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Oxygen consumption after cardiac surgery – a comparison between calculation by Fick's principle and measurement by indirect calorimetry

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Abstract. Oxygen consumption calculated by Fick's principle ($c\dot{V}O_2$) was compared to oxygen consumption measured ($m\dot{V}O_2$) by indirect calorimetry (Deltatrac Metabolic Computer) in 10 patients in the post-operative period after cardiac surgery. For 50 pairs of measurements the mean difference ($m\dot{V}O_2 - c\dot{V}O_2$) was 34±27 ml/min·m^2. The limits of agreement were −20 ml/min·m^2 to 88 ml/min·m^2. These results showed that $c\dot{V}O_2$ and $m\dot{V}O_2$ were not interchangeable in this study.

Key words: Oxygen consumption – Calorimetry – Fick Formula – Cardiopulmonary bypass

Recovery from anaesthesia is often responsible for an increase in energy expenditure as is suggested by the increase in O_2 consumption ($\dot{V}O_2$) [1]. Consequently the cardiac output (CO) and the oxygen extraction ratio (OER) increase. An inadequate adaptation in patients with cardiac disease leads to a critical level of OER [2]. Therefore the analysis of $\dot{V}O_2$ should be useful after cardiac surgery [3]. The $\dot{V}O_2$ is usually calculated according to Fick's principle ($c\dot{V}O_2$). However the precision of $\dot{V}O_2$ remains dependent of the precision of CO and of arterial and mixed O_2 contents measurements [4, 5]. The measurement of $\dot{V}O_2$ using the gasanalysis method ($m\dot{V}O_2$) removes the error that the calculation method could make. The Deltatrac Metabolic Monitor (Sensor Medics, Anaheim, California) is under clinical evaluation [6, 7]. Several studies [8–10] show a good correlation between the two methods. The aim of the study was to compare $c\dot{V}O_2$ and $m\dot{V}O_2$ measured by Deltatrac in the post-operative period after cardiac surgery.

Patients and methods

With informed consent and approval of local Ethics Committee, 10 patients, 9 males and a female, aged 67±8 years (mean±SED), were enrolled in the study (Table 1). The anaesthetic protocol was the same for all the patients and consisted of high doses fentanyl (100 µg/kg), flunitrazepam and pancuronium bromide. The extracorporeal circulation using a bullous oxygenator (Dideco 700S) was primed with a colloid-crystalloid solution. The rectal temperature was 37±1 °C at the end of the operation. All the patients were ventilated (CPU 1, Ohmeda) with a tidal volume of 10 ml/kg, inspiratory O2 fraction ($FiO_2 < 0.6$ without PEEP. Fentanyl (5 µg/kg) and pancuronium bromide (0.1 mg/kg) were discontinuously injected to adjust the patient to the ventilator. All the patients received a continuous infusion of a 5% dextrose solution. A modified gelatine solution (Plasmion, R. Bellon lab.) was the only solution used for vascular filling as required. A 7.5 Fr Swan-Ganz catheter (Edwards Lab.) was inserted via the internal jugular vein in the pulmonary artery. CO was determined by injection of 10 ml of a cold 5% dextrose solution, mean CO was the mean of a series of 4 measurements spread randomly over the ventilatory cycle. Samples for arterial blood gases were withdrawn through a radial artery catheter (Seldicath). After placing the Swan-Ganz catheter in such a location that a wedge pressure could not be obtained despite inflation of the balloon, mixed venous blood samples were withdrawn through the pulmonary artery lumen. Serial measurements were started 2 h after their arrival in the ICU.

The study in each patient consisted of 6±2 (mean±SD) serial determinations of both $c\dot{V}O_2$ and $m\dot{V}O_2$ at 30 min intervals. The following hemodynamic and biological parameters were recorded at each point: CO (Hewlett-Packard, 78552 A), arterial (PaO_2) and mixed venous O_2 tensions ($P\bar{v}O_2$) (Radiometer ABL 300, Copenhagen, Denmark), arterial (SaO_2) and mixed venous saturation ($S\bar{v}O_2$) (OSM 3, Copenhagen, Denmark). The transducers (Hewlett-Packard, 1290A opt 006) were zeroed at the beginning of every series. After a prewarming of 30 min and a gas and pressure calibration the Deltatrac was connected to the ventilator according to the constructor's recommendations. The $m\dot{V}O_2$ was measured continuously. The mean $m\dot{V}O_2$ was obtained every minute and was the mean of the last five values of $\dot{V}O_2$. The artefacts were suppressed (constructor's own algorithm). The measurement was stopped during 30 min if cough occurred or if bronchopulmonary toilet was necessary.

