Original Article

Correlation of arterial $PaCO_2$ to end tidal CO_2 in children undergoing laparoscopic abdominal surgery: An observational study

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Abstract

Background and Aims: The reliability of end tidal carbon dioxide ($ETCO_2$) as a measure of arterial carbon dioxide ($PaCO_2$) in pediatric laparoscopy is unclear. We evaluated the correlation of arterial to end tidal P(a-ET) CO_2 during pediatric laparoscopy at two hours of pneumoperitoneum as the primary objective. We also compared P(a-ET) CO_2 and alveolar to arterial oxygen gradient P(A-a) O_2 and haemodynamics at fixed time points during surgery.

Material and Methods: A cross-sectional study was conducted in 25 children undergoing laparoscopic abdominal surgery. Arterial blood gases were drawn at T0, baseline, T10: ten minutes, T1h: 1 hour, T2h: 2 hours of pnuemoperitoneum and T 10d: 10 mins after deflation. The P(a-ET) CO2, P(A-a) O_2, were measured from the blood gas and ETCO2 and FiO2 values on the monitor. The Pearson's correlation coefficient, the Wilcoxon rank test and Chi square test were used for statistical analysis.

Results: At T2h moderate correlation of P(a-ET) CO2 ($r = 0.605$, $P = 0.001$) with 40% children documenting accurate P(a-ET) CO_2, -1 to +1 mm Hg was seen. Moderate correlation was also seen at T0, T10, T 10d but poor correlation at T 1h. The P(A-a) O_2 increased progressively with surgery and did not correlate with P(a-ET) CO_2. Heart rate was stable, but systolic blood pressures at T 10 and diastolic at T10, T 1h, T 2h were higher than baseline.

Conclusion: Moderate correlation was seen between $PaCO_2$ and $ETCO_2$ at 2 h of pnuemoperitoneum and at T0, T 10, and T 10d. P(A-a) O_2 increased with surgery but did not correlate with P(a-ET) CO2.

Keywords: Carbon dioxide, laparoscopy, pediatric

Introduction

End tidal carbon dioxide ($ETCO_2$) monitoring is a minimum mandatory monitoring in anaesthesia according to the ASA guidelines, but is considered desirable and safe in specific procedures by the ISA.[1] The accuracy of $ETCO_2$ as a surrogate of arterial $PaCO_2$ remains unclear in the context of paediatric laparoscopic surgery. While some have confirmed reliability,[2,3] Laffon and co-workers have not found safe correlation[4] Discrepancies between arterial $PaCO_2$ and $ETCO_2$ measures have been demonstrated in ventilated children with cyanotic congenital heart disease and infants with respiratory failure.[5] In adults undergoing laparoscopic surgery, the arterial to end tidal gradient of carbon dioxide P(a-ET) CO_2 is variable depending upon the positioning adopted and the duration of surgery making the need for arterial carbon dioxide monitoring mandatory.[6] The purpose of this study was to determine the reliability of $ETCO_2$ as a predictor of $PaCO_2$ in healthy children undergoing laparoscopic surgery. We chose a comparison of the two at 2 h when we believed

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adequate equilibration between carbon dioxide for insufflation and ventilatory effects would have been achieved.

Our primary outcome was the correlation of arterial to end tidal carbon dioxide at 2 h of pnuemoperitoneum during the study. Secondary outcomes were comparison P(a-ET) CO_2 at other time points and alveolar to arterial oxygen gradient P(A-a) O_2, heart rate and blood pressure at predefined time points.

Material and Methods

Following Institutional Ethics Committee approval (IEC-AIMS-2018-ANES-013) dated 22-01-2018 and informed consent from parents, a prospective cross-sectional study was conducted amongst 25 children undergoing elective laparoscopic surgery between December 2018 and August 2019, (CTRI/2018/11/016439).

All children aged between 6 months and 12 years undergoing elective laparoscopic abdominal surgery lasting more than 2 h were recruited. Children with a history of congenital heart disease, and respiratory disorders and thoracic laparoscopic procedures were excluded.

The children underwent pre-operative anaesthetic evaluation on the day before surgery during which parents were counselled about the proposed study and written consent obtained. As per fasting guidelines, solid food was withheld for 6 h, breast milk 4 h, while clear fluids were allowed up to 2 h before surgery.

