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Comparison of a modified Fick method with thermodilution for determining cardiac output in critically ill patients on mechanical ventilation

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Abstract. We compared a modified Fick method for measuring cardiac output against the thermodilution method in 11 critically-ill patients on mechanical ventilation. Oxygen consumption ($\dot{V}O_2$) was calculated indirectly, by measuring the carbon dioxide elimination ($\dot{V}CO_2$) during steady state and by assuming an average respiratory quotient of 0.9. For a total of 129 measurements, the mean difference in cardiac output between both methods was 0.03 ± 1.3 l/min (95% confidence interval, -0.19 to 0.25 l/min, $p = 0.7$) standard deviation, with the largest differences being measured in the low cardiac output range (<5 l/min). No statistically significant difference was found between the cardiac output values obtained with either method. These data showed a good correlation between the two methods and suggest that the modified Fick method may be useful in determining cardiac output in seriously ill patients on mechanical ventilation not requiring pulmonary arterial catheterisation, or where facilities for undertaking metabolic measurements are not available.

Key words: Cardiac output – Modified Fick method – Assumed RQ-value – Carbon dioxide elimination – Thermodilution

Improved accuracy of gas exchange measurement has reawakened interest in the Fick principle for determining cardiac output in critically-ill patients [1, 2]. However, there are considerable technical and practical difficulties to be overcome in continuously measuring $\dot{V}O_2$ in mechanically ventilated patients [3], and the investment and maintenance costs are high. Furthermore, continuous Fick cardiac output monitoring requires expensive computer-assisted equipment [2, 4, 5, 6] and gives unreliable results in measuring $\dot{V}O_2$ when FiO_2 exceeds 0.6 [5, 7].

At high levels of FiO_2, it is possible to get a very good approximation of $\dot{V}O_2$ by measuring the carbon dioxide elimination $\dot{V}CO_2$ divided by an assumed RQ [4], as $\dot{V}CO_2$-measurement is technically easy, is generally more reliable than $\dot{V}O_2$ and is unaffected by FiO_2 [4]. This idea has been proposed previously [8] but has not been clinically tested to date. This was the basis of our modification of the Fick method, with an RQ of 0.9 ($RQ = \dot{V}CO_2/\dot{V}O_2$) being taken as typical for patients receiving balanced total parenteral nutrition (TPN).

The aim of this study was to compare the cardiac output values obtained with the modified Fick method (COF) using indirect calculation of $\dot{V}O_2$, with the standard thermodilution method (COTD) in critically ill mechanically ventilated patients. The magnitude of the error introduced in further simplifying the method, by substituting oxyhemoglobin saturation (SO_2) in the right atrium ($SRAO_2$) for that in mixed venous blood ($S\bar{v}O_2$), as well as comparing mixed expiratory carbon dioxide concentration ($FECO_2$) in a 3-litre and 60-litre sample was also studied in this patient group.

Materials and methods

Eleven patients of a surgical intensive care unit were selected for the study and the demographic data are shown in Table 1. Institutional approval and informed consent of the patients or their families were obtained in all cases. All patients required mechanical ventilation for respiratory failure. Haemodynamic monitoring included radial or femoral artery, pulmonary artery (Gould 7F SP 5007, Oxnard, California) and right atrial catheterization. All patients received balanced parenteral nutrition based on the optimal body weight according to Paauw [9].

For COF determination, the patients were ventilated to maintain a $PaCO_2$ between 35–40 mmHg with 100% oxygen for 20 min using a volume-cycled ventilator (Engström Erica, Gambro Engström AB, Sweden). The patients were sedated with fentanyl 0.1–0.2 mg and flunitrazepam 0.2–0.3 mg iv as needed. All patient measurements were performed at least 20 min after any intervention, such as suction of the endotracheal tube or turning of the patient, and there was no change in the circulatory or ventilatory state for 60 min prior to measurement. The expiratory minute volume ($\dot{V}E$) was then determined with a calibrated Wright spirometer. $FECO_2$ was determined from the expired air collected in a 3-litre bag ($n = 129$). For comparison, 25 additional measurements were obtained from a further 10 mechanically ventilated patients using a 60-litre Douglas bag. The CO_2-concentration was deter-

