Comparison between oxygen consumption calculated by Fick’s principle using a continuous thermodilution technique and measured by indirect calorimetry

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Summary
We calculated oxygen consumption by the reverse Fick principle (cVO₂) using cardiac output measured with a new technique of continuous thermal dilution and compared these values with measurements made at the same time using a gas exchange technique (mVO₂). We studied nine patients in a stable condition after cardiac surgery. In each patient six successive measurements of continuous cardiac output and mVO₂ were made over 5 min at 10-min intervals. The mean difference between the estimates (mVO₂−cVO₂) was 15 ml min⁻¹ m⁻² (95% confidence limits, −3 to 33 ml min⁻¹ m⁻²). The relative error of each method was 5% and 4% (continuous cardiac output and gas exchange methods, respectively). Calculation of VO₂ using the new cardiac output technology had good repeatability compared with direct measurement, probably because of the high precision of measurement of cardiac output (Br. J. Anaesth. 1995; 75: 719–723).

Key words

Oxygen consumption (VO₂) is classically calculated according to the reverse Fick principle. The equation is as follows: VO₂ = cardiac output × (CAO₂ − CO₂O₂) × 10, where (CAO₂ − CO₂O₂) = arterio-venous oxygen content difference. Whereas measurements of arterial and mixed venous oxygen saturation allows a correct value of (CAO₂ − CO₂O₂), measurement of cardiac output by thermodilution may be erroneous [1]. Recently a thermodilution technique was introduced to measure cardiac output continuously. This technique uses a combination of thermal indicator dilution with stochastic system identification techniques [2]. A standard pulmonary artery catheter is modified by attachment of a thermal filament which introduces an average of 5–7.5 W of heat into the blood according to pseudo-random binary sequence. The resulting temperature change is detected in the pulmonary artery and cross-correlated with the input sequence to produce a thermodilution washout curve. Cardiac output is computed from a conservation of heat equation using the area under the curve. A recent report showed close agreement between continuous and bolus thermodilution methods in intensive care unit patients [3].

The aim of the present study was to assess the agreement between VO₂ calculated by the reverse Fick principle (cVO₂) and VO₂ measured by a gas exchange method (mVO₂), and to assess the repeatability of both methods of VO₂ determination in stable patients after cardiac surgery.

Patients and methods
After obtaining institutional approval and informed consent, we studied nine patients (six males), aged 62 (range 52–75) yr, undergoing coronary artery bypass grafting (n = 3) or aortic valve replacement (n = 6). After induction of anaesthesia and tracheal intubation, an 8-French gauge filamented flow-directed catheter (Intellilcateh Model PA3-H-8Fr, Baxter Edwards Critical-Care, Irvine, CA, USA) was inserted via the right internal jugular vein in the pulmonary artery using a standard technique. After operation, patients were transferred to the ICU. Ventilation was provided by a Servo ventilator (Siemens-Elema model 900 C). The frequency and minute ventilation were adjusted to maintain PaCO₂ within 4–4.4 kPa. PaCO₂ was maintained at 0.5 without PEEP throughout the study. Bolus doses of fentanyl 5 μg kg⁻¹ and pancuronium 0.1 mg kg⁻¹ were given i.v. to permit stable mechanical ventilation. All patients received a continuous infusion of a 5% glucose solution. For continuous cardiac output measurements, the catheter thermometer and filament leads were connected to a continuous cardiac output computer (Vigilance Monitor, Baxter Edwards Critical-Care, Irvine, CA, USA). The correct position of the Swan-Ganz catheter was verified by inspection of the waveform of the pulmonary artery pressure with the balloon deflated and wedge pressure after balloon inflation. Inspection of the right atrial pressure wave confirmed that tricuspid valve incompetence was not present (i.e. there was no V wave). After placing the Swan-Ganz...
catheter in such a location that a wedge pressure could not be obtained despite inflation of the balloon, a 6-ml samples of mixed venous blood was removed by gentle aspiration from the distal lumen of the catheter over at least 30 s [4]. Samples for measurements of arterial blood-gas tension were obtained via a radial artery catheter (Seldicath) after removal of 10 ml. Blood samples were placed on ice for transport to the laboratory. All patients had normal leucocyte counts. After a 30-min warm-up period and gas and pressure calibration with a gas mixture of 95% oxygen and 5% carbon dioxide, the Deltatrac pressure calibration with a gas mixture of 95% oxygen and 5% carbon dioxide, the Deltatrac metabolic monitor (Sensor Medics, Anaheim, CA, USA) was connected to the ventilator according to the manufacturer’s recommendations. mVO₂ was measured continuously using the gas analysis method described previously [5]. Artefacts were suppressed (manufacturer’s own algorithm). Measurements were discontinued for 30 min if cough occurred or if bronchial suction was necessary. Serial measurements were started 2–4 h after arrival in the ICU, when rectal and body core temperatures and standard haemodynamic variables were considered stable, that is rectal (electronic thermometer Hewlett Packard) and body core (thermistance of the Swan-Ganz catheter) temperatures, heart rate and mean systemic arterial pressure variations were <5% for at least 1 h.

