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Continuous measurement of cardiac output by the Fick principle in infants and children: comparison with the thermodilution method

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Abstract *Objective:* To compare a system that continuously monitors cardiac output by the Fick principle with measurements by the thermodilution technique in pediatric patients.
Design: Prospective direct comparison of the above two techniques.
Setting: Pediatric intensive care unit of a university hospital.
Patients: 25 infants and children, aged 1 week to 17 years (median 10 months), who had undergone open heart surgery were studied. Only patients without an endotracheal tube leak and without a residual shunt were included.
Methods: The system based on the Fick principle uses measurements of oxygen consumption taken by a metabolic monitor and of arterial and mixed venous oxygen saturation taken by pulse- and fiberoptic oximetry to calculate cardiac output every 20 s.
Interventions: In every patient one pair of measurements was taken. Continuous Fick and thermodilution cardiac output measurements were performed simultaneously, with the examiners remaining ignorant of the results of the other method.
Results: Cardiac output measurements ranged from 0.21 to 4.55 l/min. A good correlation coefficient was found: $r^2 = 0.98$; $P < 0.001$; SEE = 0.14 l/min. The bias is absolute values and in percent of average cardiac output was − 0.05 l/min or − 4.4% with a precision of 0.32 l/min or 21.3% at 2 SD, respectively. The difference was most marked in a neonate with low cardiac output.
Conclusion: Continuous measurement of cardiac output by the Fick principle offers a convenient method for the hemodynamic monitoring of unstable infants and children.

Key words Fick principle · Thermodilution · Cardiac output · Infants · Cardiac surgery

Introduction

In the last 5 years the value of monitoring multiple cardiopulmonary variables in critically ill patients has been established [1, 2]. Thermodilution has become the most popular method of cardiac output determination in the ICU. However, in recent years several devices have become available to monitor continuously mixed venous and arterial O_2 saturation as well as oxygen uptake and carbon dioxide production [3–6]. In adults these devices, coupled with a microcomputer, have been used to measure cardiac output continuously by the Fick principle [7–10]. The purpose of this study was to compare such a system with the cardiac output determination by the thermodilution technique in critically ill pediatric patients.

Methods

The components of the system based on the Fick principle are commercially available and in widespread use. Respiratory gas exchange was monitored by the Deltatrac Metabolic Monitor I (Datex, Finland) with a pediatric mixing chamber. Mixed venous O_2 saturation was continuously measured using a fiberoptic pulmonary artery catheter and the Oximetrix III system (Abbott). These two devices were calibrated regularly according to the recommendations of the manufacturer. Arterial O_2 saturation was obtained from a Nellcor 200 pulse oximeter (Nellcor, Hayward, Calif.). Continuous values for heart rate and for mean systemic and pulmonary arterial blood pressures were obtained from a monitoring system (Hewlett Packard, Waltham Mass.).

A personal computer was used to process data from the measuring devices and the keyboard. The metabolic monitor, pulse oximeter, and mixed venous O_2 saturation systems communicated digital information via asynchronous communication ports while the data from the monitoring system were received by an analog-to-digital converter. A computer program (Dataperformance, Munich, FRG) was written to acquire, process, and store the data. Calculation of hemodynamic parameters was performed every 20 s using the following formula:

$$CO = \frac{VO_2}{CaO_2 - CmvO_2}$$

$$CaO_2 = 10\ [(SaO_{2(\text{pulse oximetry})} - F_c) \times 1.39\ Hb + 0.003\ P_aO_2]$$

$$CmvO_2 = 10\ [(SmvO_{2(\text{mixed venous oximetry})}) \times 1.39\ Hb + 0.003\ P_{MV}O_2]$$

$$F_c = SaO_{2(\text{pulse oximetry})} - HbO_2$$

where CO is cardiac output, VO_2 is oxygen uptake, and CaO_2 and $C_{MV}O_2$ are arterial and mixed venous oxygen content, respectively. Patient weight, height, hemoglobin content (Hb), PO_2 of arterial (P_aO_2) and mixed venous blood ($P_{MV}O_2$) were entered intermittently, along with a correcting factor (F_c) for the difference between pulse oximeter and the percentage of oxyhemoglobin (HbO_2) measured by a cooximeter. Every 2–6 h arterial and mixed venous blood gases and hemoglobin were analyzed immediately after sampling with a Radiometer ABL 520, which includes a cooximeter. These values were then entered into the computer system and into the mixed venous oximetry system for calibration.

