Capnometry and the paediatric laryngeal mask airway

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The laryngeal mask airway (LMA), an alternative to tracheal intubation in certain situations, has gained popularity in recent years. Initially designed for use in adults it has now become available in suitable sizes for paediatric anaesthesia. The objectives of this study were to identify the preferred site of sampling the end-tidal carbon dioxide (PETCO₂) with the LMA and to determine the accuracy of this recording when compared with arterial CO₂ (PaCO₂). We studied 30 healthy children, age one to five years and weighing between 10 and 25 kg undergoing minor surgery requiring mask anaesthesia. In each case, after induction of anaesthesia, the LMA was inserted under direct vision to eliminate the possibility of epiglottic airway obstruction. The fresh gas flow was provided by a Jackson Rees modification of an Ayre's T-piece and was determined according to the following formula: $3 \times (1000 + (100 \times \text{body weight}))$ LPM. Blood pressure, ECG, O₂ saturation, temperature and end-tidal gas concentrations were recorded. The measures of peak PETCO₂ were taken at pre-determined distances from the elbow connector down the LMA shaft. During the sampling sequence an arterial blood sample was taken for gas analysis. The PaCO₂ was 63.5 ± 9.3 mmHg (mean $\pm$ SD). At any given sampling site, mean PETCO₂ values were less than PaCO₂ ($P < 0.05$). However, in eight patients PETCO₂ values measured at the distal site were higher than the PaCO₂ (negative P(a-ET)CO₂ gradients). The results of this study suggest that when the LMA is used in children undergoing minor surgery who are spontaneously breathing halothane, the PETCO₂ values obtained from different sites underestimate the value of the PaCO₂. The preferred site for measuring PETCO₂ in these children is the distal end of the shaft although this value is less

than PaCO₂ ($P < 0.05$). In addition, use of the LMA does not prevent the hypercapnia associated with halothane anaesthesia in children breathing spontaneously.

De plus en plus utilisé depuis quelques années, le masque laryngé permet dans certains cas d'éviter l'intubation. Destiné d'abord aux adultes, il est maintenant disponible en plusieurs grandeurs pour usage pédiatrique. Cette étude vise à trouver sur le masque laryngé le site d'échantillonnage idéal pour le gaz carbonique téléexpiratoire (PETCO₂) et évaluer la précision de cette mesure comparativement au CO₂ artériel (PaCO₂). Trente enfants âgés d'un à cinq ans et pesant de 10 à 25 kg, programmés pour une intervention chirurgicale mineure avec anesthésie au masque, font partie de l'étude. Dans chacun des cas, le masque laryngé est inséré sous vision directe pour éliminer toute possibilité d'obstruction par l'épiglotte. Les gaz frais sont fournis par un tube en T d'Ayre modifié par Jackson Rees avec un débit calculé selon la formule suivante: $3 \times (1000 + (100 \times \text{poids}))$ L · min⁻¹. La pression artérielle, l'ECG, la saturation, la température et les concentrations téléexpiratoires sont enregistrées. Les échantillons de PETCO₂ sont prélevés à distances prédéterminées du raccord le long de la tubulure fixée au masque laryngé. En même temps que la capnométrie, on prélève un échantillon de sang pour l'analyse des gaz artériels. La PaCO₂ est de $63,5 \pm 9,3$ mmHg (moyenne $\pm$ ET). A chacun des sites d'échantillonnage gazeux, les valeurs moyennes de PETCO₂ sont moindres que la PaCO₂ ($P < 0,05$). Cependant, chez huit patients, au site le plus distal, les valeurs de PETCO₂ dépassent la PaCO₂ (gradient P(a-ET)CO₂ négatif). Les résultats de cette étude suggèrent que l'usage du masque laryngé, chez l'enfant soumis à une chirurgie mineure sous anesthésie à l'halothane en ventilation spontanée, procure des mesures de PETCO₂ qui sous-estiment la PaCO₂. Chez ces enfants, il est préférable de prélever les échantillons de PETCO₂ à la partie distale de la tubulure fixe du masque bien que cette valeur soit moins élevée que la PaCO₂ ($P < 0,05$). L'utilisation du masque laryngé ne prévient pas non plus l'hypercapnie associée à l'anesthésie à l'halothane en ventilation spontanée.

Key words

ANAESTHESIA: paediatric;
CARBON DIOXIDE: end tidal;
EQUIPMENT: laryngeal mask;
MEASUREMENT TECHNIQUES: capnometry.