In each patient we performed six serial determinations of both cVO₂ and mVO₂ at 10-min intervals. Continuous cardiac output monitor data for 5 min and average flow were computed. Mean mVO₂ was obtained every 1 min as the mean of the last five values of mVO₂. Thus continuous cardiac output and mVO₂ values were obtained at the same time. The following measurements were recorded at each set of cardiac output and mVO₂ measurements: arterial (Pao₂), and mixed venous oxygen tension (PvO₂), arterial (Sao₂) and mixed venous oxygen saturation (SvO₂), and arterial haemoglobin concentration (Radiometer ABL 500, OSM 3, Copenhagen, Denmark).

The following variables were calculated according to standard formulae: arterial oxygen content (CaO₂, ml d⁻¹ = (1.39×Hb×Sao₂) + 0.0225×Pao₂; mixed venous oxygen content (CvO₂, ml d⁻¹ = (1.39 × Hb × SvO₂) + 0.025 × PvO₂; arteriovenous oxygen content difference (ml d⁻¹) = (CaO₂ – CvO₂); cVO₂ (ml min⁻¹ m⁻²) = (cardiac output/body surface area) × (CaO₂ – CvO₂)×10⁻³.

Values are expressed as mean (SD). The coefficients of variation of heart rate, mean arterial pressure, and rectal and body core temperatures were calculated to assess their relative stability throughout the study. Statistics are described in tables 1 and 2. In the first step (table 1), agreement between both methods of VO₂ evaluation was assessed by the method of Bland and Altman [6, 7]. In the second step (table 2), one-way analysis of variance was performed to assess repeatability of each method of VO₂ measurements. In the third step the effect of cardiac output and on (CaO₂ – CvO₂) on cVO₂ repeatability was assessed by studying the repeatability of cardiac output, CaO₂, CvO₂ and (CaO₂ – CvO₂) (methods described in table 2, replacing the VO₂ values by the corresponding measurements).

Because cVO₂ is dependent on cardiac output and (CaO₂ – CvO₂), the expected relative error (RE) of cVO₂ (RE(cVO₂)) could be derived from those of cardiac output and (CaO₂ – CvO₂) as follows: expected RE(cVO₂) = RE²(cardiac output) + RE²((CaO₂ – CvO₂)) / 2. The relation between cardiac output and (CaO₂ – CvO₂) was assessed for testing the independence between these variables.

Results

The coefficients of variation for heart rate, mean arterial pressure, and rectal and body core temperatures were 2%, 5%, 1%, and 1%, respectively.
Calculated and measured oxygen consumption

Fifty-four haemodynamic and biological measurements were undertaken. Mean cardiac output was 5.1 (1.4) litre min\(^{-1}\). Mean \(\text{Ca}_{\text{VO}}\) was 15.3 (2) \(\text{ml} \text{dl}^{-1}\) and \(\text{CVO}_{2}\) was 11.4 (1.8) \(\text{ml} \text{dl}^{-1}\). Mean \((\text{Ca}_{\text{VO}} - \text{CVO}_{2})\) was 4.1 (0.7) (3.1–5.7) \(\text{ml} \text{dl}^{-1}\). Median \(\text{cVO}_{2}\) was 112 (78–142) \(\text{ml} \text{min}^{-1} \text{m}^{-2}\); median \(\text{mVO}_{2}\) was 127 (97–163) \(\text{ml} \text{min}^{-1} \text{m}^{-2}\). Table 3 shows \(\text{cVO}_{2}\), \(\text{mVO}_{2}\), \(\text{Ca}_{\text{VO}}\), \(\text{CVO}_{2}\) and \((\text{Ca}_{\text{VO}} - \text{CVO}_{2})\) values.

