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Estimation of cardiac index by means of the arterial and the mixed venous oxygen content and pulmonary oxygen uptake determination in the early post-operative period following surgery of congenital heart disease

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Abstract. *Objective:* To assess the reliability of estimation of cardiac index based on the mixed venous oxygen saturation and methods of improving the estimation of cardiac index.
Setting: PICU in an university hospital.
Design: In the post-operative period following complete repair of congenital heart disease we carried out 55 measurements of blood gases in 25 infants and children (mean age 16.1 months, mean body surface 0.43 m^2) from a systemic artery (arterial) and the pulmonary artery (mixed venous). We also determined the pulmonary oxygen uptake and calculated the cardiac index (CI) using Fick's principle. In the analysis we compared the CI with the mixed venous oxygen saturation ($S_{\bar{v}}O_2$) and with the quotient of the arterial oxygen content (C_aO_2) and the oxygen extraction ($C_{a-\bar{v}}DO_2$). This quotient is equal to arterial oxygen delivery (DO_2) divided by the oxygen consumption ($\dot{V}O_2$).
Results: Pearson's correlation coefficient was 0.77 when $S_{\bar{v}}O_2$ was compared to CI in a linear regression model. Assuming an inverse relationship between $S_{\bar{v}}O_2$ and CI the correlation was much better ($r = 0.90$). However, the best estimation of CI provides the quotient $C_aO_2/C_{a-\bar{v}}DO_2$ ($r = 0.93$).
Conclusions: $C_aO_2/C_{a-\bar{v}}DO_2$ correlates much better with CI than the $S_{\bar{v}}O_2$, therefore CI could be better estimated based on $C_aO_2/C_{a-\bar{v}}DO_2$. Furthermore $C_aO_2/C_{a-\bar{v}}DO_2$ provides good information about the oxygen supply situation of the body.

Key words: Children – Complete repair of congenital heart disease – Pulmonary artery catheter – Cardiac index

The cardiac index (CI) and the body oxygen supply are important variables in the management of severely ill infants and children. Both can be assessed indirectly by observing the heart rate and the blood pressure, the urine production and the difference between rectal and peripheral temperature. Direct measurements of CI by the thermodilution method [1–4] or using Fick's principle [5–10] could improve therapy in this setting [11, 12]. Many attempts have been made to estimate CI and its changes by measuring the mixed venous oxygen saturation ($S_{\bar{v}}O_2$). These studies yielded conflicting results; some authors found a good correlation between CI and $S_{\bar{v}}O_2$ [13–15], whereas others did not [16–18]. The purpose of our study was to asses the correlation between CI and $S_{\bar{v}}O_2$ in the early post-operative period following complete repair of congenital heart disease and to find out if the estimation of CI could be improved substantially by adding more parameters for its calculation.

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Method

We studied 25 infants and children (mean age 16.1±9.6 months, age range 5.6 to 38.0 months) following complete repair of congenital heart disease. The patients had a mean weight of 8.7±2.6 kg (range 5.3–13.5 kg) and a mean body surface area of 0.43±0.10 m^2 (range 0.30–0.65 m^2). In these patients we performed 55 samples of blood gases from a systemic artery (A. radialis or A. femoralis) and simultaneously another 55 samples from the pulmonary artery. The samples were analyzed by an ABL 300 – Blood Gas Analyzer (Radiometer, Copenhagen, Denmark) which measures PO_2 and calculates the corresponding O_2 saturation. At the same time we determined the pulmonary oxygen uptake.

All blood samples were drawn from catheters placed intra-operatively for routine post-operative monitoring. For determination of the pulmonary oxygen uptake we used the Deltatrac Paed Monitor (Datex Instrumentarium Corp., Helsinki, Finland). This device measures the oxygen concentration with the paramagnetic difference pressure method. Therefore a gas sample of 150 ml is taken from the inspiratory limb of the ventilator. Furthermore the exhaled gas is sampled in a mixing chamber to determine its oxygen content. From the difference between inspired and expired oxygen the pulmonary uptake can be calculated [2, 19–21]. All measurements were made while the patients were on controlled ventilation (Servo 900 C, Siemens, Elema, Sweden) and under steady state conditions. For sedation the children received continuous i.v. medication of midazolam and fentanyl. We defined steady state as