Deltatrac measures $\dot{V}O_2$ as follows: After calculation of CO_2 production $\dot{V}CO_2 = Q \cdot Fe^*CO_2$ where Q is the total flow (the flow leaving the mixing chamber where room air and expired gas flow from the ventilator are mixed) and Fe^*CO_2 is the CO_2 concentration in this expired flow, RQ is then calculated using the Haldane transformation $RQ = (1 - FiO_2/[FiO_2 - FEO_2)/FECO_2 - FiO_2]$ where FEO_2 is the mixed expiratory O_2 fraction, $FECO_2$ is the mixed expiratory CO_2 fraction. FiO_2 is measured from the inspired limb of the ventilator immediatly after the humidifier. $\dot{V}O_2$ is then calculated: $\dot{V}O_2 = \dot{V}CO_2/RQ$.

The following parameters were calculated according to standard formulae:

- Cardiac Index (Cl, l/min·m^2) = CO/Body Surface Area.
- arterial O_2 content (CaO_2, ml/dl) = $(1.34 \cdot Hb \cdot SaO_2) + 0.0031 \cdot PaO_2$.

Table 1. Clinical characteristics of the patients

Patients	Sex	Age (yr)	Operation
1	M	69	CABG
2	M	67	CABG
3	M	65	CABG + AVR
4	M	76	AVR
5	F	47	AVR + MVR
6	M	59	CABG
7	M	69	MVR
8	M	73	CABG
9	M	74	AVR
10	M	69	AVR

CABG, coronary artery bypass grafting; AVR, aortic valve replacement; MVR, mitral valve replacement

- mixed venous O_2 content ($C\bar{v}O_2$, ml/dl) = $(1.34 \cdot Hb \cdot S\bar{v}O_2) + 0.0031 \cdot P\bar{v}O_2$.
- $c\dot{V}O_2$ ($ml/min \cdot m^2$) = $CI \cdot (CaO_2 - C\bar{v}O_2) \cdot 10$

Statistical analysis

$c\dot{V}O_2$ were compared to $m\dot{V}O_2$ (mean of the last 5 min). The data were analyzed with the method described by Bland and Altman [11]. The difference between two measurements is the error, and the average error is the bias. The bias is the offset that could possibly be subtracted from the measured variable ($m\dot{V}O_2$) to yield better agreement with the standard ($c\dot{V}O_2$) which is not the true value. The mean of the absolute value of the error was determined. This result is the magnitude of average disagreement between the two methods. Measurements for each patient and for both methods were analyzed with ANOVA to search a time-effect.

Results

Fifty hemodynamic and metabolic measurements were carried out. The types of cases included in the study are listed on Table 1. Table 2 shows the $c\dot{V}O_2$, $m\dot{V}O_2$ and bias for each patient. The median $m\dot{V}O_2$ was 153 ml/min·m^2 (range, 130 to 193 ml/min·m^2); median $c\dot{V}O_2$ was 120 ml/min·m^2 (range, 73 to 171 ml/min·m^2). Figure 1 shows the difference between $c\dot{V}O_2$ and $m\dot{V}O_2$ measurements versus the average measurement for the two methods. As shown, the bias was 34 ml/min·m^2, with standard deviation of 27 ml/min·m^2, and the absolute error was 38±21 ml/min·m^2. Approximately 95% of the errors were within −20 to 88 ml/min·m^2. The bias of 34 ml/min·m^2 had a 95% confidence interval of 26 to 41 ml/min·m^2. This confidence interval depending on the study sample size showed that, for this size population, the average error was statistically different from zero. The limits of agreement of −20 to 88 ml/min·m^2 were also dependent on the population size. The 95% confidence interval for the lower limit of −20 ml/min·m^2 was −33 to −7 ml/min·m^2. The 95% confidence interval for the upper limit of 88 ml/min·m^2 was 75 to 101 ml/min·m^2. No time-effect was shown for each patient and for both methods.