All children had an IV line as per surgical team protocols and were given 1 mg/kg ketamine and 10 µg/kg glycopyrrolate IV at separation unless they were cooperative. General anaesthesia was induced with IV propofol 1-2 mg/kg, 2 µg/kg fentanyl with isoflurane as inhalational agent. Intubation was performed 3 mins after atracurium 0.5 mg/kg IV and ventilation with air-oxygen mixture (FiO_2 0.5) and isoflurane at 0.7-1.0 MAC using the GE Avance CS^2 anaesthesia work station. Pressure controlled volume guaranteed (PCV-VG) mode of ventilation was used. Tidal volumes of 6-8 ml/kg were set and respiratory rate adjusted to maintain $ETCO_2$ values between 32 and 36 mmHg. Inspiratory: Expiratory ratio of 1:2.5 and PEEP of 4-5 cm H_2O was set. The ventilatory rate was increased during the surgery to maintain the $ETCO_2$ in the reference range and tidal volume adjusted to maintain a peak pressure less than 30 cm H_2O by reduction in tidal volumes and increase in respiratory rate.

Monitoring included ECG, SpO_2, non-invasive blood pressure, temperature and $ETCO_2$. $ETCO_2$ was measured with infrared side-stream capnometer, with sampling port between the proximal end of endotracheal tube and paediatric breathing circuit. An arterial line is often inserted for long laparoscopic procedures at our institution and we had used it in the surgeries mentioned for the study. The procedure was explained to the parent and written informed consent was obtained for each patient. A radial arterial line was inserted under anaesthesia by the senior consultant using 22 G Insyte (Becton Dickinson Infusion Therapy Systems Inc, Sandy, UT) and connected to a 5 cm extension with a flush. If more than 2 attempts were taken the procedure was abandoned and patients excluded from the study (flow diagram).

Samples were drawn at fixed time intervals, T0: baseline, T10: 10 minutes after the creation of pnuemoperitoneum, T 1h: 1 h, T2h: 2 h after pnuemoperitoneum and T10d: 10 minutes after deflation and were compared to the values of $ETCO_2$ obtained simultaneously. At the end of surgery, neuromuscular blockade was reversed by inj glycopyrrolate 0.01 mg/kg and inj neostigmine 0.05 mg/kg and the children extubated and shifted to the postoperative ICU for further care as per standard protocol. The arterial line was removed in the theatre prior to shifting the child to the recovery and post anaesthesia care unit.

As per the reference article,[4] P(a-ET) CO_2 differences were classified as Negative: P(a-ET) CO_2 below-1 mm Hg, Accurate: P(a-ET) CO_2-1 mm Hg to + 1 mm Hg and Positive: P(a-ET) CO_2 >1 mm Hg. The P(A-a) O_2 was calculated by the formula

$$\begin{aligned} P(A\text{-}a)\,O_2 &= PAO_2 - PaO_2 \\ &= \{713 \times FiO_2 - PaCO_2 \times 1.25\} - PaO_2 \end{aligned}$$

PAO_2 = alveolar oxygen pressure

PaO_2 = arterial oxygen pressure

The Alveolar dead space fraction (AVDSF) was

$$\text{derived by} = \frac{PaCO_2 - ETCO_2}{PaCO_2}$$

As we did not find existing literature correlating the $PaCO_2$ to $ETCO_2$ we conducted a pilot study with 10 children aged between 1-10 y. On the basis of the pilot study, a moderate correlation of r = 0.602 was obtained at 2 h of surgery ($PaCO_2$ 36.75 ± 2.75 vs. $ETCO_2$ 36.2 ± 2.70 mm Hg). Using this correlation and 80% power with 95% confidence interval the sample size was estimated as 19. We included 25 children with 5 samples each in our study.

Statistics

To analyse the association of categorical variables, Chi square with Fisher's exact test was applied. Continuous variables are represented in mean ± SD, and categorical variables as percentage. To compare the mean difference of hemodynamic parameters from the base line in case of non-normality Wilcoxon signed-rank test was applied. To find the correlation between $PaCO_2$ and P(A-a) O_2 with P(a-ET) CO_2, Pearson correlation was applied. A *P* value <0.05 was considered as statistically significant. Statistical analysis was done using IBM SPSS 20.0 (SPSS Inc, Chicago, USA).

Results

Twenty-five children undergoing laparoscopic abdominal surgeries were included and a total of 125 readings were analysed [Flow diagram]. The mean age in months was 49.56 ± 38.58, range (10-20), weight (kg) 17.2 ± 11.74, range (7-56), and M:F 12:13. The types of surgery included pyeloplasty (n = 11), nephrectomy (n = 8), appendicectomy (n = 3), salpingo-oophorectomy (n = 1), choledochal cyst (n = 1) and splenic cyst (n = 1) excision.