Table 1. Patients

Diagnosis	Number	Sex m/f	Age in months Mean ± SD	Body surface area (m^2) Mean ± SD	Body weight (kg) Mean ± SD
Ventricular septal defect	11	7/4	15.6 + 12.1	0.42 + 0.12	8.2 + 2.9
Tetralogy of Fallot	7	5/2	16.3 + 5.2	0.48 + 0.07	10.4 + 1.8
Atrioventricular septal defect	7	1/6	16.6 + 9.8	0.41 + 0.08	7.9 + 2.0
Overall	22	10/12	16.0 + 9.9	0.43 + 0.10	8.7 + 2.6

constant oxygen uptake and stable circulation and it was reached at approximately 1 h after the post-operative arrival in our intensive care unit. There were 23 determinations carried out on the day of the operation, another 20 on the first post-operative day, 8 measurements were done on the 2nd post-operative day, 3 on the 3rd post-operative day and one on post-operative day 4. Anthropometric data and diagnoses are listed on Table 1. The cardiac index was calculated on Fick's principle from the quotient of oxygen uptake ($\dot{V}O_2$) and oxygen extraction (difference between the arterial oxygen content and the pulmonary arterial (= mixed venous) oxygen content), corrected for the individual body surface area. Like the thermodilution method the calculation of CI on Fick's principle indicates the pulmonary blood flow, which can differ from the systemic blood flow in cases of irregular connections between the systemic and the pulmonary circulation (left to right shunt, i. e. ventricular septal defect, right to left shunt, i. e. uncorrected tetralogy of Fallot). We did not exclude patients with residual left to right shunts after closure of ventricular septal defects. Right to left shunts are not expected in our patients because all children with tetralogy of Fallot underwent total correction with enlargement of the right ventricular outflow tract and the closure of the ventricular septal defect (VSD).

Furthermore we calculated the quotient of arterial oxygen content (C_aO_2) to oxygen extraction ($C_{a-\bar{v}}DO_2$) which is equal to the quotient of arterial oxygen delivery (DO_2) to oxygen consumption ($\dot{V}O_2$). Therefore this ratio provides information about the oxygen supply situation of the body. Under steady state conditions oxygen consumption and pulmonary oxygen uptake must be the same.

For analysis we determined mean and standard deviations of $S_{\bar{v}}O_2$, $\dot{V}O_2/m^2$, $C_aO_2/C_{a-\bar{v}}DO_2$ and of CI. Furthermore we calculated the correlation coefficient between $S_{\bar{v}}O_2$ and CI and compared it to the correlation coefficient between $C_aO_2/C_{a-\bar{v}}DO_2$ and CI.

The following formulae were used:

i) Calculation of cardiac index (CI) using Fick's principle

$$CI = \frac{\dot{V}O_2 \cdot 100}{C_{a-\bar{v}}DO_2 \cdot m^2} \text{ [ml/min]}$$

with: $\dot{V}O_2$: pulmonary oxygen uptake (= oxygen consumption)
$C_{a-\bar{v}}DO_2$ (oxygen extraction) =

$$(Hb \cdot 1.34 \cdot S_aO_2) + (0.0031 \cdot P_aO_2) - (Hb \cdot 1.34 \cdot S_{\bar{v}}O_2) - (0.0031 \cdot P_{\bar{v}}O_2)$$

ii) Calculation of oxygen delivery (DO_2)

$$DO_2 = C_aO_2 \cdot CO \cdot 10^{-2} \text{ [ml/min]}$$

with: C_aO_2 (arterial oxygen content) =

$$(Hb \cdot 1.34 \cdot S_aO_2) + (0.0031 \cdot P_aO_2)$$

$$CO \text{ (cardiac output)} = CI \cdot m^2 \text{ [ml/min]}$$

iii) Calculation of the body oxygen supply situation

$$\frac{DO_2}{\dot{V}O_2} = \frac{C_aO_2 \cdot CO}{C_{a-\bar{v}}DO_2 \cdot CI \cdot m^2} = \frac{C_aO_2}{C_{a-\bar{v}}DO_2}$$

Results

Table 2 shows means, standard deviation, minimum and maximum of $S_{\bar{v}}O_2$, the oxygen consumption corrected for the individual body surface, the arterial oxygen content, the quotient of arterial oxygen content to oxygen extraction and the CI. The last column of the table contains the normal range of the determined values [1, 22]. All means are within the normal range. $S_{\bar{v}}O_2$, $\dot{V}O_2/m^2$ and C_aO_2 show little variability (SD < 20% of the mean).

Assuming an inverse relationship between $S_{\bar{v}}O_2$ and CI the correlation coefficient ($r = 0.90$, Fig. 1) was much better than for a linear regression curve ($r = 0.77$). However, the best estimation of CI was achieved by using the quotient $C_aO_2/C_{a-\bar{v}}DO_2$. The correlation between this quotient and the CI was 0.93 (Fig. 2). This correlation coefficient could not be improved further.

