Continuous central venous oxygen saturation (ScvO₂) measurement using a fibre optic catheter in newborn infants

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Abstract

Aims—To describe the range of central venous oxygen saturation (ScvO₂) values in stable newborn infants breathing room air; to examine the correlation between ScvO₂ and arterial oxygen saturation (SaO₂); to describe fractional oxygen extraction; and the shunt index, an estimate of the venous admixture.

Methods—A prospective clinical observational study was made of 10 preterm infants breathing room air after the acute phase of respiratory distress syndrome, and with an umbilical venous catheter in situ. A fibre optic catheter remained in the right atrium for continuous measurement of oxygen saturation.

Results—ScvO₂, SaO₂, blood pressure and heart rate were registered every 15 minutes. Fractional oxygen extraction and shunt index were calculated. SaO₂ and ScvO₂ were 93.4 (SD 3.7)% and 73.56 (5.25)%, respectively. In seven patients ScvO₂ values correlated significantly with SaO₂. Fractional oxygen extraction was 0.21 (0.04) and was significantly correlated with ScvO₂. The shunt index was 24% (12) and was significantly correlated with SaO₂.

Conclusions—Stable preterm infants breathing room air had an ScvO₂ ranging from 65% to 82% (5th and 95th percentile), which corresponded to SaO₂ ≥86%. ScvO₂ values were significantly correlated with SaO₂ in most patients.

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Keywords: fibre optic catheter; central venous oxygen saturation (ScvO₂); arterial oxygen saturation.

The optimal level of oxygenation in sick newborn infants is not well established. Hyperoxia has been associated with oxygen toxicity related cell injury,¹ retinopathy of prematurity,² and bronchopulmonary dysplasia.³ Hypoxia has been associated with vasoconstriction of the pulmonary vascular bed,^{4,5} redistribution of the cardiac output,⁶ and oxygen insufficiency at tissue level, with anaerobic metabolism leading to cell damage.

Arterial partial pressure of oxygen (PaO₂) and/or arterial oxygen saturation (SaO₂) are widely used for judging oxygen needs. These are limited because they do not measure other factors that determine tissue oxygenation, such as haemoglobin concentration, cardiac output, local tissue blood flow and oxygen consumption.

Central venous oxygen saturation (ScvO₂) reflects residual oxygen after tissue oxygen extraction and accounts for all the mentioned variables.⁷ Measuring the ScvO₂ in newborn babies may help minimise unnecessary oxygen administration, and thus decreasing long term morbidity associated with oxygen injury.⁸ ScvO₂ measurement could be used to define insufficient oxygen delivery to tissues when arterial oxygen content and cardiac output are decreased or when oxygen consumption is increased.

In this study we attempted to define the normal range of ScvO₂ values in stable newborn infants who were breathing room air after a period of respiratory insufficiency. The measurement of both SaO₂ and ScvO₂ (dual oximetry) made it possible to calculate fractional oxygen extraction and the shunt index.⁹ Fractional oxygen extraction is an estimation of the peripheral tissue oxygen extraction coefficient. As oxygen delivery falls, oxygen consumption can be maintained by an increase in the extraction of oxygen delivered to the tissues.¹⁰ Shunt index represents an estimate of the venous admixture. Pulmonary venous admixture reflects the degree of mixture of arterial blood and mixed venous blood. We examined the range of these two variables and their relation with SaO₂ and ScvO₂.

Methods

This study was approved by the ethics committee of the Academic Hospital of Maastricht.

We used a size 4 French fibre optic catheter (Oximetrix System, Abbott Laboratories, Chicago, Ill), which permitted both a continuous measurement of oxygen saturation at the tip of the catheter and infusion of fluids and medication. The continuous measurement of oxygen saturation is based on reflection spectrometry. The light source, consisting of three diodes, emits light at three different wavelengths through a fibre optic bundle. The back scattered light from the oxygenated and unoxygenated blood is transmitted by the receiving fibre optic bundle to a photodetector in the optical module. The oximeter computes per cent of oxygen saturation values based on the electrical signals from the optical module. The average value for oxygen saturation over a five second period is displayed digitally, and the value updated each second.