As per our classification only 48% of patients had an accurate P(a-ET) CO_2 (-1 mm Hg to +1 mm Hg) at T 0 that decreased during laparoscopy to a lowest of 28% at T 1 h but recovered to 76% at T 10 d, none of the patients had a positive gradient at T 10d [Figure 1].

The primary outcome was the correlation between arterial and end-tidal CO_2 P(a-ET) CO_2 at 2 h of pneumoperitoneum. The $PaCO_2$ at 2 h was 37.12 ± 3.73 and $ETCO_2$ 36.56 ± 2.53 mm Hg, and correlation coefficient 0.605 (*P* = 0.001). 40% of children had an accurate (a-ET) CO_2 at 2 h of pneumo-peritoneum, [Table 1, Figure 2]. Negative gradient below -1 mm Hg was maximum at T 2 h at 28% [Figure 1].

The $PaCO_2$ and $ETCO_2$ at the other time points showed a moderate correlation at T 0, T 10, and at T 10d. The correlation appeared poor at 1 h into laparoscopy T 1h, [Table 1, Figure 2].

We compared the heart rate, systolic and diastolic pressures as changes from the baseline value [Figure 2]. The heart rate did not show changes from the baseline at any of the time points. The systolic pressure was significantly higher at T 10 and comparable at other time points. The diastolic pressure was significantly higher in comparison to the baseline at T 10, T 1h and T 2h [Figure 3].

The P(A-a) O_2 increased progressively for the duration of surgery from base line and was significantly higher than the baseline value at other time points, [Table 2]. We compared to the see if the changes in P(A-a) DO_2 correlated to the changes in P(a-ET) CO_2 but we did not find a correlation between the two, [Table 2].

We looked at the alveolar dead space fraction (AVDSF) derived from Enghoff's modification of Bohr's equation and its associations with P(a-ET) CO_2. The AVDSF decreased with time of surgery and was nearly 0 at T 10d. [Table 3].

Discussion

We conducted this study to assess if the $ETCO_2$ is a reliable predictor of arterial carbon dioxide in laparoscopic surgery in children. We found that a difference of -1 mm Hg to ±1 mm Hg was found in only 48% children at T 0 but in 76% children at T 10 d **[**Figure 1].

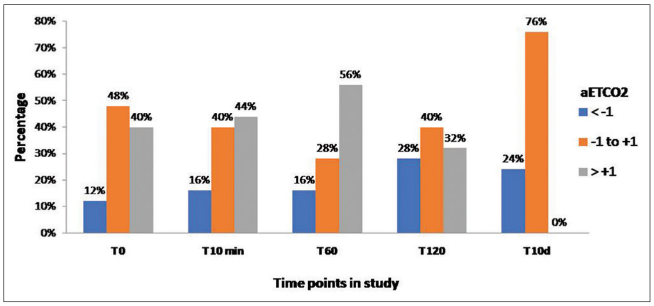


Figure 1: Grading of (a-ET) CO2 at time points

Table 1: Correlation of $PaCO_2$ and ET CO_2

Time Points	Mean±SD		ρ Pearson Correlation*	*P*
	$PaCO_2$	$ETCO_2$		
T0	32.76±4.34	33.56±3.8	0.627	0.001
T 10	36.80±3.46	35.2±3.43	0.495	0.012
T 1 h	37.28±4.90	36.08±2.96	0.359	0.078
T 2 h	37.12±3.73	36.56±2.53	0.605	0.001
T 10 d	33.56±4.57	33.28±3.04	0.695	0.000

**Correlation at $PaCO_2$ to $ETCO_2$. ρ: Pearson coefficient: Values of 0.6 imply moderate positive correlation. P<0.05. significant statistically*

Table 2: P(A-a) O_2 Variations from Baseline and Versus P(a-ET) CO_2

Time points	P(A-a)O_2 mean±sd	*P*	P(A-a) O2 vs. P(a-ET) CO_2	
			Pearson correlation* ρ	*P*
T 0	97.12±52.49	-	-0.019	0.928
T 10	112.48±57.63	0.049	0.012	0.956
T 1 h	122.68±52.10	0.006	-0.047	0.822
T 2 h	144.96±51.77	0.007	-0.038	0.858
T 10 d	122.44±53.78	0.019	0.073	0.727

*P(A-a) O_2: Alveolar to arterial gradient. P(a-ET) CO_2: Arterial to end tidal CO_2. P<0.05 significant. ρ: Pearson correlation comparing P(A-a) O_2 vs. P(a-ET) CO_2. *Values of 0 imply no correlation*