Table 2. $c\dot{V}O_2$, $m\dot{V}O_2$ and bias for each patient

Patients	$c\dot{V}O_2$ (ml/min·m^2)	$m\dot{V}O_2$ (ml/min·m^2)	bias (ml/min·m^2)
1	82±6	137±5	56±3
2	82±7	143±9	61±10
3	109±29	149±13	40±25
4	144±36	159±24	17±49
5	147±19	148±12	2±17
6	131±16	146±10	15±18
7	119±16	177±24	53±13
8	126±24	157±10	38±24
9	129±10	174±4	45±14
10	115±15	144±16	29±18
Mean±SD	120±27	153±17	34±27

Values expressed as mean±SD

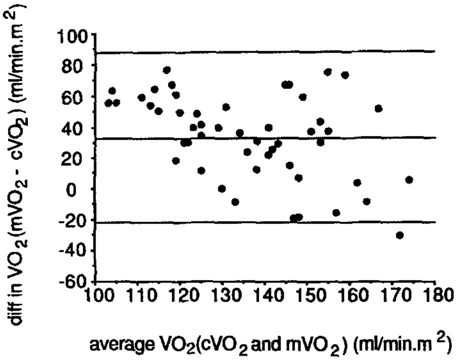

Fig. 1. Limits of agreement. The difference ($m\dot{V}O_2 - c\dot{V}O_2$) is plotted against the mean $\dot{V}O_2$ values ($c\dot{V}O_2 + m\dot{V}O_2$) for 50 measurements in 10 patients. The mean difference (bias) was 34 ml/min·m^2 and is designated with a *horizontal line*. Lines designating the mean difference ±2SD indicate the limits of agreement. The standard deviation was 27 ml/min·m^2

Discussion

When two measurement methods are compared, neither the correlation coefficient nor techniques such as regression analysis are appropriate [11]. In our patients, measurements of $m\dot{V}O_2$ by Deltatrac were not in agreement with $c\dot{V}O_2$ calculated according to Fick's principle which suggested that the two methods were not interchangeable. A value of 38 ml/min·m^2 for the absolute error showed that, on average, $m\dot{V}O_2$ measurement differed from $c\dot{V}O_2$ by 38 ml/min·m^2 for a given instance. The 95% confidence interval on the bias included zero; thus, in this study it was impossible to add an offset to the $c\dot{V}O_2$ measurements to yield better agreement. The bias and large magnitude of 2SD for each patient indicated the considerable variation in repeated measurements on the same subject [11].