Discussion

In the management of severely ill infants and children it is important to optimize body oxygen supply which can be calculated from arterial oxygen content and cardiac output [22]. Optimal mechanical ventilation can augment the pulmonary part of oxygen uptake and therefore improve the arterial oxygen content. The second variable, cardiac output, can be improved with inotropic drugs as well as by manipulations of the preload and the afterload. For monitoring the cardiac output it is not sufficient to control the heart rate and the blood pressure only [11, 23]. Indices which make it possible to distinguish be-

Table 2. Means, standard deviations, minimum, maximum and normal values

Variable	Mean ± SD	Minimum	Maximum	Normal values
$S_{\bar{v}}O_2$ [%]	71.7 ± 10.2	40.0	94.0	> 60
$\dot{V}O_2/m^2$ [ml/min/m^2]	152.1 ± 27.7	100.3	216.9	160 ± 50
C_aO_2 [ml/min]	17.45 ± 2.72	11.09	24.24	16.8 ± 6.1
$C_aO_2/C_{a-\bar{v}}DO_2$	4.15 ± 1.94	1.72	14.43	4.25 ± 1.25
CI [l/min/m^2]	3.71 ± 1.95	1.48	13.13	4.5 ± 1.0

$S_{\bar{v}}O_2$, mixed venous oxygen saturation in %; $\dot{V}O_2/m^2$, pulmonary oxygen uptake corrected for one m^2 of body surface area; C_aO_2, arterial oxygen content; $C_aO_2/C_{a-\bar{v}}DO_2$, arterial oxygen content devided by the difference between arterial and mixed venous of oxygen content; CI, cardiac index

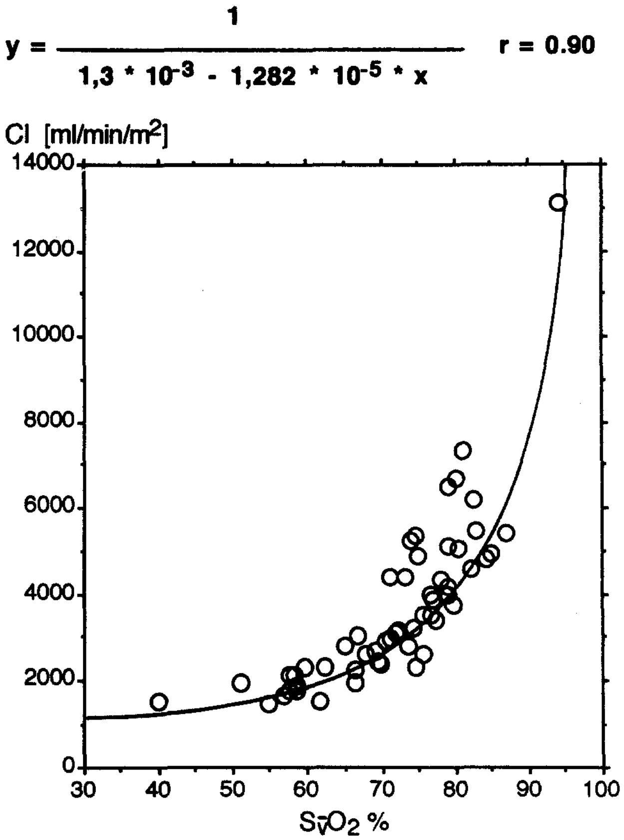

Fig. 1. Cardiac index (*CI*) correlated with the mixed venous oxygen saturation ($S_{\bar{v}}O_2$) assuming an inverse relationship

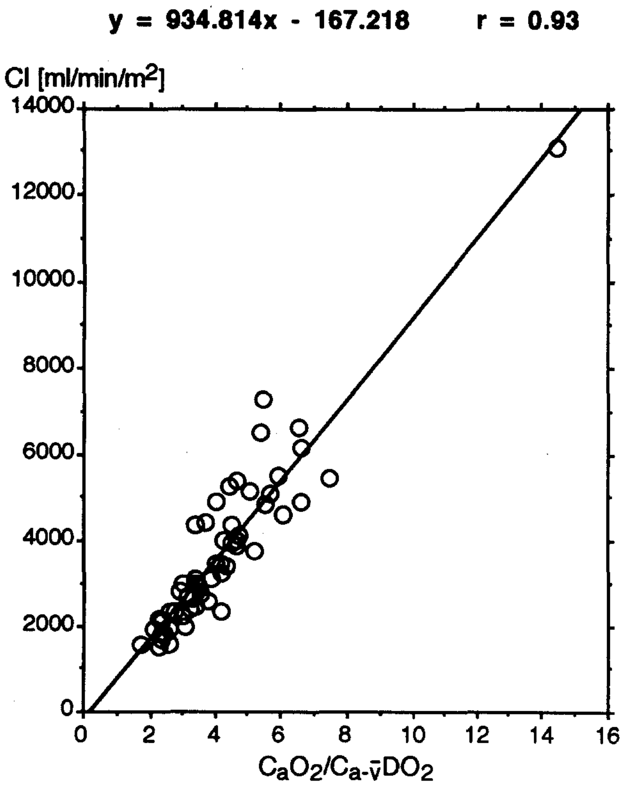

Fig. 2. Cardiac index (*CI*) correlated with the quotient of arterial oxygen content to oxygen extraction ($C_aO_2/C_{a-\bar{v}}DO_2$) assuming a linear relationship

