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Changes in blood-gas tensions during apnoeic oxygenation in paediatric patients

T. M. COOK, A. R. WOLF AND A. J. W. HENDERSON

Summary

We report changes in arterial blood-gas tensions for up to 5 min of apnoeic oxygenation in 26 anaesthetized paediatric patients (21 children, five infants). Changes in oxygen and carbon dioxide tension were greatest in the first minute of apnoeic oxygenation. In subsequent minutes, rates of change in gas tension were approximately constant. The rate of decline in oxygen tension (31 (95% confidence interval (CI) 20.1–42.2) mm Hg min^{-1}) was more than three times that reported in studies in adults. The rate of increase in carbon dioxide tension (4.2 (95% CI 3.7–4.7) mm Hg min^{-1}) was similar to that reported in adults. After successful preoxygenation, oxygen tension remained greater than 290 mm Hg in all children (age >1 yr) throughout the study. This was not the case in infants. We found no correlation between changes in blood-gas tensions and age or weight of patients. The small number of infants studied showed rapid decreases in oxygen tension which if sustained would be expected to limit the safe duration of apnoeic oxygenation, unlike adults where apnoeic oxygenation is limited by hypercapnia. Extrapolation of our results suggests that when preoxygenation has been successful, apnoeic oxygenation could continue safely in children for at least 10 min. Infants may become hypoxic after only 2 min. (*Br. J. Anaesth*. 1998; **81**: 338–342).

Keywords: oxygen, saturation; oxygen, partial pressure; carbon dioxide, partial pressure; ventilation, apnoea; anaesthesia, paediatric

Apnoeic oxygenation is delivery of oxygen to an apnoeic patient and it is usually preceded by a period of preoxygenation so that maximal alveolar oxygen tension is achieved. Oxygen is then delivered to the patient with no effort to provide ventilation. Oxygenation depends on denitrogenation of the alveoli and airways so that oxygen uptake leads to mass transport of additional oxygen to the alveoli without nitrogen accumulation.

Apnoeic oxygenation is usually applied without attempts to increase airway pressure. However, apnoeic oxygenation may also be practised during continuous positive airway pressure (CPAP).[1] The delivery device may be in the pharynx[2] or trachea, and similar changes in gas tension occur.[2] In early apnoeic oxygenation studies, oxygen was not delivered to patients, instead they were connected to an oxygen-filled spirometer.[2]

In adults, oxygen flow rates of approximately 0.1 litre kg^{-1} min^{-1} provide adequate oxygenation during prolonged apnoeic oxygenation.[3] Apnoeic oxygenation of up to 55 min does not lead to hypoxaemia,[3] but severe hypercapnia and acidaemia develop as alveolar ventilation is negligible. Catecholamine concentrations increase and arrhythmias may occur.[3] The rate of increase of arterial carbon dioxide tension in adults is 3–4 mm Hg min^{-1}.[1,3] In the technique of endobronchial insufflation, oxygen is delivered via small bronchial catheters, rather than a tracheal tube, and arterial carbon dioxide tension may remain stable because of enhanced gas exchange.[4]

As neither arterial carbon dioxide tension nor pH are available routinely to the anaesthetist during surgery in an apnoeic patient, the safe time limit for apnoeic oxygenation is estimated. The above data suggest apnoeic oxygenation is safe in adults for at least 15 min.[2]

There are few data available on apnoeic oxygenation in paediatric patients. In particular we could find no data indicating safe limits for the technique in paediatric patients. Carbon dioxide tension may be expected to increase faster in paediatric patients because their metabolic rate is higher than that in adults relative to weight. However, apnoeic oxygenation via a paediatric tracheal tube may aid alveolar ventilation (similar to endobronchial insufflation in adults) because the small tracheal tube creates more airway turbulence and the distance from the carina to the alveolus is smaller. The relatively greater metabolic rate and potential for airway closure in paediatric patients may also result in a greater rate of decrease in oxygen tension and this could limit the safe duration of apnoeic oxygenation in this group.

Apnoeic oxygenation is an established practice in paediatric anaesthesia,[5] despite the absence of these data. We have examined the changes in blood gas variables during apnoeic oxygenation in paediatric patients. We related the effects of apnoeic oxygenation to age and weight.