The fibre optic catheter was placed in the right atrium via the umbilical vein in infants

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Table 1 Patient characteristics, physiological variables, arterial pH, PaCO_2 , PaO_2 and base excess and oxygen saturation, calculated arterial and venous oxygen content

	Mean (SD)	Range (5th, 95th percentile)
Birthweight (g)	938 (246)	
Gestational age (weeks)	27.0 (1.3)	
Haemoglobin (mmol/l)	8.4 (1.8)	7.0–10.2
Mean arterial pressure (mm Hg)	41.5 (7.4)	30–54.7
Heart rate (bpm)	165 (15)	144–192
P_{50} (kPa)	3.1 (0.4)	2.7–3.9
pH	7.36 (0.04)	7.30–7.41
pCO_2	5.5 (1.0)	4.4–7.8
PO_2	6.6 (0.1)	3.5–10.2
Base excess (mmol/l)	−2.8 (2.3)	−7.3–0.1
CaO_2 (ml/dl)	16.9 (2.2)	12.6–20.0
CcvO_2 (ml/dl)	13.2 (2.0)	9.6–16.1

who needed a central venous line for clinical management. The catheter was positioned at the mid atrial level or at the transition of the inferior vena cava to the right atrium. The position was confirmed by x-ray picture and ultrasonography. Saline diluted with heparin (0.5 U/cc) was infused continuously (0.1 cc/hour) to avoid fibrin formation over the catheter. Blood samples were withdrawn through the catheter at least every 12 hours, immediately analysed with a hemoximeter (Radiometer OSM3, Copenhagen), and compared with simultaneously recorded fibre optic catheter values. A correction was made when oxygen saturation in correlated samples showed a discrepancy of $\geq 5\%$. We have already reported the feasibility and accuracy of the fibre optic device in newborn infants.¹¹

The values of ScvO_2 were obtained from preterm patients breathing room air after the acute phase of respiratory distress syndrome (RDS). Infants were allowed to breathe room air when SaO_2 , monitored by pulse oximetry, reached $\geq 86\%$.^{12,13} ScvO_2 values were accepted when haemoglobin was ≥ 7.0 mmol/l, with normal arterial pH (7.30–7.45) and pCO_2 (4.5–8 kPa), and arterial blood pressure.¹⁴

SaO_2 was continuously measured by pulse oximetry (Hewlett Packard). Each value is the average of samples taken every 12 seconds over one minute. Arterial blood pressure was monitored through an umbilical or radial artery catheter; these catheters were also used for sampling arterial pH, PaCO_2 , PaO_2 , and base excess for clinical purposes.

ScvO_2 , SaO_2 values, blood pressure, and heart rate were registered every 15 minutes. Arterial oxygen content (CaO_2) and central

venous oxygen content (CcvO_2) were calculated using the equation:

$$\text{CaO}_2 \text{ (ml/dl)} = \text{SaO}_2 \times \text{haemoglobin (mmol/l)} \times 1.55 \times 1.36$$

and

$$\text{CcvO}_2 \text{ (ml/dl)} = \text{ScvO}_2 \times \text{haemoglobin (mmol/l)} \times 1.55 \times 1.36.$$

Fractional oxygen extraction was calculated using the equation:

$$\text{fractional oxygen extraction} = (\text{SaO}_2 - \text{ScvO}_2) / \text{SaO}_2.$$

The shunt index was calculated using the equation:

$$\text{shunt index} = 100 \times \{ (100 - \text{SaO}_2) / (100 - \text{ScvO}_2) \}.$$

Oxygen saturation and pcvO_2 were determined from samples withdrawn from the central venous fibre optic catheter and the P_{50} was calculated as described before.¹⁵