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Capnometry and capnography are required in patients whose tracheas are intubated during general anaesthesia.¹ An accurate measurement of end-tidal CO₂ (PETCO₂) is difficult to determine in infants and children due to a

combination of high fresh gas flows and small tidal volumes.² Using a mass spectrometer with a continuous sampling technique, Kaplan and Paulus demonstrated that fresh gas flows continuously through the Mapleson F circuit (such as a Jackson-Rees' modification of Ayre's T-piece) during inspiration and expiration.³ They suggested that the fresh gas flow could contaminate the exhaled gases, dilute them and lead to inaccurate estimates of end-tidal gas concentrations. Fletcher has suggested that the $P(a-ET)CO_2$ gradient is lower at large tidal volumes.⁴ He concluded that the presence of a large $P(a-ET)CO_2$ gradient indicates a low efficiency of ventilation similar to that observed at small tidal volumes. These factors produce dilution of the $PETCO_2$ and a consequent underestimation of the arterial carbon dioxide partial pressure ($PaCO_2$). Several studies have suggested alternatives to circumvent this problem.⁵⁻⁷ Sampling the $PETCO_2$ at the distal end of the endotracheal tube was shown to improve the accuracy of $PETCO_2$ in estimating $PaCO_2$ in small infants of <12 kg.⁵ Recently, a laboratory study visualizing the mixing of fresh gas and expired gas in the Mapleson D circuit showed that, regardless of fresh gas flow rates, the site of mixing is always proximal to the point of narrowing of the endotracheal tube connector.⁸ It confirms the result of two previous investigations which suggested that $PETCO_2$ sampling immediately below the connector with a needle inserted through the endotracheal tube wall was sufficient to estimate the $PaCO_2$.⁹⁻¹⁰

Because the laryngeal mask airway has a large shaft, it is possible that the dilutional effect caused by the fresh gas flow may be more important than that which is reported with an endotracheal tube. This study was therefore designed to determine the preferred site of sampling of end-tidal CO_2 and the accuracy of this site as an estimate of $PaCO_2$ in anaesthetized infants and children breathing spontaneously through a laryngeal mask airway.

Methods

After approval by the Human Subject Review Committee and obtaining informed parental consent, 30 unpremedicated healthy infants and children, ASA physical status I and II, weighing between 6.5 and 25 kg were enrolled in the study. The infants and children were fasted for three hours. All patients were scheduled for elective minor surgery requiring general mask anaesthesia and lasting less than one hour. Patients with abnormal airway anatomy or known to have cardiopulmonary disease were excluded. All children were supine and were monitored with a blood pressure cuff, ECG, transcutaneous oxygen saturation, and end-tidal gas monitor and an axillary temperature probe. Following administration of atropine

FIGURE 1 A size #2 laryngeal mask airway was used. The elbow connector was modified and the modification consisted of two ports which allowed placement of a flexible fibreoptic and an $ETCO_2$ sampling catheter. Sampling sites are as follows; E = elbow; 1,2,3 = 4.5, 6, 11 cm from the elbow; D = distal (17 cm from the elbow); T = tracheal (3 cm into the trachea).

$0.02 \text{ mg} \cdot \text{kg}^{-1} \text{ iv}$ anaesthesia was induced with either thiopentone $5 \text{ mg} \cdot \text{kg}^{-1} \text{ iv}$ or halothane (in increments of 0.5% up to 3%) by mask. Anaesthesia was maintained with halothane and 70% N_2O in O_2 . Spontaneous respiration was allowed in all cases.

A size #2 laryngeal mask airway was inserted under direct vision to ensure its correct placement. The elbow connector (Gybeck-Dryden Corporation, Indianapolis, IN) was modified by the addition of two ports which allowed placement of a flexible fibreoptic bronchoscopy and an $ETCO_2$ sampling catheter (Figure 1). The fresh gas flow was provided by means of a Mapleson F circuit (Jackson-Rees' modification of an Ayre's T-piece) and was determined according to the formula: $3 \times (1000 + (100 \times \text{body weight in kg})) \text{ LPM}$.¹¹ If rebreathing was observed on the capnometer the fresh gas flow was increased until it could be eliminated. The end-tidal carbon dioxide partial pressures were recorded at steady-state by a Puritan-Bennett/Datex 255 infrared sidestream capnometer (Datex Instrumentarium Corp., Helsinki, Finland) calibrated before each study with dry gas of known composition (5% CO_2 and 36% N_2O). All values of $PETCO_2$ were corrected for BTPS.¹² The measurements of peak end-tidal CO_2 were taken in random order at predetermined distances from the elbow connector down the LMA shaft using a #19 standard-wire gauge Deseret Intracath (Beckton Dickinson Deseret Medical, Sandy, UT) inserted through the lateral Luer lock port at the elbow connector. If respiration was cyclical the highest $PETCO_2$ was recorded for analysis. Samples were taken proximally at the elbow connector and distally from the elbow connector at levels of 4.5 cm, 6 cm, 11 cm, 17 cm (the distal end of the laryngeal mask airway) and

20 cm (3 cm into the trachea) (Figure 1). During the sampling sequence an arterial blood gas was drawn from each patient by radial stab. Respiratory rate and tidal volumes were measured by means of a Wright Pediatric Respirometer (Ohmeda, Mississauga, Ontario).