Patients and methods

The study was approved by the local Research Ethics Committee. We studied 22 children (aged >1 yr) and

T. M. COOK, BA, FRCA, Sir Humphrey Davy Department of Anaesthesia, Bristol Royal Infirmary, Bristol BS2 8HW. A. R. WOLF, MD, FRCA, A. J. W. HENDERSON, MD, FRCP, FRCPCH, Royal Bristol Hospital for Sick Children, Bristol BS2 8BJ. Accepted for publication: April 24, 1998.

Correspondence to A. R. W.

Table 1 Patient details (median [range] or mean (SD))

Variable	
Age (months)	44 [1–142]
Weight (kg)	15.6 [3.7–48.6]
Haemoglobin (g dl^{-1})	10.8 (1.5)
Diagnosis (*n*)	
Patent ductus arteriosus	19
Minor coarctation of aorta	4
Mild pulmonary stenosis	2
Other	3

six infants (age <1 yr), ASA I or II, undergoing cardiac catheterization, after obtaining written parental consent. Patients were excluded if they had significant cardiac shunt or abnormal cardiac performance, lung pathology or metabolic disturbance likely to alter metabolic rate, such as pyrexia or sepsis. Patients most suitable for this study were those undergoing mechanical closure of patent ductus arteriosus who were studied after duct closure.

Patients aged more than 4 months were premedicated 1 h before anaesthesia with diazepam 0.5 mg kg^{-1} orally and topical EMLA cream. Younger patients received EMLA cream only. In all cases cardiac catheterization was performed under general anaesthesia and intermittent positive pressure ventilation with standard anaesthetic monitoring, including capnography. Anaesthesia was induced with propofol 2–5 mg kg^{-1} and fentanyl 2 μg kg^{-1}. Intubation was preceded by pancuronium 0.1 mg kg^{-1} and an appropriately sized tracheal tube was passed to ventilate both lungs with minimal leak. The tip of the tracheal tube was positioned 2–3 cm beyond the vocal cords and confirmed radiographically. Anaesthesia was maintained with an infusion of propofol 8 mg kg^{-1} min^{-1}. Patients were draped with insulating materials to maintain body heat during the study. Fifteen minutes before the end of the procedure, atracurium 0.3 mg kg^{-1} was administered to maintain neuromuscular block. Ventilation was adjusted to achieve a stable end-expired carbon dioxide tension of 25 mm Hg. We anticipated that mild hyperventilation might lengthen the safe period of apnoeic oxygenation. The lungs were ventilated for 5 min with an FI_{O_2} of 1.0 before starting apnoeic oxygenation. During apnoea, oxygen was delivered to the anaesthetic system (Ayre's T-piece) at a rate of 1 litre min^{-1} throughout the period of apnoea (except where stated).The first arterial blood-gas sample was obtained at the same time as ventilation was stopped. Arterial blood samples were then obtained every 1 min for up to 5 min.

All blood-gas measurements were performed on blood obtained from a femoral artery cannula required for cardiac catheterization. After deadspace removal, 0.2 ml of blood was obtained for analysis. Measurement was performed immediately after sampling using a Ciba Corning 288 blood-gas analyser (Ciba Corning Diagnostics Corporation, Medfield, MA, USA).

The study was stopped if arterial carbon dioxide tension increased to greater than 70 mm Hg, pH decreased to less than 7.0, arterial oxygen tension decreased to less than 80 mm Hg or oxygen saturation decreased to less than 90%. The study was also stopped if the patient showed signs of respiratory effort, clinical desaturation or cardiovascular instability, such as ectopic beats, arrythmia or hypotension.

Statistical tests included Pearson correlation and regression analysis. The Wilcoxon–Mann–Whitney test was used for comparison between infant and non-infant groups. Tests were performed using Microsoft Excel 5.0 for Windows 3.1. $P<0.05$ was considered statistically significant.