Table 1. Clinical diagnosis and demographic data of patients

Clinical diagnosis	Sex	Age	Height (cm)	Weight (kg)	No. of measurements
1. Perotonitis, sepsis	m	73	169	53	22
2. Thoraco-abdominal aneurysectomy, renal failure post-op.	m	58	164	60	2
3. Head injury, multiple fractures	m	32	175	65	6
4. Hepatic lobectomy	m	57	171	86	4
5. Pancreatitis, sepsis, ARDS	m	37	176	80	18
6. Abdominal aortic aneurysectomy	m	64	175	72	2
7. Multiple fractured ribs, sepsis, ARDS	m	59	178	88	27
8. Abdominal aortic aneurysectomy, myocardial infarction post-op.	m	65	175	98	4
9. Peritonitis, pneumonia	f	72	160	48	34
10. Colectomy, nephrectomy	m	63	176	51	1
11. Sepsis, ARDS	m	55	188	130	9
	mean	57.7	173.4	75.6	
	±SD	±3.9	±2.2	±7.4	

mined by means of an infrared analyser (Hartmann and Braun, Frankfurt, FRG). Before each comparison, the analyser was calibrated with calibration gases (CO_2 in oxygen), covering the gas concentration range expected in the patients. During the collection of expired gas, arterial and mixed venous blood samples were drawn for immediate blood gas analysis using a Corning 178 blood gas analyser (IMA Gilford, Giessen, FRG). The mean of two sets of triple measurements of COTD, immediately before and after the gas sampling, was taken as the representative value. The injection was timed to occur at the end of expiration (10 ml normal saline 17°–22 °C, injection time < 3 s), using a standard cardiac output computer (Franke, Herne, FRG). Haemoglobin (Hb) and oxyhaemoglobin saturation (SO_2) were measured with an oximeter (OSM2, Radiometer, Copenhagen). SO_2 was determined in both pulmonary artery and right atrial blood ($n = 90$).

Description of modified Fick method

The calculations used for estimating the modified Fick cardiac output are based on the following equations:

$$COF = \dot{V}O_2 / CaO_2 - C\bar{v}O_2$$

$$CaO_2 - C\bar{v}O_2 = [(SaO_2 \times Hb \times 1.36) + (0.003 \times PaO_2)] - [(S\bar{v}O_2 \times Hb \times 1.36) + (0.003 \times P\bar{v}O_2)] \ldots [10].$$

where $\dot{V}O_2 = \dot{V}CO_2/RQ$

$$\dot{V}CO_2 = FECO_2 \times \dot{V}E \ldots [3]$$

where $CaO_2 - C\bar{v}O_2$ = arteriovenous oxygen content difference (ml/l). Oxygen consumption ($\dot{V}O_2$) was calculated indirectly by assuming an RQ of 0.9 and directly measuring $\dot{V}CO_2$. Since $\dot{V}CO_2$ was determined under ATPS conditions, allowance was made for $\dot{V}O_2$ to be converted to STPD. The appropriate average conversion factor at 20 °C and at sea level is 0.9 [11].
Thus

$$\dot{V}O_2\ (STPD) = 0.9 \times \dot{V}CO_2\ (ATPS)/RQ$$

and with RQ = 0.9

$$\dot{V}O_2\ (STPD) \cong \dot{V}CO_2\ (ATPS).$$

Cardiac output was then calculated from the modified Fick equation

$$COF = \dot{V}CO_2\ (ATPS)/CaO_2 - C\bar{v}O_2.$$

Data are presented as the mean (SD) or range. Linear regression analysis using the least squares method was employed for correlation statistics. Statistical significance was assessed using the paired Student's t-test.

To examine if bias might exist between the two methods of measuring cardiac output, the difference between methods was compared with the average of the two methods as described by Bland and Altman [12]. This approach was also used for comparing $SRAO_2$ and $S\bar{v}O_2$.