Statistical analysis

All demographic and parametric data are expressed as mean $\pm$ standard deviation (SD). The normally distributed data were analyzed with repeated-measures ANOVA and the Student-Neuman-Keuls tests for multiple comparisons. $P < 0.05$ was accepted. The degree of agreement between measurements at the proximal and distal sites and arterial PCO_2 was calculated using the method of Bland and Altman.¹³ We decided, a priori, that a clinically acceptable range of deviation from the "true" CO_2 value (PaCO_2) would be ± 5 mmHg, i.e., a PETCO_2 measurement in the range of 35–45 mmHg would be acceptable for a PaCO_2 value of 40 mmHg. Subsequently, from prospectively collected PETCO_2 measurements, the 95% confidence interval between paired CO_2 measurements was calculated by the mean ± 2 SD. Assuming a normal distribution, 95% of the differences between paired CO_2 would fall within the range of mean $+ 2$ SD and mean $- 2$ SD. If this calculated 95% confidence interval falls within the previously set clinically acceptable range, the degree of agreement between the two methods is considered to be good. Coefficients of determination (r^2) for the PETCO_2 recorded at the proximal and distal site were compared to PaCO_2 using a linear regression analysis. Both coefficients of determination were compared using an unpaired t test. The two different analyses were chosen to show that the coefficient of determination measures the strength of relationship between the two variables, not the agreement between them.

Results

The age and weight of the children were 3.9 ± 1.5 yr and 16.6 ± 3.6 kg respectively. The mean respiratory rate was $45 \pm 8 \cdot \text{min}^{-1}$ and the mean tidal volume was $2.2 \pm 0.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{breath}^{-1}$. At the distal and tracheal sampling sites, rebreathing of 4–5 mmHg CO_2 was noted which could not be eliminated by increasing the fresh gas flow. The preset fresh gas flow was sufficient to avoid rebreathing at any of the other sampling sites.

The mean PaCO_2 measured by a single arterial stab during the sampling sequence was 63.5 ± 9.3 mmHg. Measured PETCO_2 rose progressively as sampling became more distal from the elbow (Figure 2). Mean PETCO_2 values measured at each sampling site were less than the PaCO_2 ($P < 0.05$). The coefficient of determinations (r^2) for the proximal (E) and the distal (D) sites (Figure 1) were 0.20 and 0.50 respectively and they were different

FIGURE 2 The mean ($\pm$ SD) for end-tidal CO_2 measurements obtained at predetermined distances from the elbow connector down to the distal end of the laryngeal mask airway and within the trachea. * $P < 0.05$ represent each site compared to PaCO_2 .

FIGURE 3 PETCO_2 (mmHg) (■ distal and □ proximal) measurements are plotted against the PaCO_2 (mmHg). The coefficient of determination (r^2) for distal and proximal were 0.5 and 0.2 respectively.

($P < 0.05$) (Figure 3). The paired mean difference between the airway capnometry CO_2 and the PaCO_2 for the proximal site was 9.34 ± 9.9 mmHg with 95% confidence interval 2.94 to 15.74 mmHg (Figure 4). Figure 5 shows the same graphical analysis for distal PETCO_2 . The mean difference was 2.02 ± 6.9 mmHg, 95% confidence interval from -2.46 to 6.50 mmHg. There was no correlation between the weight of the children and the gradient between arterial and end-tidal PCO_2 values whether measured at the proximal or distal sites.

One child developed a brief episode of laryngospasm during LMA insertion which was treated with positive

FIGURE 4 The differences in paired proximal end-tidal CO_2 measurements are plotted against PaCO_2 . The mean, mean + 2D and mean - 2SD values are shown in the graph.

FIGURE 5 The differences in paired distal end-tidal CO_2 measurements are plotted against PaCO_2 . The mean, mean + 2D and mean - 2SD values are shown in the graph.

pressure ventilation. There were no other episodes of oxygen desaturation due to placement or removal of the laryngeal mask airway. There were no complications as a result of this study.