Thermodilution cardiac output computation was performed by the cardiac output computer of the Abbott Oximetrix III. Study protocol consisted of the giving of three iced 5%-dextrose injections at end expiration. Injection volumes were 3 ml or 5 ml, according to the patient's weight. Simultaneously with each injection, the Fick cardiac output was noted and the three measurement averaged. The examiners performed cardiac output measurements blind to the results of the other method. The study protocol was approved by the Institutional Review Board.

Patients

Twenty-five infants and children, aged 1 week to 17 years (median 10 months), weighing 3.4–40 kg (median 6.4 kg) were studied following corrective cardiac surgery. Eight patients underwent repair of an atrioventricular septal defect and 11, of a VSD. None of the patients had a significant residual shunt as demonstrated by color Doppler echocardiography. All patients were nasotracheally intubated and were mechanically ventilated with a Siemens Servo 300 or 900C ventilator (Siemens-Elema, Sweden) with an inspired oxygen concentration of less than 50%. In all patients, a French 4-fiberoptic catheter was placed intraoperatively for postoperative monitoring of the mixed venous O_2 saturation [4]. Only patients without an audible endotracheal tube leak were included in the study [11, 12].

Statistical analysis

For the statistical evaluation of the agreement between the thermodilution method and the continuous Fick cardiac output method, only one randomly assigned, paired measurement of each patient was used. The difference between every thermodilution or continuous Fick cardiac output measurement and its mean was determined and the result were plotted against one another. Agreement between the two methods was estimated by calculating the mean difference between them ± 2 SD, as suggested by Bland and Altman [13]. The difference between the two measurements of each pair was evaluated not only in absolute values but also as a percentage of the average cardiac output of each pair:

$$\text{percentage difference} = \frac{\text{cont. Fick CO} - \text{thermodilution CO}}{(\text{cont. Fick CO} + \text{thermodilution CO})/2} \times 100$$

Reproducibility studies in adults have shown that a difference of 15% (using three determinations for one measurement) between successive measurements is necessary to indicate a significant change in cardiac output [14]. For this reason, percentage differences > 15% between thermodilution and continuous Fick cardiac output were regarded as clinically significant. For each method, the average of these standard deviations was calculated. The mean difference between the two methods was evaluated with the Wilcoxon signed rank test. The variability between the three measurements for one averaged cardiac output determination was calculated for each of the two methods as the mean difference and standard deviation in percent of the average cardiac output.

Results

In all patients, the system worked unproblematically. Cardiac output determinations ranged from 0.21 to 4.27 l/min for the continuous Fick cardiac output (CFCO) method and from 0.33 to 4.55 l/min for the thermodilution method. Linear regression analysis revealed a correlation coefficient $r^2 = 0.98$; $P < 0.001$; SEE = 0.14 l/min. The regression line is described by: CFCO = 0.05 + 0.94 × thermodilution CO; (CO: cardiac output) (Fig. 1). Despite this good correlation, the difference between the two methods ± 2 SD = -0.05 ± 0.32 l/min or -4.4 ± 21.3% of the mean cardiac

