Original Article

The Effect of Decreased Respiratory Compliance during Pneumoperitoneum and the Trendelenburg Position on the Reliability of End Tidal Carbon Dioxide Monitoring

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Objective: To demonstrate the reliability of $ETCO_2$ in patients with decreased respiratory compliance during pneumoperitoneum and Trendelenburg position for laparoscopic surgery. The decrease in respiratory compliance can increase dead space ventilation; therefore, the gradient between $PaCO_2$ and $ETCO_2$ ($PaCO_2$-$PETCO_2$) might be higher during pneumoperitoneum than at baseline.

Materials and Methods: Twenty women who underwent laparoscopic gynecological surgery were enrolled. Arterial blood gas samples were collected 10 minutes after induction of anesthesia (T0), 45 minutes after pneumoperitoneum and placement in the Trendelenburg position (T1), and after CO_2 desufflation and placement in the supine position (T2).

Results: The static respiratory compliance significantly decreased from T0 to T1 and increased from T1 to T2. The $PaCO_2$-$PETCO_2$ significantly increased from 2.3 (0.3 to 3.9) at T0 to 3.9 (3.0 to 5.1) at T1 (p=0.025). The correlation between $ETCO_2$ and $PaCO_2$ was still acceptable at T0 (r=0.513, p=0.021), T1 (r=0.486, p=0.030), and T2 (r=0.539, p=0.014). Adjustment of the ventilator settings according to the $ETCO_2$ level was not associated with respiratory acidosis at T0, T1, and T2. The plateau pressure during pneumoperitoneum was correlated with the increase in $PaCO_2$-$ETCO_2$ (r=0.456, p=0.043). The ratio of the partial pressure of oxygen to the fraction of inspired oxygen (PaO_2/FiO_2 ratio) significantly decreased from 516.0 (433.7 to 583.5) at T0 to 415.0 (311.8 to 468.5) at T1 and 398.0 (350.0 to 475.7) at T2.

Conclusion: The decrease in respiratory compliance during pneumoperitoneum and the Trendelenburg position associated with the increase in $PaCO_2$-$PETCO_2$, which was predicted by the plateau pressure.

Keywords: Carbon dioxide, Compliance, Laparoscopy, Pneumoperitoneum, Trendelenberg position

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Increasing numbers of laparoscopic surgical procedures are being performed because of their benefits in terms of reducing the hospital stay, facilitating faster recovery, and inducing less post-operative pain compared with conventional open surgery. However, pneumoperitoneum for laparoscopic surgery, which is performed by insufflation of carbon dioxide (CO_2) into the abdominal cavity, can cause significant disturbances in the cardiovascular and respiratory systems.

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The increased abdominal pressure that occurs during laparoscopic gynecological surgery causes an increase in the right atrial pressure, mean arterial pressure (MAP), and systemic vascular resistance; however, the stroke volume remains stable if the abdominal pressure is maintained at less than 12 mmHg[1]. The plateau pressure is increased, and the respiratory compliance is decreased primarily by cephalad displacement of the diaphragm during pneumoperitoneum[2-4]. These changes deteriorate when the patient is placed in the Trendelenburg position[5,6]. Thus, compensatory ventilation should be implemented to prevent acute respiratory acidosis. Although measurement of the end-tidal CO_2 ($ETCO_2$) is widely used for intraoperative monitoring of the partial pressure of CO_2 in arterial blood ($PaCO_2$), the normal correlation of $ETCO_2$ with $PaCO_2$ is reduced during impairment of ventilation or perfusion or

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increased dead space[3,7,8]. In such circumstances, the $PaCO_2$ to $ETCO_2$ pressure gradient ($PaCO_2$-$PETCO_2$) is abnormally high.

The aim of the present study was to demonstrate the effect of decreased respiratory compliance on $PaCO_2$-$PETCO_2$ during pneumoperitoneum and the Trendelenburg position. Furthermore, the authors hypothesized that the increased $PaCO_2$-$PETCO_2$ might be able to be predicted by the change in respiratory compliance.