Discussion

The results of this study show the PETCO_2 values measured at different sites in the LMA are less than the PaCO_2 in children breathing halothane spontaneously ($P < 0.05$). The best approximation of the PaCO_2 is the PETCO_2 value measured at the distal end of the shaft of the LMA but the correlation remains poor (coefficient of determination (r^2) = 0.5).

The use of capnometry is recognized as a means of estimating PaCO_2 in adults. In infants and children, however, PETCO_2 measurement is more difficult and its value as a means of estimating PaCO_2 levels remains controversial. Both the type of anaesthetic circuit and the sam-

FIGURE 6 Capnogram.

pling site appear to influence the accuracy of end-tidal capnometry.¹⁴ It has been shown that in children weighing more than 12 kg with tracheas intubated and lungs ventilated by intermittent positive pressure ventilation using the same partial rebreathing circuit as in this study, both distal and proximal samples approximated PaCO_2 values.⁵ In a study using single breath end-tidal CO_2 as a means of estimating arterial PCO_2 in infants and children, it was suggested that proximal measurements of PETCO_2 accurately estimate PaCO_2 provided that the fresh gas flow is interrupted during the period of measurement.⁹ Recently, in a laboratory study, it was reported that using a 3.5 mm endotracheal tube and fresh gas flows as large as $20 \text{ L} \cdot \text{min}^{-1}$ delivered by a Mapleson D circuit, dilution of the expired gases by the fresh gas flow occurred only as far as the connector.⁸ In another laboratory investigation using intubated rabbits and a Mapleson D circuit, it has been shown that PETCO_2 values are accurate if measured distally to the connector regardless of the mode of ventilation.¹⁰

There are several factors that may explain the differences between the results of this and previous studies. Firstly, the internal diameter of the shaft of the LMA (7 mm) is larger than an endotracheal tube used in a child of the same size. The LMA also maintains an artificial "pharyngeal" cavity which is bypassed by tracheal intubation.¹⁵ Secondly, the patients in this study were breathing spontaneously with a combination of high respiratory rates and low tidal volumes. This pattern of respiration increases the dilutional effect of the fresh gas flow due to the smaller expired volume of gases. Thirdly, a rapid respiratory rate causes inaccuracy in capnometer readings.¹⁶ The respiratory rates recorded in this group of patients varied from 40 to 70 breaths per min. This was in most cases fast enough to modify the recording pattern and affect phase III (plateau phase) of expiration.¹⁷ At high respiratory rates no good plateau phase could be observed (Figure 6). This would lead to an underestimation of the real PETCO_2 .

The eight negative PaCO_2 - PETCO_2 are more difficult to explain. In the case of cyclical respiration we took the highest PETCO_2 for analysis. We may have overestimated the PETCO_2 as it has been shown that the PaCO_2 is close to the time-weighted average of alveolar CO_2 , which is lower than the PETCO_2 in cyclical respiration.¹⁸ The other explanations for negative a- ETCO_2 gradients (low respiratory rate, big tidal volume, sloping phase III) do not apply in children with rapid shallow respirations.¹⁹

The hypercapnia observed in our patients after approximately 30 min of spontaneous ventilation with an inspired halothane concentration of 2% may be explained as follows. Hypoventilation is produced by a concentration of halothane in excess of twice the minimal alveolar concentration.^{20,21} In a recent study investigating minute ventilation during mask halothane anaesthesia in infants and children it was shown that halothane reduces minute volume, tidal volume and increases breathing frequency.²¹ In addition, the magnitude of the dead space produced by the larger internal diameter of the laryngeal mask airway compared with the small tidal volume of spontaneously breathing children resulted in rebreathing at both the distal and tracheal sampling sites.

Several studies have identified sources of inaccuracy in measurements of PETCO_2 in children. These have been avoided in the present study. Thus, the sampling aspiration rate of the end-tidal gas monitor was $150 \text{ ml} \cdot \text{min}^{-1}$ which has been shown to ensure an accurate estimate of the alveolar CO_2 content without entrainment of fresh gas.²² Severinghaus pointed out that the availability of water-permeable catheters has led to an incorrect calibration practice.¹² Our PETCO_2 values have been corrected for BTPS.

In conclusion, the results of this study show that children under halothane anaesthesia and breathing spontaneously through a laryngeal mask airway become hypercapnic. The anaesthetist may not be aware of the level of hypercapnic as the PETCO_2 measurements do not correlate well with PaCO_2 . The most accurate sample site for PETCO_2 sampling is within the trachea. However, using this site defeats the purpose for using a laryngeal mask airway which is to provide a satisfactory airway without trespassing beyond the glottis.

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