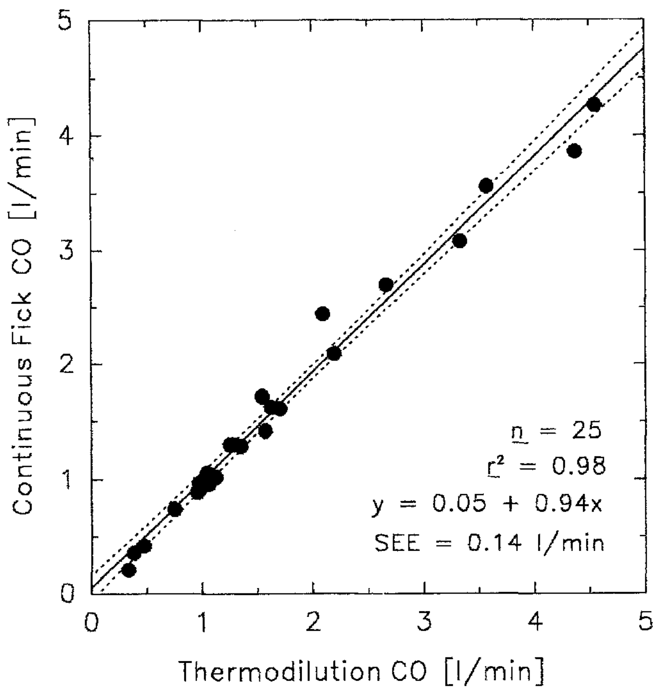

Fig. 1 Continuous Fick cardiac output plotted vs simultaneous thermodilution cardiac output measurement. The *straight line* indicates the regression line and the *dotted lines* indicate the 95% confidence intervals

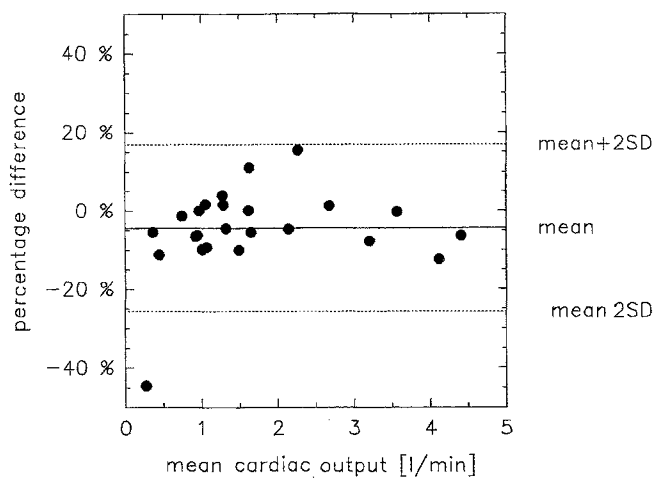

Fig. 2 Percentage difference plotted against the mean cardiac output.

$$\text{percentage difference} = \frac{[\text{Fick-CO} - \text{Thermodilution-CO}]}{(\text{Fick-CO} + \text{Thermodilution-CO})/2} \times 100$$

For further details see text

output. The small difference between the two methods was statistically significant ($P = 0.039$). In one patient the percentage difference was > 15% and in one patient it was borderline at 15.4%. This bias plot in Fig. 2 shows the percentage difference between the two methods vs the mean of the two methods. The percentage difference was most marked in one newborn with low cardiac output. This was due to a low VO_2 of 21 ml/min as measured by the metabolic monitor, as compared to the VO_2calculated by thermodilution and the reversed Fick principle. Excluding this patient leads to a mean percentage difference ± 2 SD of $-2.7\% \pm 13.6\%$. The variability of the three averaged measurements expressed as mean difference ± 1 SD in percent of the average cardiac output was $2.1\% \pm 11.7\%$ for the continuous Fick cardiac output and $2.4\% \pm 14.5\%$ for the thermodilution cardiac output.