Materials and Methods

The present research was reviewed and approved by the Ethics Committee of Ramathibodi Hospital, Mahidol University, Thailand. Written informed consent was obtained from each patient after the full details of the research had been disclosed. This research was conducted in 20 women aged 18 to 65 years that underwent laparoscopic gynecological surgery under general anesthesia. The exclusion criteria were pre-existing cardiopulmonary disease or an abnormal preoperative arterial blood gas or chest radiograph.

When the patients arrived in the operating room, they underwent electrocardiography, pulse oximetry, and automated non-invasive arterial blood pressure measurement before the initiation of anesthesia. The intravenous induction agents were thiopental (4 to 5 mg/kg) and atracurium (0.5 to 0.6 mg/kg). The intravenous opioids were titrated to the desired effect. Endotracheal intubation was performed under direct laryngoscopy with a 7.5-mm endotracheal tube. Anesthesia was maintained by sevoflurane (1.0 to 1.5 minimum alveolar concentration), oxygen (1 L/minute), and nitrous oxide (1 L/minute). Atracurium was subsequently administered at 0.2 mg/kg every 30 minutes. Intravenous morphine was added depending on the clinical response. The blood pressure and heart rate were maintained within the normal limits throughout the procedure. Intravenous fluid (acetar solution or 5% dextrose in a half amount of normal saline) was infused to maintain normal hemodynamics. Normothermia was maintained by a forced air warming device.

After endotracheal intubation, the sidestream $ETCO_2$ monitor from the anesthetic machine (Avance CS2; GE Healthcare, Chicago, IL, USA) was used to monitor $ETCO_2$ in all patients. The same type and brand of $ETCO_2$ monitor was used for every patient in the study. The ventilator settings were a tidal volume of 8 ml/kg of predicted body weight, inspiratory time of one second, fraction of inspired oxygen (FiO_2) of 0.5, and positive end-expiratory pressure (PEEP) of 5 cmH_2O. The respiratory rate was adjusted to maintain an $ETCO_2$ of 28 to 35 mmHg. A 22-G radial arterial catheter was inserted in the left or right arm. A previous study showed that the $PaCO_2$ level reaches a plateau 30 minute after the beginning of CO_2 insufflation[9]. Therefore, samples for arterial blood gas analysis were collected 10 minutes after induction of anesthesia (T0), 45 minutes after pneumoperitoneum and placement in the Trendelenburg position (T1), and after CO_2 desufflation and placement in the supine position (T2). Arterial blood gas analysis was performed with the same arterial blood gas machine (RAPIDLab 348EX System; Siemens, Munich, Germany) for every sample. The blood samples for arterial blood gas analysis were collected only when the patients had stable hemodynamics and body temperature.

The following patient characteristics and perioperative data were recorded: MAP, heart rate, body temperature, respiratory rate, urine output, intraoperative blood loss, intraoperative fluid volume, angle of operative table, abdominal pressure, and duration of anesthesia. The following ventilatory parameters were recorded at T0, T1, and T2: set tidal volume, peak inspiratory pressure, plateau pressure, minute ventilation, and $ETCO_2$.

The static respiratory compliance was calculated as follows: Static respiratory compliance (ml/cmH_2O) = tidal volume / (plateau pressure – PEEP)

Each laparoscopic gynecological procedure was performed by a gynecologist who was not involved in the research. Every procedure was performed by conventional multiport access. Pneumoperitoneum was induced by CO_2 insufflation. The abdominal pressure was initially set at less than 12 mmHg, but the gynecologist was able to adjust the pressure to optimize the surgical field. The anesthesiologist could request to adjust the abdominal pressure when necessary.

At the end of the operation, 0.5 mg/kg of neostigmine and 0.02 mg/kg of atropine were administered to reverse the muscle relaxant. All patients were extubated at the end of the operation.

Statistical analysis

The sample size was calculated using the significant increase in $PaCO_2$-$PETCO_2$ after pneumoperitoneum from the previous study[6] with 80% power and alpha error of 0.05. The minimum requirement of the sample size was 6. The authors increased the sample size to 20 cases.