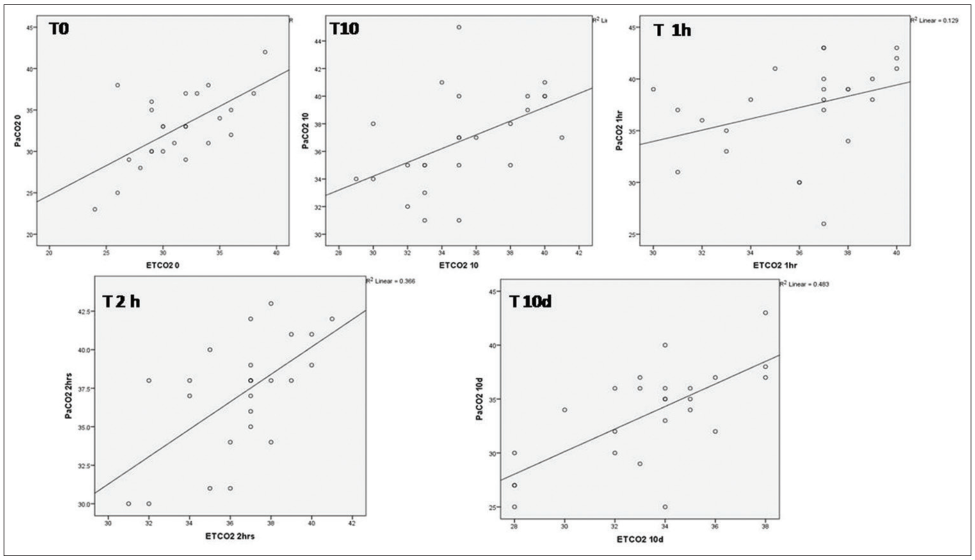


Figure 2: Correlation of PaCO2 vs. ETCO2 at fixed time points

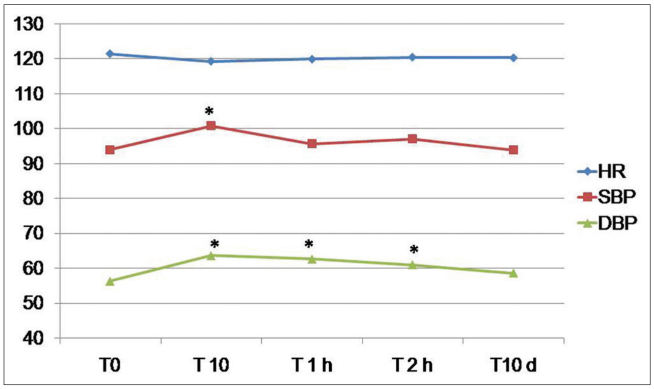


Figure 3: Hemodynamic changes at fixed time points

Table 3: Alveolar Dead Space Fraction

Time points	$PaCO_2$-$ETCO_2$ mm Hg Mean±SD	AVDSF Mean±SD	AVDSF Value at Time Points vs T0. *P*
T 0	1.44±3.50	0.37±0.10	
T 10	1.60±3.46	0.04±0.09	0.882
T 1 h	1.32±4.40	0.22±0.13	0.294
T 2 h	0.6±3.07	0.08±0.08	0.600
T 10 d	-0.8±3.82	0±0.11	0.326