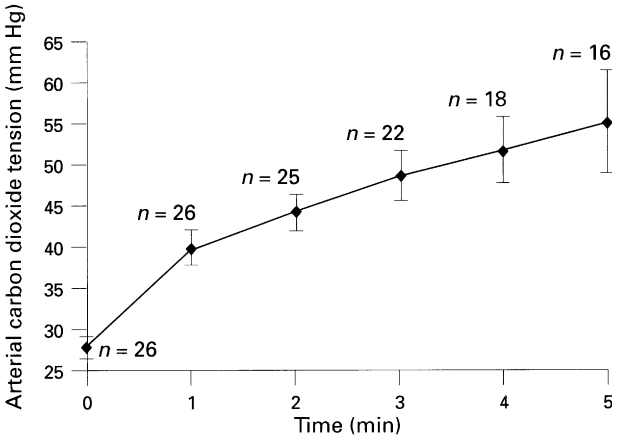

Figure 2 Changes in mean arterial carbon dioxide tension during the study. Error bars represent the outer limits of the 95% confidence interval.

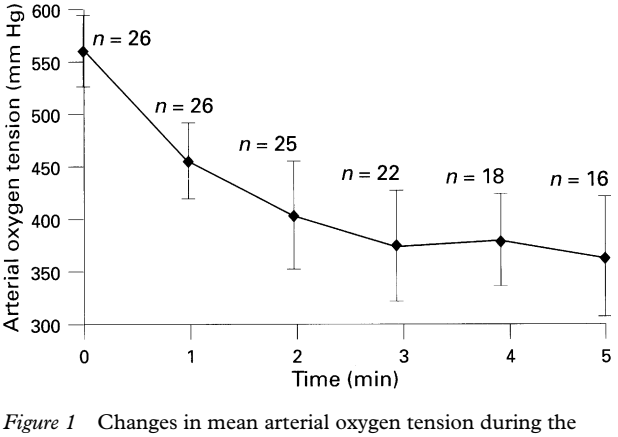

Figure 1 Changes in mean arterial oxygen tension during the study. Error bars represent the outer limits of the 95% confidence interval.

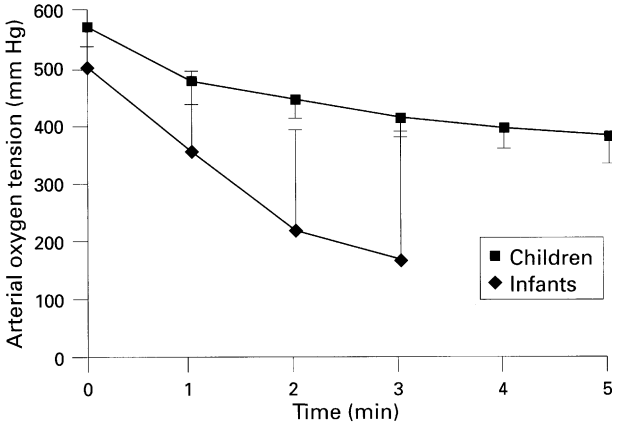

Figure 3 Mean oxygen tensions *vs* time for children and infants. Error bars represent the limits of the 95% confidence intervals.

Table 2 Blood-gas tensions (mean 95% confidence intervals)

	$t=0$	$t=1$ min	$t=5$ min
P_{O_2} (mm Hg)	561 (527–595)	456 (419–492)	366 (307–421)
Decrease in P_{O_2} (mm Hg)		105 (84–125)	195 (150–238)
P_{CO_2} (mm Hg)	27.7 (26.5–29.0)	39.9 (37.9–42.1)	55.3 (49.1–61.5)
Increase in P_{CO_2} (mm Hg)		12.2 (10.5–13.9)	27.6 (21.5–32.6)
PH	7.48 (7.46–7.49)	7.38 (7.36–7.40)	7.29 (7.26–7.31)
Base excess (mmol litre^{-1})	0.78 (−1.6 − 0.1)	−0.8 (−1.5 − 0.0)	−2.2 (−3.2 to −1.1)

Table 3 Infants compared with children. Data are mean (95% confidence interval), unless stated.