Continuous data were expressed as mean ±

Table 1. Patient characteristics and perioperative details

Age (years), Mean±SD	42.4±7.9
Height (cm), Median (IQR)	158.0 (155.2 to 166.5)
Weight (kg), Mean±SD	63.8±11.6
Body mass index (kg/m^2), Median (IQR)	24.2 (20.6 to 27.9)
ASA physical status, n (%)	
I/II	19 (95)
III	1 (5)
Underlying medical condition, n (%)	
Diabetes mellitus	2 (10)
Malignancy	1 (5)
Hypertension	1 (5)
Procedure, n (%)	
Myomectomy	3 (15)
Hysterectomy	8 (40)
Hysterectomy with salpingo-oophorectomy	7 (35)
Ovarian cystectomy	2 (10)
Abdominal pressure during pneumoperitoneum (mmHg), Mean±SD	13.3±1.9
Angle of the operative table (°), Median (IQR)	30.0 (30.0 to 43.7)
Duration of anesthesia (minute), Mean±SD	238.7±52.7
Intraoperative fluid (ml), Mean±SD	1884.7±587.9
Intraoperative blood loss (ml), Median (IQR)	200.0 (100.0 to 337.5)
Urine output (ml/hour), Mean±SD	96.7±41.6

SD=standard deviation; IQR=interquartile range; ASA=American Society of Anesthesiologists

standard deviation, and non-normally distributed data were expressed as median with interquartile range. Categorical data were expressed as number (%). Statistical analysis was performed using the Statistical Package for Social Sciences software (SPSS 24.0 for Windows; IBM Corp., Armonk, NY, USA). A paired t-test was used to compare normally distributed variables, while the Wilcoxon signed-rank test was used to compare nonparametric variables among T0, T1, and T2. The chi-square test was used to compare categorical data. Multiple linear regression analysis was performed for prediction of $PaCO_2$-$PETCO_2$ from independent variables. The correlation between nonparametric variables was compared using Spearman's correlation, while the correlation between normally distributed variables was compared using Pearson's correlation. All results were considered statistically significant at p-value smaller than 0.05.

Results

Twenty patients were enrolled. The patient characteristics and surgical details were shown in Table 1. Most patients (95%) had the American Society of Anesthesiologists physical status of I or II. The angle of the operative table was 30° (30.0° to 43.7°). The mean abdominal pressure during pneumoperitoneum was 13.3±1.9 mmHg.

The static respiratory compliance decreased significantly from T0 to T1 and increased after CO_2 desufflation at T2 (Figure 1A, Table 2). The $PaCO_2$ increased from T0 to T1 and decreased from T1 to T2 (Figure 1B, Table 2). $PaCO_2$-$PETCO_2$ significantly increased from 2.3 (0.3 to 3.9) to 3.9 (3.0 to 5.1)

Table 2. Perioperative hemodynamics and respiratory variables

Variables	T0, Median (IQR)	T1, Median (IQR)	T2, Median (IQR)
PaO_2 (mmHg)	258.0 (216.8 to 291.7)	207.5 (155.9 to 234.2)*	199.0 (175.0 to 237.8)*
PaO_2/FiO_2	516 (433.7 to 583.5)	415.0 (311.8 to 468.5)*	398.0 (350 to 475.7)*
$PaCO_2$ (mmHg)	32.7 (28.7 to 34.0)	37.1 (35.6 to 38.9)*	35.7 (31.6 to 38.4)*
$PaCO_2$-$PETCO_2$ (mmHg)	2.3 (0.3 to 3.9)	3.9 (3.0 to 5.1)*	2.85 (1.7 to 5.4)
Static compliance (ml/cmH_2O)	32.1 (28.7 to 44.3)	21.8 (17.4 to 24.9)*	31.18 (25.2 to 37.0)*,†
pH, Mean±SD	7.48±0.03	7.41±0.04*	7.41±0.05*
Minute ventilation (L/minute), Mean±SD	6.2±0.8	7.2±0.8*	7.1±1.0*
MAP (mmHg)	80.5 (71.2 to 88.7)	77.0 (74.2 to 84.7)	73.0 (67.0 to 78.5)
Heart rate (bpm)	67.5 (59.2 to 79.5)	65.0 (59.2 to 76.5)	65.5 (60.5 to 83.7)
Body temperature (°C), Mean±SD	36.4±0.3	36.2±0.4*	36.1±0.6*