Results

Cardiac outputs ranged from 3 to 16 l/min. The mean difference between CO-values obtained with both methods was 0.03±1.3 l/min, $t = 0.29$, degrees of freedom = 127, $p = 0.7$, (95% confidence interval of −0.19 to 0.25 l/min). The mean COTD was 8.2 (1.94) l/min and the mean COF was 8.1 (2.32) l/min and no statistically significant difference was found between these. There was a high degree of statistical correlation between the two methods (Fig. 1). Although the largest differences between both methods were in the low cardiac output range (CO < 5 l/min), statistical significance was not reached.

A significant positive correlation was also obtained from a total of 90 comparisons of oxyhaemoglobin saturation in blood samples from the pulmonary artery ($S\bar{v}O_2$) [y] and the right atrium ($SRAO_2$) [x]: $y = 0.88x + 8.34$; $r = 0.98$, $n = 90$, $p < 0.01$. The mean $S\bar{v}O_2$- and $SRAO_2$-values were 78.9 (10.25)% and 80.32 (11.38)% respectively (mean and SD). The mean difference between SO_2 values obtained with both methods was −1.6%±2.7%, $t = -5.6$, degrees of freedom = 88, $p = 0.0001$, (95% confidence interval of −1.03 to 2.13 percentage points).

Mixed expiratory CO_2-concentrations ($FECO_2$) determined in a 60-litre [x] and a 3-litre [y] sample from 10 patients, were almost identical ($y = 1.02x - 0.01$; $r = 0.99$, $n = 25$ and $p < 0.001$). The mean $FECO_2$ (60 l) was 2.33 (0.5)% and for $FECO_2$ (3 l) was 2.38 (0.52)%.

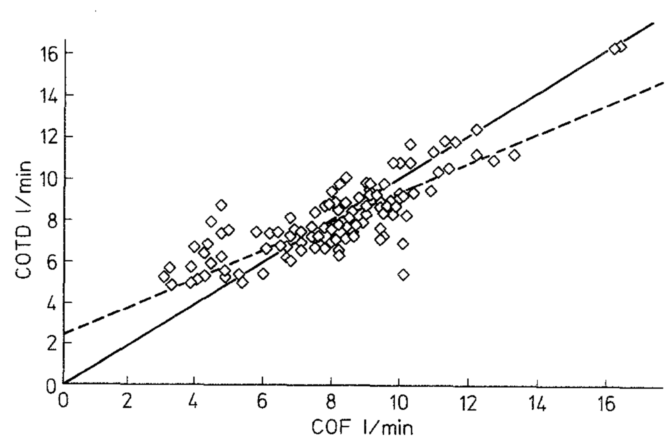

Fig. 1. Regression analysis of cardiac output measured with the thermodilution (*COTD*) and the modified Fick method (*COF*). Regression equation: $y = 0.7x + 2.53$; $r = 0.83$; $p < 0.001$, $n = 129$. – – – Regression line; ——— line of identity

Discussion

In studies of intermittent cardiac output measurement in mechanically ventilated patients, comparing the classical Fick and the thermodilution methods, correlation coefficients between 0.7 and 0.8 have been reported [13, 14]. Our results compare well with these studies, although, unlike these authors, we did not directly measure $\dot{V}O_2$. By plotting the difference between both methods (COTD vs. COF) against its mean, we observed a good agreement between the standard (COTD) and the modified Fick method of measuring cardiac output. The discrepancies between the two methods were evaluated by calculating the mean differences, the standard deviation of the differences and the 95% confidence interval of the mean difference [12]. The magnitude of this difference would seem to be small enough to allow use of the COF method in place of the standard COTD method. However, caution has to be exercised in the interpretation of these results, as some bias may have been introduced due to repeat measurements in some patients. Although there was only a small difference between the mean values of cardiac output measured with the two methods, some measurements showed a wide variation, being most marked at cardiac outputs under 5 l/min. However, the resulting high oxygen extraction as seen in low cardiac output states should tend to increase the accuracy of the Fick method on theoretical grounds [5], and may be more reliable here than COTD, which tends to overestimate cardiac output in the low output range [15].