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>(\text{cVO}_{2}) (ml min(^{-1}) m(^{-2}))</th>
<th>(\text{mVO}_{2}) (ml min(^{-1}) m(^{-2}))</th>
<th>Bias (ml min(^{-1}) m(^{-2}))</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>137 (5)</td>
<td>155 (5)</td>
<td>19 (7)</td>
</tr>
<tr>
<td>2</td>
<td>113 (10)</td>
<td>127 (10)</td>
<td>13 (9)</td>
</tr>
<tr>
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<td>102 (5)</td>
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<td>132 (5)</td>
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<td>109 (6)</td>
<td>123 (1)</td>
<td>11 (5)</td>
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<td>101 (3)</td>
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<td>8</td>
<td>117 (9)</td>
<td>139 (3)</td>
<td>15 (14)</td>
</tr>
<tr>
<td>9</td>
<td>120 (8)</td>
<td>127 (3)</td>
<td>8 (7)</td>
</tr>
<tr>
<td>Mean</td>
<td>112 (17)</td>
<td>127 (15)</td>
<td>15 (9)</td>
</tr>
</tbody>
</table>

Discussion

We have found that the two methods of obtaining \(\text{VO}_{2}\) (measurement and calculation) did not provide similar results. The limits of agreement were –3 to 33 ml min\(^{-1}\) m\(^{-2}\) between the two methods. These differences may be clinically significant suggesting that \(\text{cVO}_{2}\) could not predict \(\text{mVO}_{2}\). However, repeatability of \(\text{cVO}_{2}\) was good compared with \(\text{mVO}_{2}\).

The lack of agreement between both methods of \(\text{VO}_{2}\) may be explained by the higher variability of calculated values as a consequence of cumulative effects of the errors of measurements of the variables in the Fick equation [8], that is cardiac output and \((\text{Ca}_{\text{VO}} - \text{CVO}_{2})\) for \(\text{cVO}_{2}\) calculation.

Several obligatory conditions must pertain for measurement of \(\text{VO}_{2}\) by the Deltatrac metabolic monitor [5], and these conditions are often violated in ICU patients [8–13]. \(\text{VO}_{2}\) is calculated from the difference between two relatively large terms (inspiratory and mixed expiratory oxygen fractions). Any small error in each term increases \(\text{PO}_{2}\) increases. However, the precision of measurement of \(\text{VO}_{2}\) under steady-state conditions by the Deltatrac metabolic monitor is good when \(\text{PO}_{2}\) is < 0.6, with a mean error of 4 ± 4 % in \(\text{VO}_{2}\) in ventilator measurements [12]. These results are in agreement with those in the present study, where \(\text{mVO}_{2}\) had an RE of 4 %.