SD=standard deviation; IQR=interquartile range; T0=after induction of anesthesia; T1=45 minutes after pneumoperitoneum and placement in Trendelenburg position; T2=after carbon dioxide desufflation and placement supine position; PaO_2=partial pressure of oxygen in arterial blood; $PaCO_2$=partial pressure of carbon dioxide in arterial blood; $PETCO_2$=end-tidal carbon dioxide; MAP=mean arterial pressure

* $p<0.05$ compared with T0, † $p<0.05$ compared with T1

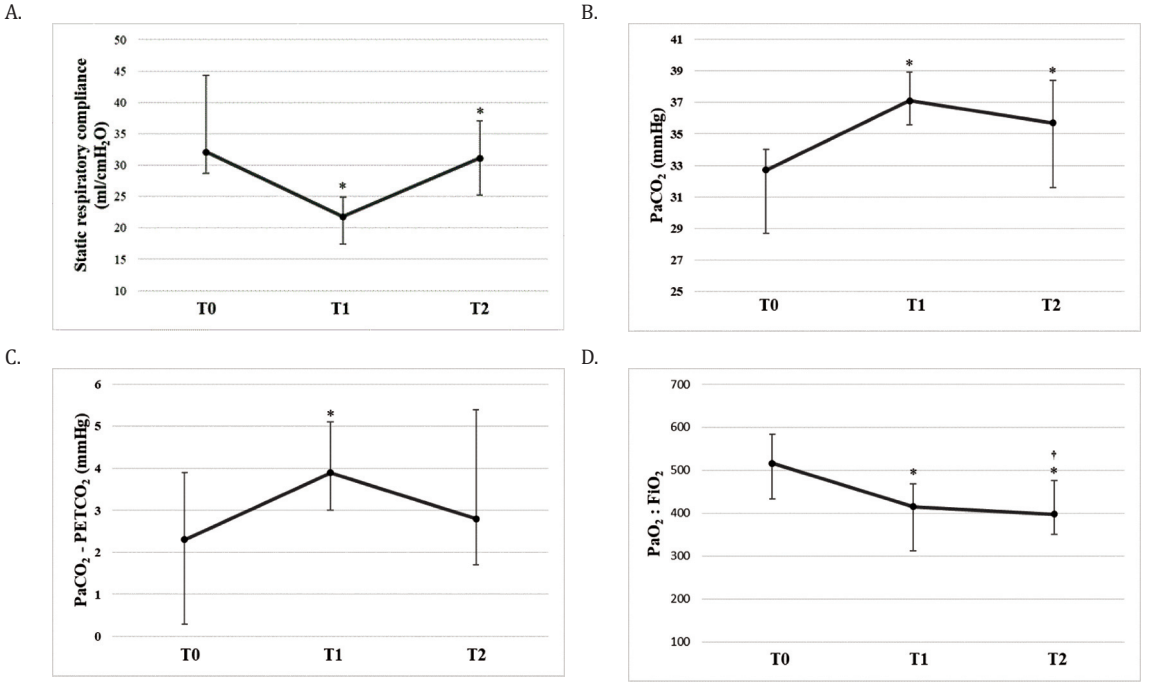

Figure 1. (A) Static respiratory compliance, (B) partial pressure of carbon dioxide ($PaCO_2$), (C) arterial to end-tidal carbon dioxide pressure gradient ($PaCO_2$-$PETCO_2$), (D) ratio of partial pressure of arterial oxygen to fraction of inspired oxygen (PaO_2/FiO_2) after induction of anesthesia (T0), 45 minutes after pneumoperitoneum and placement in the Trendelenburg position (T1), and after carbon dioxide desufflation and placement in the supine position (T2).

