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Continuous measurement of oxygen consumption using the reversed Fick method

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Abstract: We developed a continuous oxygen consumption (Vo_2) measurement system employing the reversed Fick method, in which Vo_2 is computed from continuously measured arterial and mixed venous oxygen saturation assessed by pulse oximetry and mixed venous oximetry, respectively, and cardiac output by the heat deprivation technique. This system was compared with the conventional intermittent reversed Fick method in 7 patients during surgery and with indirect calorimetry in 4 intensive care unit (ICU) patients. The Vo_2 measured by the continuous reversed Fick method showed a high correlation with those simultaneously measured by the intermittent Fick method ($r = 0.97$, $P < 0.01$) and by indirect calorimetry ($r = 0.74$, $P < 0.01$). The 95% confidence limits (bias ± 2 SD) of the continuous reversed Fick method were $-0.6 \pm 45\,\mathrm{ml \cdot min^{-1}}$ with the intermittent Fick method and $-31 \pm 56\,\mathrm{ml \cdot min^{-1}}$ with indirect calorimetry. The continuous Fick method is in satisfactory agreement with the conventional methods for the measurement of Vo_2 and potentially allows for convenient assessment of Vo_2 in critically ill patients.

Key words: Indirect calorimetry, Monitor, Pulse oximetry, Shock, Heat deprivation

Introduction

Oxygen consumption (Vo_2) has been measured as part of the perioperative management of critically ill patients by methods employing the reversed Fick principle or indirect calorimetry [1–9]. In the reversed Fick method, Vo_2 is calculated from hemoglobin concentration (Hb), arterial and mixed venous oxygen saturation (Sao_2, Svo_2), arterial and mixed venous oxygen tension (Pao_2, Pvo_2), and cardiac output (CO) as follows:

$$Vo_2\ (\mathrm{l \cdot min^{-1}}) = [0.134 \cdot \mathrm{Hb} \cdot (Sao_2 - Svo_2) + 0.031 \cdot (Pao_2 - Pvo_2)] \cdot \mathrm{CO}.$$

In the conventional reversed Fick method, Hb, oxygen saturation, and oxygen tension are intermittently determined by laboratory analysis, and CO is obtained by the thermodilution technique. Therefore, this method requires simultaneous collection of blood from the artery and mixed vein and injection of chilled fluid to determine CO.

In indirect calorimetry, Vo_2 is continuously estimated using respiratory gas analysis [8–10]. However, this method has more stringent preconditions than the reversed Fick method to obtain valid measurements, such as stable inspired fraction of oxygen (Fio_2) of less than 0.5, adequate humidity, whole collection of expired gases, and so on. Furthermore, its clinical applications in the intensive care unit (ICU) and operation rooms are limited by its high cost and the large size of the equipment.

Frequent measurement of Vo_2 is highly desirable to detect critical changes in patients in unstable condition. In the present study, we developed a continuous Vo_2 measurement system using the reversed Fick method, and we compared it with the intermittent reversed Fick method and indirect calorimetry in patients.

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Materials and methods

Patients

The study protocol was approved by the Ethics Committee of the Department of Anesthesiology of Kyoto

Table 1. Patients undergoing surgery

	Sex	Age	Weight (kg)	Height (cm)	Time (h)	Diagnosis
1	F	56	67	159	3:20	Pheochromocytoma
2	F	61	54	151	3:50	Ovarian cancer
3	F	66	47	154	3:40	Renal tumor
4	F	68	58	155	3:40	Rheumatic arthritis in the hip
5	M	34	49	160	4:50	Bilateral hip joint necrosis
6	F	61	43	150	5:10	Pheochromocytoma
7	F	63	50	153	4:40	Cervical carcinoma

Table 2. Patients in the ICU

	Sex	Age	Weight (kg)	Height (cm)	Diagnosis
1	M	70	74	162	Cardiac failure
2	M	46	69	171	Cardiac failure
3	M	67	52	157	Post operation for perforation of the esophagus
4	M	75	42	150	Post operation for perforation of the sigmoid colon

Prefectural University of Medicine. When the present study was conducted, this committee was the only body at the university with the authority to approve or disapprove of human studies. Seven patients who underwent major surgery (Table 1) and 4 patients who were admitted to the ICU of our university hospital were studied (Table 2). The purpose and potential risks of the study were explained to all patients and their families before we obtained their informed consent. Invasive hemodynamic monitoring was required in all patients as part of the clinical evaluation for major surgery and intensive care.