Variability in cardiac output may also limit the accuracy of \(\text{VO}_{2}\) estimation via the Fick method. In the present study RE, that is precision of cardiac output, was good (approximately 6 %) in comparison with precision of cardiac output measured by the thermodilution using the bolus method [14, 15]. The continuous cardiac output technique eliminates the potential for error related to inconsistent or incorrect injection technique and requires no user calibration [3]. The measurement errors from \((\text{Ca}_{\text{VO}} - \text{CVO}_{2})\) are also not negligible [1, 14]; approximately 5 % in the present study. When one calculates oxygen contents from standard formulae, one also has to consider the impact of random and systematic error propagation of the variables (\(\text{Pa}_{\text{O}}\), \(\text{P}_{\text{O}}\), \(\text{Sa}_{\text{O}}\), \(\text{SV}_{\text{O}}\), \(\text{Hb}\)) The
blood-gas analyser and the co-oximeter used in the present study provided good accuracy for \( F_{O_2} \), \( S_O_2 \), and \( Hb \) measurements, with maximum errors of 1 (0.4)%, 0.04 (0.1)% and 0.4 (0.2)% for \( F_{O_2} \), \( S_O_2 \), and \( Hb \), respectively (manufacturer’s specifications). Consequently, errors in calculated oxygen contents remain clinically acceptable, at approximately 2 % and 3 % for \( C_aO_2 \) and \( C_vO_2 \) in our study, if blood samples are handled correctly [4]. Also, the small \((C_aO_2 - C_vO_2)\) values in high cardiac output states may amplify the error of Fick-derived \( \dot{V}_O_2 \) values. This problem was observed in our study as a dependence between cardiac output and \((C_aO_2 - C_vO_2)\) was present. This relation could explain the difference between the observed and expected value of RE \((c\dot{V}_O_2)\). However, the observed RE \((c\dot{V}_O_2)\) was 5 % comparable with RE \((m\dot{V}_O_2)\). In contrast, the coefficient of variation of calculated \( \dot{V}_O_2 \) observed in previous studies was 9 % [1] to 23 % [8].

In the present study \( m\dot{V}_O_2 \) was consistently larger than \( c\dot{V}_O_2 \) (12 (5)%). Even if the variability in \( c\dot{V}_O_2 \) and \( m\dot{V}_O_2 \) was small, an undefined systematic measurement error in cardiac output and content difference could account for the difference in the estimate of \( \dot{V}_O_2 \) obtained by the two methods. Although the 95 % confidence interval on the bias included zero, the lower limit \((-3 \text{ ml min}^{-1} \text{ m}^{-2})\) did not differ much from zero (the 95 % confidence interval of the lower limit included zero). Thus, in this study, we could theoretically add an offset to the \( c\dot{V}_O_2 \) measurements to yield better agreement. It has been suggested that the individual difference between \( c\dot{V}_O_2 \) and \( m\dot{V}_O_2 \) [5, 12] and between Fick-derived cardiac output and thermodilution cardiac output [16] would be explained by pulmonary oxygen consumption rather than a hypothetical increase in coronary or bronchial blood flow [17]. In this study oxygen consumption in the lung was averaging 13 % of whole-body \( \dot{V}_O_2 \). This hypothesis remains to be tested in cardiac surgical patients.

Although the results of the present study seemed promising with regard to the accuracy of \( c\dot{V}_O_2 \), one has to consider the limitations of this study. \( \dot{V}_O_2 \) measurements were made in patients with cardiorespiratory stability where the coefficient of variations of heart rate, mean arterial pressure, and rectal and body temperatures were <5 % throughout the study. It is a fundamental assumption that measurements were made during steady state because the aim of the study was to assess repeatability of \( c\dot{V}_O_2 \). It is important to distinguish between repeatability, where data are obtained under the same condition, and reproducibility, where data are obtained under different conditions. Some authors prefer examining changes in \( \dot{V}_O_2 \) rather than absolute values [18, 19]. Nevertheless, the ability to distinguish random fluctuations from actual physiological change is extremely important, and it becomes difficult if random fluctuations are large. In the present study, the accuracy and precision of \( c\dot{V}_O_2 \) were established over a wide range of \( \dot{V}_O_2 \) between subjects but changes in \( c\dot{V}_O_2 \) and \( m\dot{V}_O_2 \) were not tested. However, for \( m\dot{V}_O_2 \) and \( c\dot{V}_O_2 \) measurements, PE values of 5 and 7, respectively, were obtained. Determining with 95 % certainty that an actual change was taking place would require a plus or minus change of 10 and 14 ml min\(^{-1}\) m\(^{-2}\) for \( m\dot{V}_O_2 \) and \( c\dot{V}_O_2 \) values, respectively.

In conclusion, in this patient population, \( \dot{V}_O_2 \) calculated by Fick’s principle using a continuous cardiac output thermodilution technique did not accurately predict \( \dot{V}_O_2 \) measured by a gas exchange method. However, calculation of \( \dot{V}_O_2 \) exhibited good repeatability compared with direct measurement, probably because of the good precision of measuring continuous cardiac output.

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Calculated and measured oxygen consumption