	Infants	Children
n	5	21
Age (months) (median (range)	4 (1–7)	49 (15–142)
Weight (kg) (median (range))	6.5 (3.7–9.3)	20.1 (7.2–48.6)
Initial oxygen tension (mm Hg)	505 (384–625)	574 (539–609)
Decrease in oxygen tension in first minute (mm Hg)	148 (44–254)	95 (79–111)
Subsequent rate of decrease in oxygen tension (1–3 min)	60 (−10–129)	26 (21–31)
Initial carbon dioxide tension (mm Hg)	29 (24.5–33.4)	27.4 (25.9–28.9)
Increase in carbon dioxide tension in first minute (mm Hg)	14.9 (9.0–20.0)	11.6 (9.7–13.4)
Subsequent rate of increase in carbon dioxide tension (mm Hg)	3.7 (2.3–5.1)	4.3 (3.8–4.8)

Results

We studied 28 patients and one patient was studied twice. Patients were aged 1 month to 11 years 10 months; six patients were aged <1 yr (table 1). Two patients (one child and one infant) were excluded when initial blood-gas measurements showed that preoxygenation had been ineffective. Eleven patients were studied for less than 5 min: 10 began to breathe after 4 or 5 min, and in one infant oxygen tension decreased to 60 mm Hg after 3 min. There were no clinical sequelae to these events. No other patient was excluded because of clinical deterioration.

Mean oxygen tension decreased from 561 (95% confidence interval (CI) 527–595) mm Hg to 456 (95% CI 419–492) mm Hg at 1 min and 366 (95% CI 307 − 421) mm Hg at 5 min. Mean carbon dioxide tension at the start of apnoeic oxygenation was 27.7 (95% CI 26.5–29.0) mm Hg and increased to 39.9 (95% CI 37.9–42.1) mm Hg at 1 min and 55.3 (95% CI 49.1–61.5) mm Hg at 5 min. The changes in oxygen and carbon dioxide tensions with time are shown in figures 1–4. The greatest carbon dioxide tension recorded at 5 min was 80.4 mm Hg; the least pH was 7.16. Other data are summarized in table 2.

Oxygen tension decreased in all patients with the greatest decrease in the first minute in all but two patients. The mean initial decrease in oxygen tension was 105 (95% CI 84–125) mm g in the first minute and 31 (95% CI 20.1–42.2) mm Hg min^{-1} over the next 4 min (fig. 1).

The increase in carbon dioxide tension was greater in the first minute than in subsequent minutes in all patients. The mean increase in carbon dioxide tension was 12.2 (95% CI 10.5–13.9) mm Hg over the first minute and 4.2 (95% CI 3.7–4.7) mm Hg min^{-1} over the next 4 min (fig. 2).

One patient was studied on two occasions. On the first occasion oxygen was delivered at 1 litre min^{-1} and on the second occasion at 10 litre min^{-1} (equivalent to 0.03 and 0.3 litre kg^{-1} min^{-1}). Changes in oxygen and carbon dioxide tensions were remarkably similar in each study and were not suggestive of enhanced ventilation with the higher gas delivery.

Five infants (aged <1 yr) were studied. All weighed less than 10 kg. All four patients aged less than 6 months demonstrated rapid decreases in oxygen tension (fig. 3). One was withdrawn after 3 min because of low oxygen tension. Two did not complete 5 min of apnoeic oxygenation because they began to breathe. In one infant oxygen tension decreased from 487 to 115 mm Hg after 2 min of apnoeic oxygenation but decreased little in the next 3 min. The oldest infant, aged 7 months, weighing 9.3 kg, remained well oxygenated throughout 5 min of apnoeic oxygenation and the final oxygen tension was 351 mm Hg. Carbon dioxide tension increased at the same rate in infants as in children (14.9 mm Hg in the first minute, 3.7 mm Hg min^{-1} subsequently for infants; 11.6 mm Hg, 4.3 mm Hg min^{-1} for children) (table 3). There was no apparent difference in diagnosis between the five infants and 21 children.

Analysis of changes in oxyhaemoglobin saturation

showed that it remained greater than 99% in all but two patients throughout the study. Mean saturation after 5 min of apnoeic oxygenation was 99.5%.

There was no significant correlation between changes in blood-gas tensions and patient age, weight or initial blood-gas tension.

Discussion

We have studied blood-gas tensions during apnoeic oxygenation via a tracheal tube in paediatric patients. By conducting the study during cardiac catheterization, we knew that cardiac shunt was not present.