Continuous Vo_2 measurement systems using reversed Fick method

The physical solubility of oxygen in aqueous media is low; therefore, the Fick equation can be simplified by ignoring this factor, as follows [11]:

$$Vo_2\ (l\cdot min^{-1}) = 0.134 \cdot Hb \cdot (Sao_2 - Svo_2) \cdot CO.$$

In the present study, this simplified equation was utilized for reversed Fick methods.

Vo_2 was continuously computed from continuous measurements of Sao_2, Svo_2, and CO together with Hb values derived from blood samples. Sao_2 was measured with a pulse oximeter (N1000, Nellcor, Hayward, CA, USA), and Svo_2 by mixed venous oximetry (Oximetrix3, Abbott Critical Care Systems, North Chicago, IL, USA or CV202, Terumo, Tokyo, Japan). CO was continuously measured using a heat deprivation technique in the pulmonary artery for which the method has been reported [12]. In brief, a thermistor in the pulmonary artery is heated by a constant electric current and senses heat deprivation which is proportional to the velocity of blood flow. Using the values of CO simultaneously measured by the intermittent thermodilution technique, the measured velocity was converted to CO. This method is known as continuous cardiac output measurement (CCOM), and the catheter (CO-C7111H, Terumo, Tokyo, Japan) and a processor (CO203, Terumo) for the CCOM system are commercially distributed for clinical use in Japan. Hb was measured from blood samples with a laboratory hemoximeter (OSM3, Radiometer, Copenhagen, Denmark).

Protocol and measurements

The Vo_2 values obtained by the continuous reversed Fick method were compared with simultaneously measured Vo_2 values obtained by the intermittent reversed Fick method during surgery and by indirect calorimetry in the ICU. Pulmonary arterial catheters were percutaneously inserted via the right internal jugular vein and/or the cubital veins. Correct position of the catheter was confirmed by a fluoroscope.

In the patients undergoing surgery, two 7F pulmonary arterial catheters were utilized, one for the measurement of Svo_2 (Opticath P7110 and Oximetrix3, Abbott Critical Care Systems) and the other for the CCOM system. The oximetric catheter was advanced until its balloon occluded the pulmonary artery, and the tip of the CCOM catheter was placed at the stem of the pulmonary artery. All the analog data for CO, Sao_2, and Svo_2 were saved in an analog data recorder (MR30, TEAC, Tokyo, Japan), and Vo_2 values were computed at intervals of 10s with a signal processor (7T17, NEC Sanei, Tokyo, Japan).

After the induction of general anesthesia, each surgical patient was mechanically ventilated through a cuffed tracheal tube with F_{IO_2} of 0.3–0.5. Continuous V_{O_2} measurement using the reversed Fick method proceeded during general anesthesia. The intermittent reversed Fick method was also repeated at intervals of 1 h during the same period. In the intermittent reversed Fick method, arterial and mixed venous blood samples were simultaneously withdrawn for determination of Sa_{O_2}, Sv_{O_2}, and Hb using the laboratory hemoximeter (OSM3), and this was immediately followed by CO determination in duplicate by the thermodilution technique using 10 ml of chilled saline. In the calculation of V_{O_2} using the intermittent reversed Fick method, the physical solubility of oxygen was ignored. The determined Hb value was also used for the calculation of continuous V_{O_2} measurement.