To simplify the calculations, we stated that $\dot{V}O_2$ (STPD) $\cong \dot{V}CO_2$ (ATPS), and assumed thereby an RQ of 0.9 and an ambient temperature of 20 °C at a barometric pressure of 760 mmHg which corresponds to a conversion factor (ATPS to STPD) of 0.9 [11]. Based on standard tables of correction factors over a temperature range from 17°–23 °C, and at a barometric pressure ranging from 730–770 mmHg [16], this assumption would lead to a maximum error of ±4.1%. For measurements obtained at temperatures and pressures outside this range, reference may be made to appropriate tables [11] for the relevant conversion factors.

The use of $\dot{V}CO_2$ (ATPS) as an estimate of $\dot{V}O_2$ (STPD) may be challenged for relying on an assumed fixed RQ as proposed in previous reports [5]. Neuhof describes an RQ of 0.9 as being typical for patients with increased carbohydrate metabolism during severe illness [17]. More recent metabolic studies on mechanically ventilated, mainly surgical, ICU patients receiving balanced enteral [18] and parenteral [10, 19, 20, 21] nutrition, would seem to confirm this, with mean RQ-values ranging from 0.83 to 0.96 being determined. A comparison of metabolic parameters in studies of critically ill patients is extremely difficult to make however, due to a large number of poorly controlled factors [22] including inhomogenous patient groups, differing TPN regimes and different measurement techniques. Bearing this in mind, our modification may appear to be a gross oversimplification of a complex metabolic situation. The above-mentioned results of other investigators would suggest, nonetheless, that the error introduced in assuming an RQ of 0.9 is small, not exceeding 8%, for most patients receiving balanced TPN. Other authors have reported that the assumption of a fixed RQ should not lead to an error greater than 7% when the RQ is changed from 0.7 to 1 and is unlikely to exceed 3.5% in most cases [23]. The greatest deviation from an RQ of 0.9 is to be expected in patients who are anaerobic, starving, hyperventilating or receiving hyperalimentation [4], and the RQ-value should be adjusted appropriately to fit the particular situation. Particular attention has to be paid to carrying out the measurement under steady-state conditions and using the modified Fick method in hemodynamically unstable patients could lead to errors in $\dot{V}CO_2$-measurement, if CO_2-homeostasis can not be assumed [16].

Measurement of $FECO_2$ in a 3-litre sample led to an average overestimation of 2.1%, in comparison to the more usual 60-litre sample. Similarly, substituting $SRAO_2$ for $S\bar{v}O_2$ led to an average overestimation of 1.8%. The influence of this overestimation on the final cardiac output will depend on the individual values for haemoglobin, $\dot{V}O_2$ and $S\bar{v}O_2$ but will be less than 5% in the vast majority of cases. The mixed venous oxyhaemoglobin saturation [$S\bar{v}O_2$] is regarded as being the most accurate trend indicator of the relationship of O_2-supply to O_2-consumption and thus of the overall adequacy of tissue perfusion and oxygenation [24] and the substitution of $SRAO_2$ for $S\bar{v}O_2$ has been criticised [25], as being unreliable, especially in the haemodynamically unstable patient. The good correlation found in our study however, between $SRAO_2$ and $S\bar{v}O_2$ is in keeping with the results of previous authors [25, 26] and suggests that $SRAO_2$, although showing wide divergence from $S\bar{v}O_2$ in the higher SO_2-range in some patients, is still a useful parameter for following trends in oxygen saturation when mixed venous blood samples are not available [25]. In contrast to the thermodilution method, the Fick method provides a more comprehensive physiological assessment of the patient than is available with the thermodilution method alone [5]. Substituting $\dot{V}CO_2$ for $\dot{V}O_2$, allows the method to be performed within 10 min, utilising basic equipment available in every ICU. The technical difficulties associated with the direct determination of $\dot{V}O_2$ in ventilated patients are avoided and in particular, the results are not affected by high or changing FiO_2 [4]. Our modification of the classical Fick method is thus a useful alternative to the thermodilution method of measuring cardiac output in mechanically ventilated patients and provides a valuable trend analysis in situations where a pulmonary artery catheter or continuous metabolic studies are not available or are contraindicated.

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