* $p<0.05$ compared with T0, † $p<0.05$ compared with T1

from T0 to T1 (p=0.02) (Figure 1C, Table 2). At T2, $PaCO_2$-$PETCO_2$ returned to 2.8 (1.7 to 5.4) mmHg, which was not significantly different from baseline at T0 (p=0.24). However, the correlation between $ETCO_2$ and $PaCO_2$ was still acceptable at T0 (r=0.51, p=0.02), T1 (r=0.48, p=0.03), and T2 (r=0.53, p=0.01). During pneumoperitoneum, the minute ventilation increased from 6.2±0.8 to 7.0±0.8 L/minute (14.4±17.6% increase) (Table 2) to maintain the $ETCO_2$ at 28 to 35 mmHg. There was no evidence of respiratory acidosis at T0, T1, or T2 (Table 2).

At T1, there was a significant correlation between the plateau pressure and $PaCO_2$-$PETCO_2$ (r=0.45, p=0.04). The multiple linear regression analysis was performed with adjustment for age and MAP. These parameters have been previously shown to be associated with increased $PaCO_2$-$PETCO_2$ during pneumoperitoneum[3]. Other known variables associated with increased $PaCO_2$-$PETCO_2$ were excluded because they failed to show a significant relationship with $PaCO_2$-$PETCO_2$ in the present study. This is because the authors planned to study only the effects of respiratory mechanics on $PaCO_2$-$PETCO_2$; thus, the authors controlled many confounders from the beginning of the study. The body mass index (BMI) had a moderate correlation with the plateau pressure (r=0.61, p<0.01). The BMI and abdominal pressure had collinearity with the plateau pressure; therefore, only the plateau pressure was chosen for the regression model. After age and MAP were adjusted in the model, the plateau pressure remained significantly associated with increased $PaCO_2$-$PETCO_2$ during pneumoperitoneum (regression coefficient=0.36, p=0.03) (Table 3). The R^2 was 0.40 and the adjusted R^2 was 0.29. The linear regression model was 2.73+(0.36×plateau pressure during pneumoperitoneum).

There was no significant difference in the hemodynamic variables (heart rate and blood pressure) among T0, T1, and T2 (Table 2). The urine output was greater than 1 ml/kg/hour, indicating adequate tissue perfusion throughout the operative period. However, the body temperature significantly decreased from 36.4±0.3°C at T0 to 36.2±0.4°C at T1, (p=0.03) and to 36.1±0.6°C at T2, (p=0.03) (Table 1). The difference in body temperature was not clinically significant.

Table 3. Multiple linear regression model for prediction of arterial to end-tidal carbon dioxide pressure gradient ($PaCO_2$-$ETCO_2$)

Independent variables	Unstandardized coefficient (B)	95% confidence interval of B	p-value
Constant	2.731	–18.279 to 23.741	0.786
Plateau pressure	0.362	0.024 to 0.700	0.037
Mean arterial pressure	–0.174	–0.388 to 0.040	0.104
Age	0.142	–0.078 to 0.363	0.190

PaO_2=partial pressure of oxygen in arterial blood; $ETCO_2$=end-tidal carbon dioxide

The FiO_2 was kept constant at 0.5, the ratio of the partial pressure of oxygen in arterial blood to the fraction of inspired oxygen (PaO_2/FiO_2 ratio) decreased significantly from T0 to T1 and from T0 to T2 (Figure 1D, Table 2). The oxygenation was lower than baseline at T2. However, when the authors divided the decline in PaO_2/FiO_2 into a small decline group (decrease in PaO_2/FiO_2 by less than 100 from T0 to T2, n = 10) and large decline group (decrease in PaO_2/FiO_2 by more than 100 from T0 to T2, n = 10), there was no significant difference in the hospital length of stay (74.2 versus 79.9 hour in the small versus large decline group, respectively; p=0.17). Only one patient in the large decline group required oxygen therapy.