In each of the ICU patients, we used a special 7.5F pulmonary catheter (no model number, Terumo) which was custom-designed for the dual purposes of CCOM system and oximetry. The CCOM thermistor was placed at a 5-cm distance from the tip of the catheter, and the catheter was advanced until the balloon occluded the pulmonary artery. The oximetry processor for this new catheter (CV 202, Terumo) computes V_{O_2} at intervals of 1 s or more employing the measured Sv_{O_2} values, transmitted data for CO and Sa_{O_2}, and key input Hb values. These processed results were transferred to a personal computer (PC-386, Epson, Tokyo, Japan) through a RS-232C port and saved on a disk. Graphical changes of the data were displayed on the computer monitor using custom-made software (Terumo). All the ICU patients were mechanically ventilated with an F_{IO_2} of less than 0.4 using a volume-limited respirator (Servo 900C, Siemens-Elema, Solna, Sweden). For the indirect calorimetry method, a metabolic monitor (Meta Scope 3-A, Cybermedic, Louisville, KY, USA) which calculates V_{O_2} at intervals of 1 min was utilized. The continuous reversed Fick method system was also programmed to calculate averages over 1 min. V_{O_2} was continuously measured for 20 min twice in each patient.

Data analysis

Correlation and agreement of two values were studied between pairs of V_{O_2} values simultaneously determined by two of the methods. When warnings of low signal levels were observed in the pulse oximeter or the mixed venous oximeter, the obtained data were excluded from the analyses.

Results

During surgery, we obtained 25 pairs of simultaneously measured V_{O_2} values by the two methods. The values of V_{O_2} ranged from 80 to 614 ml·min^{-1} by the intermittent reversed Fick method and from 81 to 601 ml·min^{-1} by the continuous version. The regression analysis yielded: $y = 4.9 + 0.98x$, $r = 0.97$, $P < 0.01$ (Fig. 1). The 95% confidence limit (bias ± 2 SD) was −0.6 ± 45 ml·min^{-1} (Fig. 2).

In the ICU patients, 126 pairs of reliable measurements were obtained. The V_{O_2} ranged from 151 to 287 ml·min^{-1} by indirect calorimetry and from 120 to 275 ml·min^{-1} by the continuous reversed Fick method. The regression analysis yielded: $y = 36 + 0.70x$, $r = 0.74$, $P < 0.01$ (Fig. 3). The 95% confidence limit was −31 ± 56 ml·min^{-1} (Fig. 4).

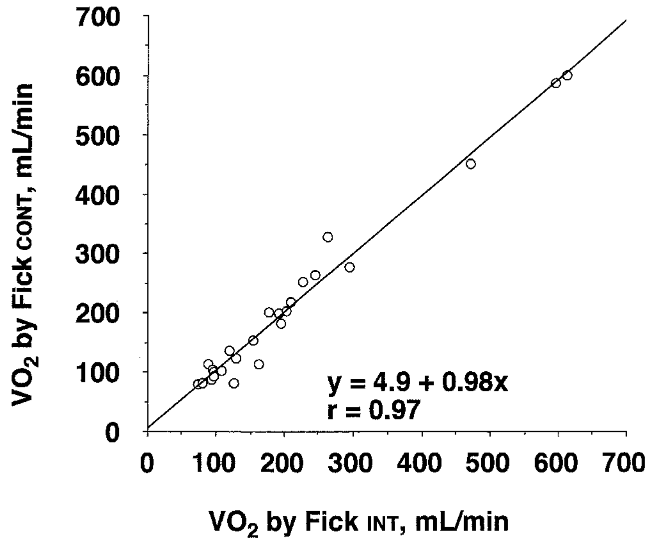

Fig. 1. Correlation between oxygen consumption (V_{O_2}) values simultaneously measured by the methods of intermittent reversed Fick (*Fick INT*) and continuous reversed Fick (*Fick CONT*)