STATISTICS

The paired Student's *t* test was used to compare the hemoximeter values with the simultaneously recorded fibre optic catheter readings. For each patient we determined mean value and standard deviation for SaO_2 and ScvO_2 . The range was defined by the 5th and 95th percentiles. To compare SaO_2 with ScvO_2 , a separate linear regression analysis within each infant was performed to avoid erroneous combining of observations from different individuals.¹⁶ A slope (the regression coefficient) for each individual was calculated to obtain an average slope for the group.¹⁶ To compare fractional oxygen extraction and shunt index with SaO_2 and ScvO_2 , the same statistical analysis was performed. Tests were considered to be significant when $P < 0.05$.

Results

In 10 preterm infants breathing room air, ScvO_2 could be monitored continuously (table 1). The monitoring time ranged from 10–82 hours. The mean age of the infants when ScvO_2 was monitored was 52 hours (range 18–168). A total of 1061 ScvO_2 and SaO_2 values were obtained simultaneously with blood pressure and heart rate. The validity of the ScvO_2 values was confirmed, as hemoximeter values and simultaneously recorded fibre optic catheter readings were not significantly different: (74.7 (6.8)% vs 73.8 (6.3)%).

SaO_2 and ScvO_2 were mean (SD) 93.4 (3.7)% and 73.56 (5.25)%, respectively. The SaO_2 and ScvO_2 values ranged, respectively, from 87 to 99% and from 65% to 82% (5th and 95th percentile). When analysed for each patient separately, ScvO_2 (lowest 5th and highest 95th percentile) ranged from 60.1% to 83.5% (table 2). Linear regression analysis comparing SaO_2 and ScvO_2 for each patient yielded a slope (regression coefficient) and a correlation coefficient *r* (table 2, fig 1). In seven patients a significant correlation was found (fig 1).

Fractional oxygen extraction was 0.21 (0.04). The 5th and 95th percentiles were 0.15 and 0.29, respectively. When analysed for each

Table 2 Mean (SD) range (5th and 95th percentiles), correlation coefficient and slope of SaO_2 and ScvO_2

Case No	Samples	SaO_2			ScvO_2			Correlation	
		Mean (SD)	Percentile 5th	Percentile 95th	Mean (SD)	Percentile 5th	Percentile 95th	Correlation coefficient	Slope
1	59	91.1 (2.1)	87	99	70.5 (4.4)	61	78	0.34*	0.71*
2	67	93.1 (1.8)	90	96	71.3 (3.4)	65	77	0.05	0.10
3	57	90.2 (2.3)	87	94	70.6 (4.4)	63	77	0.65*	1.2*
4	56	92.1 (3.5)	86	98	70.5 (4.3)	62	77	0.25	0.30
5	40	93.2 (3.0)	87	97	69.9 (4.6)	60	76	0.60*	0.92*
6	45	90.5 (3.2)	86	98	70.6 (5.0)	62	78	0.18	0.28
7	81	91.4 (2.2)	88	95	72.6 (4.7)	64	80	0.73*	1.6*
8	184	93.3 (3.3)	87	99	72.5 (4.9)	65	81	0.35*	0.78*
9	144	89.7 (1.9)	86	93	72.2 (2.2)	69	75	0.69*	0.69*
10	328	97.2 (2.0)	93	100	77.9 (4.5)	68	83	0.57*	1.33*

* $P < 0.05$.

Figure 1 Central venous oxygen saturation (ScvO₂) values corresponding to simultaneously obtained arterial oxygen saturation (SaO₂) values. Linear regression lines are drawn for each patient. In seven patients a significant correlation was found. An average regression equation was obtained: $ScvO_2 = 0.46 \pm 0.77 \times SaO_2$.

patient separately, a range was found (lowest 5th and highest 95th percentile) from 0.13% to 0.33%. Figure 2 shows the relation between fractional oxygen extraction and ScvO₂. Fractional oxygen extraction and ScvO₂ were significantly correlated in all patients. SaO₂ and fractional oxygen extraction were significantly correlated in only six patients with a lower range of correlation coefficients (range $r = -0.28$ – -0.48). Analysis of the relation between fractional oxygen extraction and haemoglobin yielded a correlation coefficient $r = -0.14$ ($P < 0.01$).