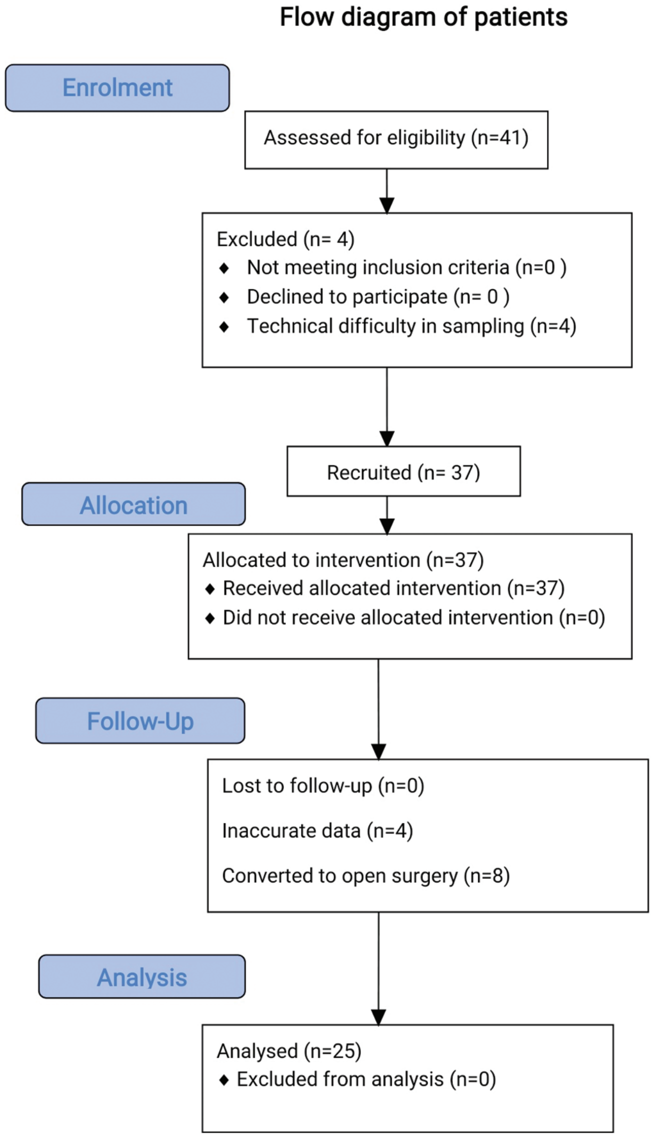
P<0.05 significant. AVDSF: Alveolar dead space fraction: $\frac{PaCO_2 - ETCO_2}{PaCO_2}$

Unlike the P(A-a) O_2 gradient the factors that influence the P(a-ET) CO_2 even in adults is poorly understood. Ickx and associates have proposed that in children the (a-ET) CO_2 is very narrow and that the $ETCO_2$ represents accurately the $PaCO_2$ in children older than 8 months.[3] However although the mean of the P(a-ET) CO_2 difference in their study was only 1.6 mm Hg, the range appeared to be wide (SD = 4.3 mm Hg). Our results showed similar differences in the mean 1.4 ± 3.5 mm Hg at the start (T0) to -0.8 ± 3.82 mm Hg at deflation of pneumo-peritoneum (T 10d) but this was the congruence of a range of positive and negative values amongst patients at each point in time [Figure 1]. We correlated the values of $PaCO_2$ against the end tidal carbon dioxide and found that there was a moderate correlation ($P < 0.05$) at all time points except at T 1h.

A negative difference between the arterial and end tidal carbon dioxide is an intrigue noted consistently in pediatric ventilation.[7] It has also been noted in normal adults under anaesthesia, caesarean section and during cardiopulmonary bypass.[8,9] Shankar and associates have elegantly described the mechanism of this negative difference.[10] The $ETCO_2$ measured as a value represents the peak of phase III of the $ETCO_2$ trace or capnograph. Ventilation with large tidal volumes and low frequency recruits alveoli that may have been part of a ventilation perfusion mismatch, and the large volume may also bring the expired carbon dioxide closer to the sampling port as against a normal or low volume ventilation.

During anaesthesia in pregnancy as well in coming off cardiopulmonary bypass the ventilatory strategies induct the alveoli with low ventilation perfusion ratios contributing to a negative gradient observed. This implies that the $ETCO_2$ is not a reliable correlate of $PaCO_2$ when there is an upward slope of phase III in the capnogram.

Our representation of P(a-ET) CO_2 showed a similar profile, baseline T0 difference of 1.44 ± 3.5 mm Hg that reached 0.6 ± 3.07 at T 2h and -0.8 ± 3.82 at T 10d were the summation of a range of positive and negative values. It is noticeable that the positive values were 0 at the end T 10d, and the AVDSF was 0 at the same time that fits in with the concept that as the AVDSF decreases the P(a-ET) CO_2 also decreases.



Flow diagram

Our study showed that the negative gradient was present in 12% patients at the start increased during surgery to 16% at T 10 and T 1h, increased to 28% at T 2h and 24% at T 10d. [Figure 1] As per the explanations by researchers[9,10] we believe that the ventilatory adjustments to maintain the ETCO$_2$ in the target range may have contributed to the negative gradient.

The P(a-ET) CO2 is a reflection of alveolar dead space that can arise from temporal and spatial variations in pulmonary blood flow and alveolar mixing in the lung. In a physiological state, children have a low P(a-ET) CO2 gradient due to efficient ventilation perfusion (V/Q) matching (-0.65- +3 mm Hg) in contrast to the 2-5 mmHg difference in an adult.