Twenty-six of 28 patients achieved oxygen tensions greater than 370 mm Hg after preoxygenation. Two patients had initial oxygen tensions of less than 110 mm Hg. There was no clinical explanation for this, but gas leakage from a loose tracheal tube, atelectasis or a persisting shunt may have been responsible. We did not study these patients further and our results relate only to patients in whom preoxygenation was successful. Forty percent of patients did not remain apnoeic for the 5 min of the study and thus atracurium was not the ideal choice for neuromuscular block.

We used a fixed oxygen flow of 1 litre min^{-1} rather than varying flow with age or weight, as there is no published evidence that adequate gas flow in apnoeic oxygenation is related to weight or age, and airway geometry may be more relevant.

The only report on apnoeic oxygenation in children that we are aware of is an abstract published in 1987 by Kernisan and colleagues who studied apnoeic oxygenation in paediatric patients using oximetry. After preoxygenation, apnoeic oxygenation with oxygen flows of 0.1 litre kg^{-1} min^{-1} did not produce clinical desaturation in 3 min. Apnoea without tracheal oxygen led to desaturation in 217 s in heavy paediatric patients (>20 kg) and after 116 s in patients weighing <10 kg.[6] Our results confirm the safety of the technique in most patients: mean saturation after 5 min of apnoeic oxygenation was 99.5%. However, because two patients had low oxygen tensions after preoxygenation, and one infant became hypoxic after 3 min of apnoea, three of 28 patients were at risk of hypoxia.

We have produced a more thorough evaluation of the changes in blood-gas tensions during apnoeic oxygenation. As reported in adults,[1 2] the rates of decrease in oxygen tension and increase in carbon dioxide tension were greatest in the first minute of apnoeic oxygenation; changes in subsequent minutes continued but were reduced and largely constant. The early increase in carbon dioxide tension is caused by equilibration between alveolar and venous tension.[1]

Frumin, Epstein and Cohen[3] exposed eight adults to apnoeic oxygenation for up to 55 min; all patients remained well oxygenated with haemoglobin saturations in excess of 97%. After 30 min, pH decreased to less than 7.0 and carbon dioxide tension increased to 160 mm Hg. Arrhythmias were noted in two patients. Fraoli, Sheffer and Steffenson[2] exposed adults to 15 min of apnoeic oxygenation. Oxygen tension decreased from 445 to 310 mm Hg, carbon dioxide tension increased from 25 to 73 mm Hg and pH decreased from 7.55 to 7.20. The rate of decrease in oxygen tension in adults (9 mm Hg min^{-1}) was less than one-third of our value (31 mm Hg min^{-1}) The rate of increase in carbon dioxide tension in adults and paediatric patients was similar (3.2–3.8 mm Hg min^{-1} for adults, 4.2 mm Hg min^{-1} for paediatric patients). The reduction in pH in adults represents an increase in H^+ ion of 224% in 15 min. In this study, H^+ ion concentration increased 166% in 5 min.

The difference between adults and paediatric patients in the rate of decrease in oxygen tension is not surprising. Paediatric patients have a higher metabolic rate in relation to weight. As a result, the oxygen reserve in the lungs (functional residual capacity) is exhausted more rapidly.

The rate of increase in carbon dioxide in paediatric patients was less than we expected and was six-fold less than the decrease in oxygen. It is widely believed that paediatric patients have a relatively higher metabolic rate and a reduced storage capacity for carbon dioxide compared with adults and this led us to expect carbon dioxide tension to increase faster than in adults. A literature search back to 1966 found no data to support a reduced carbon dioxide storage capacity. Several methodological factors may have affected our results. The study was preceded by 5 min of preoxygenation and mild hyperventilation. Eger and Severinghaus found that the rate of increase in carbon dioxide tension in adults was reduced by approximately one-third when apnoea was preceded by hyperventilation to an initial carbon dioxide tension of 14 mm Hg.[1] We may have depleted tissue and blood carbon dioxide stores, so that storage capacity for carbon dioxide may have been artificially increased. Alternative explanations such as a significant decrease in cardiac output, regional blood flow distribution to metabolically inactive areas, or a decrease in metabolic rate are unlikely with mild hyperventilation, particularly as cardiac output and metabolic rate are higher in paediatric patients than in adults. A final possibility is that apnoeic oxygenation is providing some form of constant flow ventilation.