The shunt index was 24 (12)%. A range was found (lowest 5th and highest 95th percentile) from 7% to 53% (table 2). When analysed for each patient separately, we found a significant negative correlation with the SaO₂ value in all patients (range $r = -0.72$ – -0.95) (fig 3). Analysis

Figure 2 Fractional oxygen extraction corresponding to ScvO₂. Linear regression lines are drawn for each patient. Fractional oxygen extraction was significantly correlated with ScvO₂ in each patient. An average regression equation was obtained: fractional oxygen extraction $= 0.83 - 0.0085 \times ScvO_2$.

of the relation with ScvO₂ showed a significant correlation in five patients (range $r = -0.37$ – -0.36).

Discussion

Continuous monitoring of mixed venous oxygen saturation (ScvO₂) has been used in critically ill adult patients as a valuable alarm signal, reflecting the residual oxygen after tissue oxygen extraction and indicating the combined sufficiency of the tissue oxygen supply and demand.^{17–19} Venous oxygen saturation is used very frequently during extracorporeal life support to determine pump blood flow²⁰ and has been advocated in the care of sick preterm infants.⁸ In neonatal medicine the use of ScvO₂ could minimise unnecessary oxygen administration and hence could decrease long term morbidity associated with oxygen toxicity related injury.⁸ However, normal and safe values have not been defined for newborn infants.

In our study we observed a range from 60.1% to 83.5% (5th and 95th percentile) in 10 stable preterm infants breathing room air, while SaO₂ was $\geq 86\%$ and haemoglobin was ≥ 7.0 mmol/l. Arterial pH and arterial blood pressure were in the normal range.

This ScvO₂ range is similar to the normal range defined for adults; however, oxygen consumption in newborn infants is 5–8 ml/kg/minute, whereas in resting adults oxygen consumption is 3–5 ml/kg/minute.²⁰ Increased oxygen consumption is not compensated for by increased extraction within tissues, as ScvO₂ does not apparently differ from adult values. The oxygen delivery is determined by cardiac output and arterial O₂ content (CaO₂), which in turn is determined by haemoglobin concentration, O₂ carrying capacity, oxygen saturation (SaO₂) and PaO₂. Cardiac output and haemoglobin concentration in the newborn compensate for higher oxygen consumption. Indeed, haemoglobin concentration and CaO₂ are higher in newborn babies than in adults.²¹ Cardiac output in newborn infants determined by various methods is 230 (70) ml/kg/minute,²² whereas cardiac output in adults is 70–90 ml/kg/minute.²³ Therefore, the increased oxygen consumption in the newborn infant is counterbalanced by an increased oxygen delivery.

In seven patients a significant correlation was found between SaO₂ and ScvO₂. This indicates that when SaO₂ is reduced, oxygen consumption is preserved by a fixed oxygen extraction. In three patients SaO₂ and ScvO₂ were not significantly correlated. We might speculate that in these babies oxygen consumption was preserved by increased cardiac output. It is unlikely that oxygen consumption was decreased by SaO₂ reduction, because in stable patients with a normal blood pressure, normal haemoglobin concentration and normal oxygen saturation oxygen consumption are independent of oxygen delivery.²⁴

Oxygen delivery is normally four to five times the oxygen consumption, as shown by the normal fractional oxygen extraction of

Figure 3 The shunt index, an estimate for the venous admixture corresponding to the arterial oxygen saturation (SaO_2). Linear regression lines are drawn for each patient. Shunt index and SaO_2 were correlated in each patient. An average regression equation was obtained: $\text{shunt index} = 2.85 - 0.0278 \times \text{SaO}_2$.