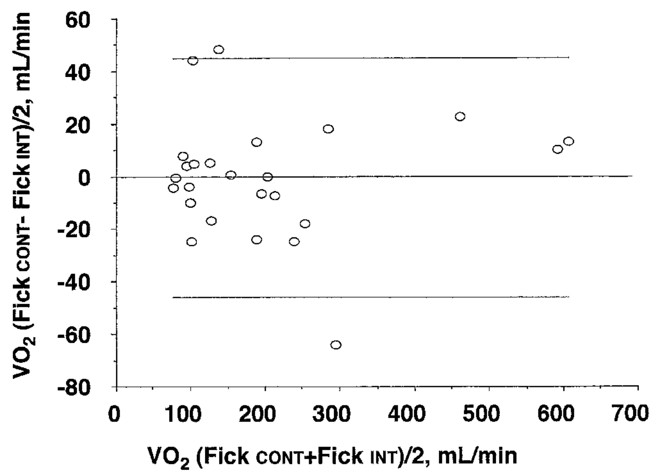

Fig. 2. Agreement of V_{O_2} by continuous reversed Fick (*Fick CONT*) with that measured by intermittent reversed Fick (*Fick INT*) for all patients and all measurements

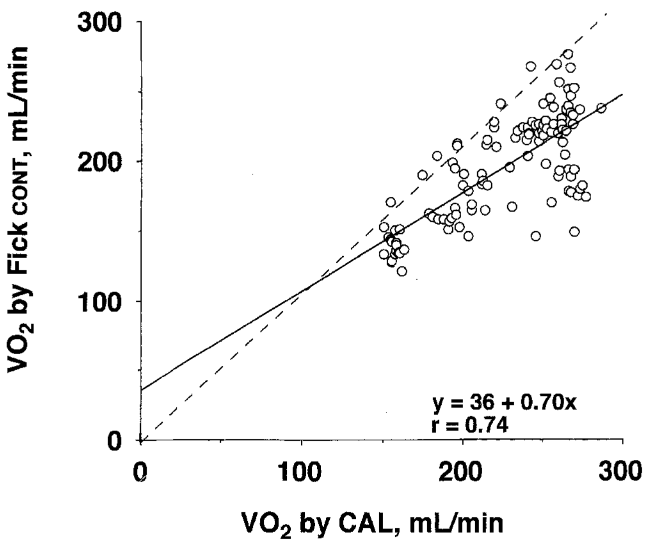

Fig. 3. Correlation between all Vo_2 values simultaneously measured by the methods of indirect calorimetry (*CAL*) and continuous reversed Fick (*Fick CONT*). *Dashed line*, identical line

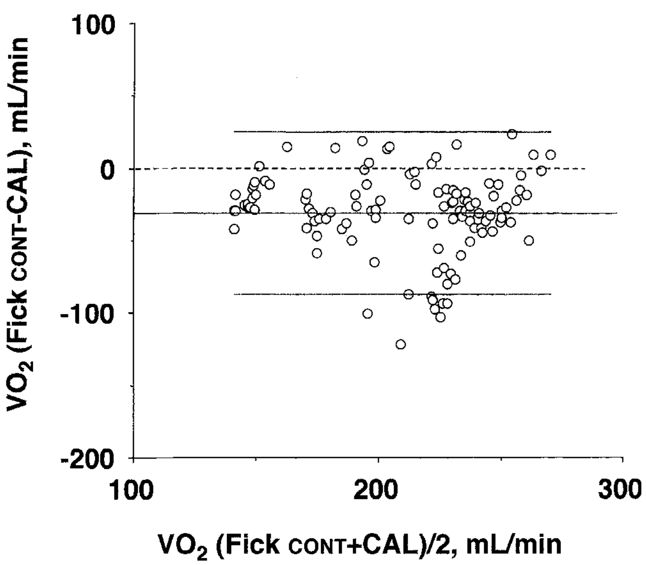

Fig. 4. Agreement of Vo_2 measured by continuous reversed Fick (*Fick CONT*) with that measured by indirect calorimetry (*CAL*) for all patients and all measurements