Physiologically $c\dot{V}O_2$ and $m\dot{V}O_2$ must be identical. Svensson et al. [12] show that $c\dot{V}O_2$ is well correlated ($r = 0.97$) to $m\dot{V}O_2$ during cardiopulmonary bypass where blood flow is maintained constant. Danek et al. [13] find that the mean of $c\dot{V}O_2$ and the mean of $m\dot{V}O_2$ measured by measuring the volume and gas concentration of inspired and expired air, are not significantly different. The high variability of the gas analysis method could be explained in this study by the method of measuring the expired volume which is not stabilized in a mixing chamber. Behrent et al. [14] report in critically surgical patients (cardiac surgery and laryngectomy) the exact correlation between c$\dot{V}O_2$ and m$\dot{V}O_2$ (Engström Metabolic Computer). Takala et al. [8] study seven patients who were on controlled mechanical ventilation after coronary artery bypass surgery; m$\dot{V}O_2$ is measured by Deltatrac and compard to c$\dot{V}O_2$. In this study, m$\dot{V}O_2$ is consistently larger than c$\dot{V}O_2$: 294±59 versus 247±58 ml/min with a mean difference of 49±25 ml/min. The same results were found in the present study. Nevertheless the author finds a good correlation between the two methods ($r = 0.89$, $p < 0.01$). Chopin et al. [15] show in 12 septic patients without shock that m$\dot{V}O_2$ is significantly 13% greater than c$\dot{V}O_2$. Recently Hankeln et al. [9], using a real-time $\dot{V}O_2$ monitoring device previously described by the same author, compare m$\dot{V}O_2$ with c$\dot{V}O_2$ in 25 patients with ARDS: m$\dot{V}O_2$ is slightly higher than the invasive measurements, but these findings are not significant. A good correlation is also found between the two methods ($r^2 = 0.60$, $p < 0.01$]. These results are in agreement with those reported by Iparraguire et al. [10] in 33 patients with acute myocardial infarction. However, even though a good correlation is found between m$\dot{V}O_2$ and c$\dot{V}O_2$ in these latter studies, no conclusion could be drawn because, as mentioned above, it is not appropriate, in a statistical point of view, to search a correlation between two variables a priori identical when none of the two methods are considered as "gold standard" [11]. Vermeij et al. [16] study $\dot{V}O_2 - \dot{D}O_2$ relationships in 13 postoperative patients and 7 septic patients. This study points out the scattering of c$\dot{V}O_2$ and m$\dot{V}O_2$ values when the difference between paired values m$\dot{V}O_2$ and c$\dot{V}O_2$ is plotted against m$\dot{V}O_2$. Finally, the central finding of the study of Light et al. [17] is that m$\dot{V}O_2$ measured by an expired gas collection is consistently more than that measured using the Fick's principle in 5 dogs with pneumonia but not in 5 dogs with normal lungs where the mean difference m$\dot{V}O_2$ − c$\dot{V}O_2$ is 4±3 ml/min·m^2. Why are these results so different? Rather than discuss an hypothetical venous admixture or lung $\dot{V}O_2$, which could explain the difference [15, 17], special attention must be focused on the errors that both methods could make. Indeed, if one method has poor repeatability, the agreement between the two methods is bound to be poor [11].

Classically the $\dot{V}O_2$ is calculated according to the Fick's principle. It depends on CO and $CaO_2 - C\bar{v}O_2$. Whereas the measurement of SaO_2 of $S\bar{v}O_2$ allows a correct value of $C(a-\bar{v})O_2$ [10], the measurement of CO by thermodilution may be erroneous so that the c$\dot{V}O_2$ is not accurate, even though some authors prefer looking at changes in $\dot{V}O_2$ and $\dot{D}O_2$ rather than at absolute values [18]. The coefficient of variation for CO is 4.3±3.3 percent in 33 patients with acute myocardial infarction [10] allowing a coefficient of variation for c$\dot{V}O_2$ of 8.5±4.4 percent. Injectate temperature, determination of blood temperature, variation in injectate volume and injection rate [4] and effect of ventilation on pulmonary blood flow [19, 20, 21] are classical sources of errors with regard to the thermodilution technique.

The Deltatrac Metabolic Computer is based on the gas dilution techniques [22]. The Haldane transform: $\dot{V}O_2 = VE[FiO_2 - FEO_2 - (FiO_2 \cdot FECO_2)]/(1 - FiO_2)$ where VE is the expiratory flow, which is used to calculate $\dot{V}O_2$ and RQ from expiratory volume, amplifies errors progressively when FiO_2 is increased [23]. Consequently the majority of the authors recommands that the FiO_2 remains inferior to 0.6 [8, 24–26]. The fluctuation of FiO_2 level during mechanical ventilation [8, 27], pressure [8] and humidity effects, use of halogenates and N_2O for anaesthesia as well as presence of thoracic drainages [28, 29] are other sources of errors with regard to the gas-exchange method. However the precision of the measurements remains satisfactory. $\dot{V}CO_2$ and $\dot{V}O_2$ are measured with an overall error of 1.5% and 1.9% respectively in the study of Phang et al. [7]. The measurements of $\dot{V}O_2$ and $\dot{V}CO_2$ are within ±7% of values predicted from $\dot{V}CO_2$ and N_2 simulations for Weissman et al. [6].

In conclusion, in this patient population, $\dot{V}O_2$ measured by indirect calorimetry did not accurately predict $\dot{V}O_2$ calculated by Fick's principle. Thus, the two method were not interchangeable.

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