END-TIDAL CARBON DIOXIDE CONCENTRATION AS AN INDICATOR OF PULMONARY BLOOD FLOW DURING CLOSED HEART SURGERY IN CHILDREN

A Report of Two Cases

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In patients with restricted pulmonary blood flow, manipulation of the lung, pulmonary artery (PA) or ductus arteriosus (PDA) can decrease the pulmonary blood flow further and result in a critical reduction in arterial oxygenation, bradycardia and systemic arterial hypotension. Since there is often a delay between the alteration in pulmonary blood flow and the appearance of changes in systemic haemodynamics, a situation can develop in which pharmacological intervention may be ineffective. Early recognition is, therefore, vital so that pulmonary blood flow can be restored immediately.

Since a marked decrease in pulmonary blood flow will also result in a decrease in carbon dioxide elimination from the lung we monitor the end-tidal carbon dioxide concentration (E'_{CO_2}) continuously in such patients. Our experience suggests that after manoeuvres which reduce pulmonary blood flow, a decrease in E'_{CO_2} is detectable within a few respirations, whereas bradycardia and systemic hypotension may not develop for several minutes. This is illustrated by two case reports.

CASE REPORTS

Patient 1

A 2-day-old boy, weighing 3.2 kg, with pulmonary atresia and an intact ventricular septum was scheduled for the creation of a shunt from the left subclavian artery to the mainstem of the PA. Prostaglandin E_1 0.04 μg kg^{-1} min^{-1} was infused to maintain the patency of the ductus arteriosus. No premedication was given. Anaesthesia was induced with ketamine 8 mg i.v. followed by suxamethonium 3 mg i.v., and the trachea was intubated with a 3.5-mm uncuffed tube. Halothane 0.4\% in oxygen, supplemented by fentanyl 10 μg was used to maintain anaesthesia. Muscle relaxation was produced by pancuronium 0.3 mg and the lungs were ventilated by a Siemens Servo ventilator. The inspired minute volume was set at 2.5 litre min^{-1} and E'_{CO_2} was measured (Siemens CO_2 Analyzer 930). Arterial pressure was measured via a catheter in the left femoral artery.

Blood-gas analysis, after skin incision, showed [H^+] 36.3 nmol litre^{-1}, P_{aCO_2} 3.9 kPa, P_{aO_2} 6.9 kPa and BE -2.8 mmol litre^{-1}. E'_{CO_2} was 2.3\%. The mainstem of the PA was occluded using a vascular snare. Within 15–20 s the E'_{CO_2} decreased to 2.3 to 0.9\% and after a delay of 1 min the heart rate decreased from 143 to 80 beat min^{-1} and the arterial pressure from 60/40 to 30/20 mm Hg. The snare was loosened. Blood-gas analysis at this time revealed [H^+] 64.6 nmol litre^{-1}, P_{aCO_2},
6.0 kPa, \(P_{A_2}\) 8.5 kPa and BE -11.8 mmol litre\(^{-1}\). Sodium bicarbonate 15 mmol was given in divided doses. The snare was tightened and once again the \(E'_{CO_2}\) decreased from 2.3 to 1.0%, to be followed, after a delay, by bradycardia and hypotension.

The prostaglandin E\(_1\) infusion was increased to 0.08 \(\mu\)g kg\(^{-1}\) min\(^{-1}\) and isoprenaline 4 \(\mu\)g kg\(^{-1}\) min\(^{-1}\) was given, but did not improve the situation. The shunt was connected to the mainstem of the PA and completed in 24 min. Heart rate had decreased to 30 beat min\(^{-1}\) and arterial pressure was 20/10 mm Hg, despite increasing the dose of isoprenaline. Blood-gas analysis showed [\(H^+\)] 38.9 nmol litre\(^{-1}\), \(Pa_{CO_2}\) 2.1 kPa, \(Pa_{O_2}\) 5.6 kPa and BE -3.6 mmol litre\(^{-1}\).

The child died 25 min later. In retrospect, tightening of the snare must have obstructed the ductus arteriosus.

**Patient 2**

A 2-month-old girl, weighing 3.2 kg, with a univentricular heart, pulmonary atresia and a PDA was scheduled for a modified Blalock-Taussig shunt. Prostaglandin E\(_1\) 0.04 \(\mu\)g kg\(^{-1}\) min\(^{-1}\) was given i.v. No premedication was given. Anaesthesia was induced with ketamine 8 mg i.v. followed by suxamethonium 3 mg i.v., and the trachea was intubated with a 3.5-mm uncuffed tube. Halothane 0.5% in oxygen, supplemented with fentanyl 15 \(\mu\)g, was used to maintain anaesthesia. Muscle relaxation was produced by pancuronium 0.3 mg and the lungs were ventilated with a Siemens Servo ventilator. The inspired minute volume was set at 3.0 litre min\(^{-1}\) and \(E'_{CO_2}\) was monitored with a Siemens CO\(_2\) Analyzer 930.