0.20–0.25. In adults, a normal range of 0.22 to 0.30 of the fractional oxygen extraction has been described.²⁵ An increased fractional oxygen extraction can partly compensate for imbalance of oxygen consumption and delivery. Increased oxygen consumption, low haemoglobin, and a low cardiac output could explain the high fractional oxygen extraction found in our study. Indeed, we found a significant negative correlation between haemoglobin and fractional oxygen extraction. The highly significant correlation between fractional oxygen extraction and ScvO_2 in all patients confirms that ScvO_2 is an excellent monitor of the balance between oxygen delivery and tissue oxygen consumption.

The shunt index is an estimate of venous admixture and can be calculated when both SaO_2 and ScvO_2 (dual oximetry) are available. It is a derived formula ($100 \times (100 - \text{SaO}_2) / (100 - \text{ScvO}_2)$). Dissolved oxygen is discounted, and it is assumed that pulmonary end capillary blood are fully saturated. Bongard *et al* demonstrated a linear relation between this index and venous admixture; when PaO_2 was low, it was largely accurate but with some overestimation of the value.²⁶ Concomitantly with fractional oxygen extraction, it has been used to titrate continuous positive airway pressure in adult intensive care.²⁷ In our patients the shunt index was significantly correlated with SaO_2 with values up to 50% in the lower SaO_2 range (fig 3). Recently, Schultze *et al* described similar values of venous admixture of $31\% \pm 9$ at an SaO_2 range between 89% and 92% in premature infants. Obviously, an increased venous admixture is present when lower SaO_2 values are encountered. As can be expected and was demonstrated in a computer model,²⁸ changes in SaO_2 alter the value of the shunt index to a greater extent than changes in ScvO_2 .

The measurement site of venous oxygen saturation is still in debate.²⁹ In adult intensive care medicine venous oxygen saturation has

been monitored continuously in the pulmonary artery. Measurement of the ScvO_2 in the right atrium instead of in the pulmonary artery has been reported.^{30–31} No evidence was found for a systematic difference between right atrial and pulmonary arterial oxygen saturations over a wide range of haemodynamic conditions, both in animal models and in adults.^{30–32} Other reports describe a poor correlation between right atrial and pulmonary arterial oxygen saturation when comparing absolute numerical values.³³ However, a better correlation was observed comparing subsequent changes of right atrial and pulmonary arterial saturations.³⁴

In neonatal medicine the use of a pulmonary artery catheter is difficult and hazardous, but umbilical venous catheters have been used frequently with a low incidence of complications. Hence measurements of venous oxygen saturation in newborn infants are limited to the right atrium. Intracardiac left-to-right shunting through the foramen ovale is common in preterm infants, and can be a reason for the higher ScvO_2 values found in preterm infants than in adults. However, intracardiac shunting at the right atrium does not produce a difference in right atrial and pulmonary arterial oxygen saturations, and, therefore, is not an argument for questioning the validity of the right atrium as measurement site.

ScvO_2 measurement has some drawbacks: because it reflects global oxygen extraction, normal values cannot exclude tissue hypoxia in individual organs.³⁵ In sepsis and multi-organ failure normal ScvO_2 values may occur despite global hypoxia due to precapillary shunting and the incapacity of tissues to extract enough oxygen.³⁶ These drawbacks do not mean that measuring ScvO_2 is not useful, but that normal and abnormal values must be interpreted together with other physiological variables in conditions such as perfusion disturbances and sepsis.⁸

In summary, we have defined a range of ScvO_2 values in preterm newborn infants when breathing room air with an $\text{SaO}_2 \geq 86\%$. Whether these values can be used in sick newborn infants to evaluate tissue oxygenation, and whether this range can be used to regulate oxygen administration, remain to be established. Further study is needed to determine the clinical utility of ScvO_2 measurements in neonatal intensive care.

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