Endobronchial insufflation of oxygen or air in animal[7 8] and adult studies[4 9] permits adequate gas exchange for periods well in excess of 1 h. Gas exchange relies on bidirectional streaming and turbulent diffusion in the larger airways. In the distal airway, gas transport may be aided by oscillations caused by transmission of cardiac contractions,[10] but this is controversial.[4] For this effect, catheters must be placed 2.0–3.5 cm beyond the carina[11] and catheters with internal diameters less than 2 mm are needed to create sufficient turbulence. Gas flows need to be large; up to 1 litre kg^{-1} min^{-1} has been used in animals and flows in excess of 0.3 litre kg^{-1} min^{-1} are generally required to maintain blood-gas stability,[12] although airway geometry may be more important than weight in determining necessary flows. In our study, all tubes were placed above the carina, had internal diameters in excess of 3.5 mm and gas flows did not exceed 0.26 litre kg^{-1} min^{-1}, making the possibility of significant continuous flow ventilation extremely unlikely. When gas flow was increased 10-fold in one patient (to 0.3 litre kg^{-1} min^{-1}), carbon dioxide accumulation was unchanged, which supports this contention.

What clinical relevance can be inferred from our

data? Oxygen tension remained greater than 290 mm Hg after 5 min of apnoeic oxygenation in all patients aged >1 yr. After the first minute, oxygen tension decreased by approximately 31 mm Hg min^{-1}. If this was sustained, hypoxia would be expected to develop after approximately 14 min of apnoeic oxygenation. Using the upper limit of our confidence interval (42 mm Hg min^{-1}), we could tentatively predict the development of hypoxia at 10 min. After 5 min of apnoeic oxygenation, carbon dioxide tension was less than 60 mm Hg in all but two patients. After the first minute, carbon dioxide tension increased by 4.2 mm Hg min^{-1} (upper limit of confidence interval 4.7 mm Hg). After 14 min of apnoeic oxygenation, carbon dioxide tension might therefore have increased to approximately 100 mm Hg. Therefore, it is likely that hypercapnia (and subsequent decrease in pH) limits the safe period of apnoeic oxygenation at a similar time to the development of hypoxia. These results contrast with the situation in adults where hypercapnia develops well before hypoxia.

The study was not designed to compare apnoeic oxygenation in infants and children but the small number of infants behaved differently from the children. Of particular concern was the fact that initial oxygen tensions were less in infants than in children, and rapid decreases in oxygen tension were seen in four of five infants.

One patient aged 7 months, weighing 9.3 kg, remained well oxygenated throughout the 5 min of apnoeic oxygenation. Mean decreases in oxygen tension for infants <6 months were 156 and 160 mm Hg in the first and second minutes, respectively (for all infants 148 and 60 mm Hg) and these were considerably greater than those in older children (95 and 26 mm Hg). As we used a fixed oxygen flow rate for all patients, infants had a higher oxygen flow relative to their size. Carbon dioxide tension increased in infants at the same rate as in children (14.9 mm Hg for the first minute, 3.7 mm Hg min^{-1} subsequently for infants; 11.6 mm Hg, 4.3 mm Hg min^{-1} in children). The large chest wall compliance of infants results in functional residual capacity being less than closing volume leading to the potential for airway collapse towards the end of expiration.[13] Awake infants can prevent airway collapse by partial closure of the glottis thereby "braking expiration".[14] In this study, paralysis and intubation would prevent this glottic braking, and subsequent airway closure may account for the rapid decrease in oxygen tension in infants. The clinical importance of these results is that hypoxia may occur in infants after 2 min of apnoeic oxygenation. Although the number of infants we studied was small, hypoxia occurred before clinically important hypercapnia. Therefore, the limiting factor for the safe duration of apnoeic oxygenation appears to be hypoxia in these patients. Oximetry is therefore mandatory to guide the safe duration of apnoeic oxygenation in infants.

On the basis of our results, we confirm that apnoeic oxygenation is safe for 5 min in most children and we would speculate that the upper limit of safe apnoeic oxygenation in children could be at least 10 min. Our results suggest that hypoxia may develop rapidly in infants.

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