Arterial pressure was measured via a catheter in the right radial artery. Blood-gas analysis after skin incision, but before manipulation of the lung, showed [\(H^+\)] 45.7 nmol litre\(^{-1}\), \(Pa_{CO_2}\) 5.3 kPa, \(Pa_{O_2}\) 5.7 kPa and BE -3.4 mmol litre\(^{-1}\). During surgery the ductus was found to be connected to a very narrow left PA. A modified Blalock-Taussig shunt was placed on the left PA distal to the ductus arteriosus. In order to assess the importance of flow to the right lung, the left PA was clamped between the bifurcation and the ductus arteriosus. This resulted in a decrease in \(E'_{CO_2}\) from 3.2 to 1.8%. The clamp was repositioned and this produced a similar response (fig.1). The clamp was repositioned again and \(E'_{CO_2}\) decreased to only 2.4% and remained at that value. Six minutes later, blood-gas analysis showed [\(H^+\)] 50.1 nmol litre\(^{-1}\), \(Pa_{CO_2}\) 5.6 kPa, \(Pa_{O_2}\) 6.3 kPa and BE -4.8 mmol litre\(^{-1}\).

It was decided to place a patch over the stenotic area in the left pulmonary artery between the origin of the ductus arteriosus and the bifurcation was clamped. The clamp was removed at the second arrow. The sequence was repeated again at the third and fourth arrows.

\[\text{DISCUSSION}\]

Heneghan, Scallan and Branthwaite (1981) found that monitoring \(E'_{CO_2}\) was unreliable in infants with restricted pulmonary blood flow because of
the magnitude of the blood–end tidal carbon dioxide gradient. We agree that $\varepsilon'_{CO_2}$ is not a reliable indicator of $P_aCO_2$, and, therefore, of the adequacy of ventilation in these children. However, $\varepsilon'_{CO_2}$ also reflects pulmonary perfusion. If ventilation is held constant, changes in pulmonary perfusion may be reflected in the $\varepsilon'_{CO_2}$ (Robinson, 1983). Therefore, recording the $\varepsilon'_{CO_2}$ can be particularly valuable in patients with restricted pulmonary blood flow undergoing an operative procedure which involves manipulation of the PA.

In our experience (patient 1), a decrease in $\varepsilon'_{CO_2}$ often occurs 1–3 min before there is evidence of bradycardia or arterial hypotension when pulmonary blood flow is restricted acutely. The state of oxygenation and the magnitude of the reduction in pulmonary blood flow may be of importance in determining the interval between a decrease in $\varepsilon'_{CO_2}$ and the occurrence of bradycardia and hypotension.

Before clamping a PA one should be confident that the contralateral lung is adequately ventilated, that any acidosis is corrected and that there is an optimal arterial pressure. During the period of clamping, the lungs should be ventilated with 100% oxygen. In the neonate, the use of prostaglandin E$_1$ may be beneficial in maintaining ductal blood flow. If, despite these measures, a significant decrease in $\varepsilon'_{CO_2}$ occurs when a PA is occluded, the possibility of traction on the mainstem of the PA or on the ductus should be considered and corrected (as in patient 2). If occlusion remains poorly tolerated, consideration should be given to an alternative operative procedure. In retrospect, this policy should have been followed in patient 1. Surgical manipulation can cause a further reduction in pulmonary blood flow and a decrease in $\varepsilon'_{CO_2}$. When this occurs the surgeon should immediately be warned, since the persistence of this situation may cause hypoxia and possibly irreversible bradycardia and hypotension.

In those patients who developed a significant decrease in $\varepsilon'_{CO_2}$ after clamping, or who have pre-existing hypoxia, arterial blood-gas analysis should be performed at frequent intervals during the period of clamping. It is imperative to correct any acidosis adequately since this can cause an increase in pulmonary vascular resistance and a further decrease in pulmonary blood flow.

In conclusion, the continuous monitoring of $\varepsilon'_{CO_2}$ during operations where the pulmonary blood flow may be partially interrupted, can give valuable information. In this situation a decrease in $\varepsilon'_{CO_2}$ often occurs several minutes before changes in systemic haemodynamics.

REFERENCES