Factors that affect the P(a-ET) CO2 are a decrease in cardiac output, V/Q mismatch as in pulmonary embolism besides diseases of the lung such as emphysema. It has been noted in ASA I and II adults undergoing laparoscopy,[11] the ETCO$_2$ is a reliable indicator of PaCO$_2$ but this is not so amongst ASA III and IV patients. This is explained by an increase in the V/Q mismatch during surgery along with factors that affect the cardiac output in this group.

In mechanical ventilated children with healthy lungs, the ETCO$_2$ from a capnograph is an reliable estimate and can be used in the calculation of the alveolar dead space fraction by Enghoff's modification of Bohr's equation, alveolar dead space fraction (AVDSF) = PaCO$_2$-ETCO$_2$/PaCO$_2$.[12] We evaluated the dead space fraction by this calculation which is reliable correlate of dead space by Bohr's equation.[13] We found that the AVDSF decreased from 37% at T 0 to 0 at T 10 d, but a comparison of the changes with the baseline were not significant statistically, Table 3. The decrease in AVDSF can be explained by ventilation with larger tidal volumes after the release of pnuemoperitoneum in the PCV- VG mode. In our analysis the decrease in AVDSF correlated with decrease in (a-ET) CO$_2$.

Surprisingly we did not see the same correlation with P(A-a) O$_2$ that would represent the V/Q mismatch and this is contradictory to the result from Goonasekara and researchers.[7] Lateral position increases the V/Q mismatch and was the position adopted in 19 children undergoing pyeloplasty and nephrectomy.[14,15] Our comparisons of P(A-a) O$_2$ versus P(a-ET) CO$_2$ lead us to believe that adjustment of ventilation can reduce the alveolar dead space even when there is a V/Q mismatch. This was seen by the narrowing of P(a-ET) CO$_2$ after deflation reflecting a time when the impact of pnuemoperitoneum on lung compliance is withdrawn but ventilatory adjustments not implemented.

We did not consider cardiac output monitoring during surgery for our patients. Non-invasive cardiac output monitoring devices are unreliable in children and esophageal doppler or TEE carry need for technical expertise and additional costs.[16] We expected hemodynamic changes as the absorption of carbon dioxide from the pnuemoperitoneum progressed. The heart rate did not show changes from the baseline but the diastolic blood pressure was higher at T 10, T 1h and T 2h during laparoscopy. Hsing and associates reported that hemodynamic changes were largely unaffected during laparoscopy,[17] while findings of Pelizzo and associates are contradictory where they had documented a fall in diastolic pressures with laparoscopy.[18]

Our study had its limitations. This was a study performed after informed parental consent in children between 6 months and 12 years presenting at our centre for laparoscopic surgery. Ventilation specific for ages or effects of position could not be assessed. The standard pediatric circuits were used for children less than 25 kg but we had used adult circuits for children weighing more than 25 kg, the contribution of the apparatus dead space was not accounted in our study. A standard pediatric HME filter with dead space of 20-25 ml was applied at the expiratory limb of the circuit and the circle absorber in all patients. It is possible that it had an influence on the arterial $PaCO_2$ although it was uniform in all patients and are assessment was the gradient with $ETCO_2$ at the measured point in time.

Temperature changes during laparoscopy that could account for changes were not measured. Positioning of the child in lateral or steep head down could have increased the V/Q mismatch and the P(A-a) O_2 amongst our patients and prospective studies in large volume centres may highlight differences more accurately.

We believe that ours is one of the few recent studies evaluating $ETCO_2$ in pediatric laparoscopy and offers insights into the safety of monitoring $ETCO_2$ in children and also into factors that may influence this. Our results showed a moderate correlation between the $PaCO_2$ and $ETCO_2$ for most points during surgery, and a close representation after deflation of pnuemoperitoneum. Although the V/Q mismatch can increase during, surgery, ventilatory adjustments can reduce AVDSF and magnitude of the difference towards the end of surgery. $ETCO_2$ provides a close correlation with $PaCO_2$ at T 10d but cannot replace arterial sampling in paediatric laparoscopy on account of varying negative and positive gradients between the two.

Conclusion

The $ETCO_2$ is a moderately reliable correlate of $PaCO_2$ at 2 h of pnuemoperitoneum and at baseline, 10 minutes after pnuemoperitoneum and 10 minutes after deflation. Pnuemo-peritoneum also increases the alveolar to arterial gradient and increases diastolic blood pressures.

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Conflicts of interest

There are no conflicts of interest.

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