Discussion

The present study showed that the continuous reversed Fick method yields values in satisfactory agreement with those obtained by the conventional methods of reversed Fick and indirect calorimetry. In particular, its high correlation with the intermittent reversed Fick method may warrant the clinical use of the device in patients who are suitable candidates for the intermittent reversed Fick method. Both of the reversed Fick methods require almost the same level of invasiveness in placement of the catheter in the pulmonary artery, but the continuous method entails greatly reduced procedural complexity. Moreover, even in case of trouble with the continuous reversed Fick method, the system is adaptable for alternative use of the intermittent reversed Fick method.

It is still controversial whether Vo_2 can be used as a predictor of the clinical outcome in critically ill patients, and this might be partially due to the poor reproducibility of the reversed Fick method in patients with unstable circulatory status [6]. The intermittent reversed Fick method reflects only the instantaneous values of Vo_2 at the time of simultaneous blood collection and CO measurement, in contrast with indirect calorimetry, which provides averaged values of Vo_2 over a certain duration. The temporal discontinuity in the measurements of Vo_2 is one problem inherent in the intermittent reversed Fick method. To obtain reproducible values for Vo_2 by this method, one must maintain stable physiological conditions during the measurements. Because of the long repetition interval, the intermittent reversed Fick method does not show rapid Vo_2 changes that are caused by body movements in poorly sedated patients and other influences. Furthermore, the measurements of Vo_2 by the intermittent reversed Fick method are affected by fluctuations of CO caused by ventilation, and such fluctuations were reported to represent 10%–15% of the CO [13]. On the other hand, the continuous reversed Fick method, which averages continuously measured Vo_2, apparently overcomes the disadvantages of the conventional intermittent method. The continuous reversed Fick method, moreover, may allow for easy access to integration of oxygen deficits; the cumulative oxygen deficit was reported as a useful predictor of survival [2,3].

The present results support those of previous reports indicating that the values of Vo_2 measured by the reversed Fick method are smaller than those simultaneously measured by indirect calorimetry [7–9]. The difference between the two methods probably reflects intrapulmonary oxygen consumption [14], and the bias of 31 $ml \cdot min^{-1}$ we obtained was similar to those seen in previous clinical studies (21–49 $ml \cdot min^{-1}$) [7–9]. Combined monitoring with the continuous reversed Fick and indirect calorimetry methods may afford a more thorough understanding of intrapulmonary oxygen consumption in critically ill patients.

The reliability of the continuous reversed Fick method is contingent on adequate measurements of the individual parameters in the Fick equation. Sufficient accuracy has been reported with pulmonary oximetry [15,16] and heat deprivation [12]. However, in pulse oximetry, the error in accuracy, which remained at less than 3% when the values of Sao_2 were higher than 83%, was increased to 8% during deeper hypoxia [17]. In the present study, all the measured values of Sao_2 were more than 96%, which might have little influence on the overall accuracy of the system. When the system is used in patients with low Sao_2, the error caused by the use of pulse oximetry should be considered. Another problem in using the system is the contribution of the physical solubility of oxygen. Such is only 5% of the oxygen content of human blood with normal Hb and Pao_2 of less than 100 mmHg, but it should be taken into consideration when the Hb is low or Pao_2 is high.

In this short-duration monitoring application in a very limited number of patients, the continuous reversed Fick method showed adequate measurement of Vo_2. With the heat deprivation technique used in this study, re-calibration was not performed during the measurements, and the signal levels of Sao_2 and Svo_2 were monitored visually by the investigator. Therefore, the method should be refined to allow automatic testing of the reliability of the measured data, and the stability of the system should be examined in monitoring of longer duration. This should be followed by larger controlled clinical studies, to establish whether the continuous reversed Fick method is useful as a general monitoring system during critical care interventions.

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