reproducibility when iced or room-temperature injectate was used [27,29]. We observed no harmful side effects of the cold injectate such as bradycardia or other arrhythmia.

The assessment of CO by the transoesophageal Doppler techniques theoretically offers several advantages over the TD technique, such as non-invasiveness and cost reduction. On the other hand, the OD determination of CO is based on several assumptions which may cause problems with accuracy [15,17,23].

The Doppler method calculates blood flow from blood velocity and vessel cross-section area. The OD method assumes that the blood flow in the descending aorta is laminar and, as only the midstream flow is assessed, the relation of midstream blood flow to total blood flow is constant. Furthermore, the angle between the ultrasound beam and the blood flow is assumed to be constant. The ODM II device estimated the cross section of the descending aorta from a nomogram. The ratio between ascending and descending blood flow is assumed to be constant, and the blood flow in the descending aorta is estimated to be 70% of left ventricular output. Furthermore, the diameter of the aorta is assumed to be constant despite changes in the cross section due to fluctuations in CO and blood pressure [30], an assumption that nonetheless seems to be clinically practical for patients over 20 years of age [31].

To compensate for inaccuracies caused by these numerous assumptions, transoesophageal Doppler devices have been developed which calibrate for aortic diameter and/or CO by transcutaneous measurements in the ascending aorta. Recent studies evaluating such OD devices using calibration procedures reported conflicting results [10,15,18]. Whereas Perrino et al. found a 2 SD of the mean difference (bias) between ODCO and TDCO of 1.4 L min$^{-1}$ and observed the trending capability to be accurate [18], Schmid and co-workers reported a SD of the bias comparable to our results [15] and judged the method to be only of limited clinical usefulness. Wong, who compared TD with a supra-sternal Doppler method in which the aortic diameter was obtained from a nomogram, found 2 SD-limits of the mean bias of nearly 4 L min$^{-1}$ in mechanically ventilated patients and, therefore, poor agreement between the two methods [8]. Thus, calibration procedures using ascending aorta CO measurements may add further error to transoesophageal Doppler measurements.

We evaluated a device which uses an aortic diameter obtained from a nomogram and found unsatisfactory agreement between OD and TD techniques. Several authors who compared ODCO and TDCO measurements used correlation coefficients and regression equations and found the Doppler technique to be a useful alternative to invasive haemodynamic monitoring [10–13]. However, these statistical methods are inappropriate for the comparison of two measurement methods [19,32]. Furthermore, repeated measurements and therefore more than one data point for each patient have been used by many authors to compute correlation coefficients [10,12,13,15,18,33]. This procedure, however, may influence the results of correlation analysis. For these reasons we performed statistical analysis using the method described by Bland and Altman [19].

We observed a scattering of the differences between ODCO and TDCO that showed a trend which increased proportionally with the mean CO, a phenomenon which has not yet been discussed by other investigators. Therefore, we additionally performed a bias analysis using log-transformed data [19]. The limits of agreement calculated by this method exceeded by far the variations accepted for CO measurements by the TD method and indicated a clinically relevant disagreement between the methods.

Whereas for sample episode A clinically steady-state conditions were guaranteed, instabilities in the haemodynamic variables during sample episodes B and C cannot be completely ruled out, although not
registered by the investigators. Such changes may have influenced CO measurements and may be responsible for the increased scattering of differences between methods for sample episodes B and C. It is unlikely that sternotomy influenced Doppler measurement for sample episode C, as CO determinations were performed before chest retraction or mediastinal movements. Furthermore, the quality of the Doppler signal was continuously monitored, and displacement of the oesophageal probe would have resulted in a decrease in ODCO values, in contrast to our observations.

Several authors suggest that the OD method may be useful for monitoring trend changes in CO even though absolute values might not agree with the TD method \[10,13\]. Our results must be discussed in view of the fact that the evaluation of a trending device by intermittent CO measurements is only possible on a limited basis. In 90% of all significant TDCO changes, ODCO changed in the same direction. However, the differences in CO changes between methods showed a wide scattering which by far exceeded the accuracy level of approximately 15% accepted, for the triplicate TD method. We analysed changes in CO under clinical conditions and cannot report the accuracy of the assessment of CO changes, due to isolated variations in preload, afterload or inotropy, which has been investigated by other authors under experimental conditions \[17,33\]. For the same reason we did not assess the reproducibility of methods, since we could not guarantee exact steady-state conditions between two measurement episodes during surgery.

In conclusion, our data suggest reduced accuracy for CO estimation by the OD method compared with the TD method when evaluated under clinical conditions.

**Acknowledgment**

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**References**


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