Discussion

The $ETCO_2$ is a standard perioperative monitoring parameter, especially during laparoscopic surgery, for which CO_2 insufflation is required to assist with surgical field visualization. In normal circumstances, the $ETCO_2$ is 2 to 5 mmHg lower than the $PaCO_2$, and anesthesiologist use this information to guide the ventilator settings in the perioperative period. However, hypoventilation occurs with the decrease in respiratory compliance caused by pneumoperitoneum and the Trendelenburg position. Thus, the amount of dead space is increased. Anesthesiologists normally increase ventilation to compensate for these changes according to the $ETCO_2$ value. However, the authors found that in some cases, the $PaCO_2$-$PETCO_2$ did not follow the general rule. $PaCO_2$-$PETCO_2$ was not constant and was sometimes unpredictably high as a result of low cardiac output or ventilation perfusion mismatch. A few studies have shown that $PaCO_2$-$PETCO_2$ increases during pneumoperitoneum to different degrees depending on the patients' age and type of operation[3,10,11]. In the present study, $PaCO_2$-$PETCO_2$ showed a 1.6 mmHg difference from baseline, and the increase was not permanent. The $PaCO_2$-$PETCO_2$ after induction of anesthesia at T0 and after CO_2 desufflation at T2 were not significantly different. Because the authors maintained normal hemodynamics during pneumoperitoneum, this can support the hypothesis that the increase in $PaCO_2$-$PETCO_2$ was solely from the increased dead space. The minute ventilation increased by 14.4% to maintain a normal $ETCO_2$. No respiratory acidosis occurred in the present patients when using $ETCO_2$ to adjust the ventilator settings. The correlation between $ETCO_2$ and $PaCO_2$ was acceptable at every time point. Therefore, although the $PaCO_2$-$PETCO_2$ increased, the $ETCO_2$ was still useful during pneumoperitoneum and the Trendelenburg position. The increase in $PaCO_2$-$PETCO_2$ was statistically significant but not clinically significant. The abdominal pressure in the present study was 13.3±1.9 mmHg and the angle of the operative table was 30°, which are close to the standard recommendation to minimize complications during laparoscopic surgery[12,13]. Therefore, the acceptable $PaCO_2$-$PETCO_2$ during pneumoperitoneum in the present study might only be able to be applied to healthy adults with similar perioperative conditions. Tomescu et al[8] reported that in patients with a BMI greater than 30 kg/m² who underwent robotic-assisted surgery for general surgery and liver transplantation, $PaCO_2$-$PETCO_2$ increased from 4.1 mmHg at baseline to 6.7 mmHg after induction of pneumoperitoneum and to 9.7 mmHg at the end of surgery. These findings support the authors assumption that the degree of increase in $PaCO_2$-$PETCO_2$ differed depending on the patient characteristics. Therefore, the authors also analyzed the prediction of the $PaCO_2$-$PETCO_2$ from the independent variables and found that the plateau pressure during pneumoperitoneum could be useful to predict $PaCO_2$-$PETCO_2$ with an R^2 of 0.402.

The increased dead space during pneumoperitoneum was only temporary during the perioperative period, but the oxygenation disturbance seemed to last longer. The PaO_2/FiO_2 ratio significantly declined from T0 to T1 and T1 to T2. Increased shunting is considered to be caused by atelectasis. Strang et al[14] demonstrated that atelectasis occurred during CO_2 pneumoperitoneum on a computed tomography

scan in 15 anesthetized pigs. The PaO_2/FiO_2 ratio did not return to the baseline level at T2; thus, the atelectasis probably did not resolve until the end of anesthesia. The decreased respiratory compliance was caused by decrease lung and chest wall compliance due to pneumoperitoneum and the Trendelenburg position. The present patients' respiratory compliance decreased from T0 to T1 and increased from T1 to T2. At T2, the respiratory compliance was slightly lower than baseline. This indicates that the major cause of the decreased respiratory compliance was mechanical compression of the diaphragm from pneumoperitoneum and the Trendelenburg position. It is possible that the persistent decrease in respiratory compliance could be explained by the residual atelectasis at T2 or just before the end of anesthesia.