Discussion

In this group of critically ill children, cardiac output measurements taken by the continuous Fick method and the thermodilution method were well correlated. To our knowledge, this is the first study that has evaluated the continuous Fick principle in critically ill children. In the adult population, similar results have been reported using the continuous Fick method (Table 1) [7–10, 15]. In pediatric patients after open heart surgery, Chang et al. found a comparable bias and precision of $-1\% \pm 29\%$ when comparing intermittent manual Fick with thermodilution cardiac output [16]. However, we observed a significant difference between the two methods in one newborn with low cardiac output. This difference was due to a low measured oxygen consumption (VO_2) of 21 ml/min, as measured by the metabolic monitor, as compared to the calculated VO_2 measured by thermodilution. The measured VO was close to the lower limit (20 ml/min) of the metabolic monitor. The patient was ventilated with the Siemens Servo 300 (Siemens-Elema, Sweden), which has a gas flow also during expiration. This led to a further dilution of the expired air, making it more difficult to measure the small oxygen uptake of this newborn with low cardiac output [12]. Excluding this patient from the statistical evaluation leads to many smaller difference. This problem may be overcome with a new version of the metabolic monitor, which is more suitable for newborns. The variability between the Fick derived and the thermodilution derived cardiac output values is due at least in part to the variability of the thermodilution technique itself, particularly in cases of a low cardiac output [17]. In this and other studies, the reproducibility of the continuous Fick cardiac output determinations was greater than that of the thermodilution measurements [7, 18], which is an important factor in documenting trends in cardiac output. Due to

Table 1 Studies comparing continuous (and manual intermittent) Fick cardiac output with simultaneous thermodilution cardiac output

Author	Carpenter [7]	Davies [15]	Davies [20]	Kleinänen [8]	Narkanishi [10]	Feustel [19]	Chang [16]	Hillis [17]
Method	Continuous Fick cardiac output						Intermittent Fick	
Patients	5 ICU	21 ICU	7 pigs –	21 ICU	17 exercise	5 –	15 infants PICU	808 cath.-lab
Measurements	–	237	251	40	–	309	60	808
Mean diff ±2 SD [l/min]	– –	0.8 2.2	–	0.2 1.3	–		– 0.01 /m^2 1.08 /m^2	0.23 0.2
Mean diff. % ±2 SD%	– –	15.39% 42.30%	–	2.94% 19.12%	–	–	0.30% 29.10%	9% 16%
Correl. coef.	$r = 0.92$	$r = 0.86$	$r^2 = 0.87$	$r^2 = 0.79$	0.80–0.86	$r = 0.85$	$r^2 = 0.88$	$r = 0.90$

Mean diff. % mean difference in percent of the average cardiac output

the higher variability, a greater change in cardiac output is required by the thermodilution technique to indicate a significant, non-random change in cardiac output.

The potential errors of the system include incorrect measurements when the patient is ventilated with a FiO_2 above 0.7–0.8 [6]. As any endotracheal tube leakage would encourage false measurements, this possibility must be ruled out [8, 11]. Similarly, determination of the end-tidal carbon dioxide by the side-stream technique has to be avoided. Systematic errors in the continuous Fick method often occur under conditions of increased pulmonary oxygen consumption in the lung, but none of our patients had a disease such as pneumonia or ARDS, which is known to create these conditions. Left-to-right as well as right-to-left shunts have be carefully excluded, as they would also lead to false measurements. However, such problems are also encountered with the thermodilution method. It has been shown that the most frequent errors in calculated cardiac output involve measurements of arterial and mixed venous O_2 saturation [19]. For this reason, we introduced a correcting factor into the formula and calibrated arterial and mixed venous O_2 saturation frequently. This type of error is most pronounced with high levels of the mixed venous O_2 saturation [19], which is rare after cardiac surgery.

A great advantage of the Fick system is that it provides virtually continuous cardiac output estimation, whereas the thermodilution technique gives only intermittent measurements. This is helpful, especially in neonates and small infants, in whom frequent thermodilution measurements may cause a fluid overload. More importantly, the continuous Fick technique permits continuous direct measurement and computation of the various components of oxygen transport, which yields more vital information about cardiorespiratory status than cardiac output alone.

We conclude that continuous measurement of cardiac output by the Fick method offers a more accurate, precise, and convenient method to monitor hemodynamically instable infants and children.

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