tween adequate cardiac output and a low cardiac output situation are peripheral perfusion, urine production and temperature difference between rectum and skin [11]. Direct measurement of cardiac output is possible by means of the thermodilution method or on Fick's principle. For the thermodilution method a Swan Ganz pulmonary artery catheter and special monitor equipment is necessary, for the calculation on Fick's principle a reliable method for the determination of the pulmonary oxygen uptake is mandatory. Therefore attempts have been made to estimate the cardiac output without thermodilution or measurement of pulmonary oxygen uptake by means of the mixed venous oxygen saturation [13, 15–18].

$S_{\bar{v}}O_2$ alone correlates poorly to CI because just one of the three parameters (C_aO_2, $C_{\bar{v}}O_2$, $\dot{V}O_2/m^2$) determining CI is used for the estimation (see formulae above). As our results show, the correlation can be improved assuming an inverse relationship between $S_{\bar{v}}O_2$ and CI (Fig. 1) [24]. The best possible estimation of CI by means of blood gases should use information from the arterial and the mixed venous (pulmonary arterial) side. So we correlated the quotient $C_aO_2/C_{a-\bar{v}}DO_2$ to CI and saw a slightly higher correlation coefficient than in the inverse model comparing CI and $S_{\bar{v}}O_2$. This correlation coefficient could not be improved further.

These results can be explained as follows: assuming constant values for $\dot{V}O_2$ and C_aO_2, Fick's equation clearly indicates an inverse relationship between CI and $S_{\bar{v}}O_2$ of the general form:

$$y = \frac{1}{a - b \cdot x}$$

with a and b being two constants. Therefore the inverse regression curve fits much better than the linear one. However, under the same circumstances ($\dot{V}O_2$ and C_aO_2 constant) transformation of the Fick equation shows a linear relationship between CI and $C_aO_2/C_{a-\bar{v}}DO_2$ of the general form:

$$y = c \cdot x - d$$

with c and d being two constants.

It has to be taken into account, that for the calculation of CI on Fick's principle the same blood gas determinations were used as for the estimation of CI by means of the quotient $C_aO_2/C_{a-\bar{v}}DO_2$. Completely independent measurements surely would show a worse correlation than do our results. Moreover, the good correlation coefficient we found is also due to a relatively small variability of $\dot{V}O_2/m^2$ and C_aO_2 in our patients, a homogeneous group of infants and children in the early postoperative phase following cardiac surgery. In patients with a greater variability of the two parameters or with oxygen consumptions differing considerably from the normal values [25] the estimation of CI would be less reliable.

Finally it has to be mentioned, that measurement of CI on Fick's principle using the pulmonary arterial oxygen content will be affected by intracardiac shunting. In cases of a relevant left to right shunt the systemic CI will be lower than the pulmonary blood flow determined on Fick's principle, in cases of a relevant right to left shunt the opposite is true. We did not exclude patients with residual left to right shunt after closure of VSD, so CI in this study stands for pulmonary blood flow corrected by the body surface area. Patients with right to left shunts are not expected to be in our study population, because all children with tetralogy of Fallot underwent total correction with closure of the VSD and enlargement of the right ventricular outflow tract. Intracardiac shunting has to be taken into account when drawing conclusions from CI measurements on Fick's principle. The same limitations are true for determinations with the thermodilution method.

The quotient of arterial oxygen content to oxygen extraction provides good information about the oxygen supply situation of a patient. It represents the relationship between the arterial oxygen delivery and the oxygen consumption of the body. Under normal circumstances the oxygen delivery exceeds by 4 times the oxygen consumption [22]. A decrease indicates worsening of the patients condition. However, this quotient is also sensitive to intracardiac shunting. In cases of relevant right to left shunting $C_aO_2/C_{a-\bar{v}}DO_2$ declines whereas a left to right shunt raises the quotient. So it can be stated, that intracardiac shunting influences CI measurement using Fick's principle, CI measurement with the thermodilution method and the estimation of CI by the quotient $C_aO_2/C_{a-\bar{v}}DO_2$ in the same way.

Nevertheless, in our experience the easily available quotient $C_aO_2/C_{a-\bar{v}}DO_2$ is helpful in the management of critically ill patients since it allows a rough estimation of CI and provides additional information regarding the body oxygen supply situation.

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