Nevertheless, the persistent decrease in oxygenation and respiratory compliance in the present study should be of no clinical concern because the PaO_2/FiO_2 ratio was still greater than 300 mmHg at T2. The decrease in oxygenation in the present study did not result in postoperative pulmonary complications or a significantly delayed hospital stay. This might be explained by the fact that the patients in the present study were mostly healthy. The authors recommend observation of the impact of pneumoperitoneum and the Trendelenburg position in patients at high risk for postoperative pulmonary complications (e.g., patients with low preoperative arterial oxygen saturation, acute respiratory infection during the previous month, older age, preoperative anemia, upper abdominal or intrathoracic surgery, a surgical duration of two hours or longer, and emergency surgery)[15]. The reduction of PaO_2/FiO_2 in the present study was 18.9% (5.3% to 36.3%) from T0 to T2. Thus, these decrease in oxygenation could be aware in patients with preoperative low oxygenation or at high risk for pulmonary complications.

In addition to the present primary research question, the study raises concern about the necessity of perioperative PEEP titration or lung recruitment maneuvers at the end of laparoscopic surgery. Maracajá-Neto et al[16] demonstrated that the application of 10 cmH_2O of PEEP during laparoscopic cholecystectomy was associated with improvement in respiratory system resistance and compliance during pneumoperitoneum. Karsten et al[17] used electrical impedance tomography to identify the ventilation distribution in the PEEP versus zero-PEEP (i.e., ZEEP) group and found that patients with a PEEP of 10 cmH_2O had a greater ventilation distribution than patients in the ZEEP group during pneumoperitoneum. Furthermore, Futier et al[18] illustrated that the application of 10 cmH_2O of PEEP with a recruitment maneuver (continuous positive airway pressure of 40 cmH_2O/40 second) could decrease $PaCO_2$-$PETCO_2$, indicating a decrease in dead space and an increase in the end-expiratory lung volume and oxygenation in both patients with obesity and those with a healthy weight. After the recruitment maneuver, the end-expiratory lung volume increased more in patients with obesity than in those with a healthy weight (20% versus 10%, respectively; p=0.02). In the present study, the authors generally used a PEEP of 5 cmH_2O for all patients as the physiologic PEEP, and found that decreases in lung mechanics and oxygenation still occurred in the present patients despite the fact that they were considered healthy.

Therefore, the present study emphasizes the disadvantages of pneumoperitoneum on respiratory mechanics that contribute to impaired oxygenation and ventilation. The authors recommend the use of a higher than physiologic PEEP and lung recruitment maneuver during the perioperative care of patients undergoing laparoscopic surgery. Future studies should focus on patients at high risk for postoperative pulmonary complications or obese patients.

Conclusion

Despite the decrease in respiratory compliance during pneumoperitoneum and the Trendelenburg position, $ETCO_2$ was still useful with an acceptable range of increased $PaCO_2$-$PETCO_2$. The plateau pressure during pneumoperitoneum is able to predict the degree of increased $PaCO_2$-$PETCO_2$.

What is already known on this topic?

End tidal CO_2 monitoring is useful during perioperative period. However, the reliability is decreased during increased dead space or ventilation perfusion mismatch. Pneumoperitoneum for laparoscopic surgery, especially in Trendelenburg position, can increase dead space ventilation from decreased respiratory or chest wall compliance and increase shunt from atelectasis. Therefore, $PaCO_2$-$PETCO_2$ is unpredictable. Evidence has shown that $PaCO_2$-$PETCO_2$ is higher during pneumoperitoneum.

What this study adds?

There was a slight increase in $PaCO_2$-$PETCO_2$, even in the low respiratory compliance. Therefore, $ETCO_2$ is still useful in this condition with the acceptable correlation with $PaCO_2$. The degrees of increased $PaCO_2$-$PETCO_2$ can be predicted by the

increase in plateau pressure during operation.

The decrease in oxygenation at the end of laparoscopic surgery and Trendelenburg position emphasize the importance of PEEP titration and lung recruitment in these patient groups.

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Conflicts of interest

The authors declare no conflict of interest.

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