Original Article

Comparison of arterial to end-tidal carbon dioxide gradient P (a-ET)CO_2 in volume versus pressure controlled ventilation in patients undergoing robotic abdominal surgery in the Trendelenburg position. A randomised controlled study

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ABSTRACT

Background and Aims: Robotic surgery is increasingly prevalent as an advancement in care. Steep head-down positions in pelvic surgery can increase the ventilation-perfusion mismatch and increase ventilatory requirements to offset carbon dioxide (CO_2) increases consequent to pneumoperitoneum. The primary objective was to assess the impact of two ventilatory strategies, volume versus pressure-controlled ventilation on the arterial to end-tidal carbon dioxide gradient P (a-ET)CO_2 in patients undergoing robotic surgery in the Trendelenburg position. The effects on alveolar to arterial oxygen gradient P (A-a)O_2, peak airway pressure (P_{aw}), dynamic compliance (C_{dyn}) and haemodynamics were also assessed. **Methods:** Fifty-one patients, 18-75 y, American Society of Anesthesiologists I-III undergoing robotic surgery in Trendelenburg position were randomised to volume-controlled ventilation (Group VCV) or pressure-controlled ventilation (Group PCV). The P (a-ET)CO_2 was measured at baseline T0, 10 min after Trendelenburg position T1, 2 h of surgery T2, 4 h T3 and at T_e, 10 min after deflation. The P (A-a) O_2, P_{aw}, C_{dyn}, heart rate and blood pressure were also measured at the same time. **Results:** The P (a-ET)CO_2 at T1, T2, T3 and at T_e was lower in Group PCV versus Group VCV. The P_{aw} was lower at T1, T2, and T3 and C_{dyn} higher at T3 and Te in Group PCV at comparable minute ventilation. Haemodynamics and P (A-a) O_2 were comparable between the groups. **Conclusion:** Pressure-controlled ventilation reduces P (a-ET)CO_2 gradient, P_{aw} and improves C_{dyn} but does not affect P (A-a) O_2 or haemodynamics in comparison to volume-controlled ventilation in robotic surgeries in the Trendelenburg position.

Key words: Carbon-dioxide, head down tilt, robotic surgical procedures

INTRODUCTION

Robotic-assisted laparoscopic surgery is increasingly replacing laparoscopic surgery and is the standard of care for prostatic malignancy. Marked changes in respiratory mechanics occur due to the combined effect of Trendelenburg position and pneumoperitoneum. A decrease in functional residual capacity, increase in shunt fraction and changes in alveolar ventilation contribute to variation in the arterial to end-tidal carbon dioxide ($ETCO_2$) gradient, i.e., P (a-ET)CO_2. The effect of pneumoperitoneum is a reduction in functional residual capacity and basal atelectasis with ventilation perfusion mismatch. Concurrently,

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absorption of carbon-dioxide (CO_2) during the creation of pneumoperitoneum increases arterial carbon dioxide ($PaCO_2$).[1,2] The increase in airway pressures and rise in $PaCO_2$ with pneumoperitoneum warrant adjustments to maintain an appropriate $ETCO_2$.

The lack of accuracy of $ETCO_2$ in predicting $PaCO_2$ has been reported in laparoscopic colorectal surgery[3] and amongst the elderly.[4] Pressure-controlled ventilation (PCV) is considered a superior ventilatory mode as its decelerating flow reduces airway pressures in comparison to volume-controlled ventilation (VCV).[5]

The primary objective was to assess the impact of two different ventilatory modes, PCV and VCV on P (a-ET) CO_2 during robotic surgery in the head-down position.

The secondary objectives included comparison of peak airway pressure (P_{aw}), dynamic compliance (C_{dyn}), alveolar to arterial oxygen gradient (P (A-a)O_2) and haemodynamics between the two groups.

METHODS

Following approval from the institutional Ethics Committee and registration with the Clinical Trials Registry of India (CTRI/2019/03/018312), a prospective randomised study was conducted at the gastro-surgery, urology and gynaec-oncology divisions of a tertiary care referral hospital between April 2019 and October 2020.

Patients scheduled for robotic pelvic surgery were screened and consenting patients belonging to American Society of Anesthesiologists physical status I, II and III between the age group of 18-75 years undergoing elective abdominal and pelvic robotic surgery in the Trendelenburg position were included.

Exclusion criteria were body mass index >35, chronic smokers, documented chronic obstructive pulmonary disease, increased pulmonary artery pressures on echocardiography, poor cardiac reserve, asthma or other chronic lung diseases.

All patients were pre-medicated as per institutional protocol with oral alprazolam 0.25 mg, pantoprazole 40 mg and oral metoclopramide 10 mg on the night before and on the morning of surgery as per the policy of the surgical unit.

Patients were shifted to the operating room, and after placement of monitors, an intravenous line and a radial arterial line were inserted under local anaesthesia. The baseline heart rate and blood pressure were recorded and room air arterial blood gas was obtained. All patients received general anaesthesia as per a standardised protocol with intravenous midazolam 0.05 mg/kg, fentanyl 2 μg/kg, propofol titrated to loss of verbal response and intubation with atracurium at 0.5 mg/kg or rocuronium (0.9 mg/kg). Low flow anaesthesia with 1.0 L air oxygen mixture (50% oxygen) and sevoflurane at 0.7-1.0 minimum alveolar concentration was used.

All patients were initially ventilated in the VCV mode with the tidal volume of 7 ml/kg predicted body weight (PBW), inspiratory: expiratory (I: E) ratio1:2, positive end expiratory pressure (PEEP) of 5 cm of H_2O and fractional inspired concentration of oxygen (FiO_2) 0.5. The PBW was calculated by the formula: PBW kg = 50 + 0.91{Height cm − 152.4} in men and 45 + 0.91{Height (cm) − 152.4} in women. The respiratory rate was adjusted to maintain an $ETCO_2$ of 35 − 45 mm Hg using Dräger Perseus^R A 500 workstation with a side-stream capnometer and I: E ratio constant at 1:2. The apparatus dead space between the Y connection of the circle system and the tip of the tracheal tube was negligible. Heat and moisture exchange filters with 42 ml dead space each were used at the point of attachment of the endotracheal tube to the Y connector and at the machine end of the expiratory limb in all patients.

After marking the port sites and the creation of CO_2 pneumoperitoneum patients were placed in Trendelenburg position (30^0) (Smart Tool factory app Angle meter). Intra-abdominal pressure was maintained below 12 mmHg during surgery with da Vinci robotic system.

Patients were randomised into either Group PCV or Group VCV by a computer-generated random number sequence of numbers and concealed allocation ensured by sequentially numbered opaque sealed envelopes. Readings were taken by the anaesthesiologist assigned to the operating room.

In Group PCV, the inspiratory pressure (P_{insp}) cm H_2O was set to deliver a target tidal volume of 7 ml/kg PBW and the respiratory rate adjusted to maintain an $ETCO_2$ between 35 and 45 mmHg. If the $ETCO_2$ rose above 45 mm Hg, the respiratory rate was increased at 2 breaths every 2 minutes to a maximal rate of 25 breaths per minute. Simultaneously, the P_{insp} was increased in increments of 2 cm H_2O until the target

$ETCO_2$ was achieved to maximal airway pressures not exceeding 35 cm H_2O.

In group VCV, tidal volume of 7 ml/kg PBW and respiratory rate adjusted to $ETCO_2$ of 35–45 mm Hg to a maximum rate of 25 breaths per minute was set. If the airway pressures increased above 35 cm H_2O, the tidal volume was reduced in decrements of 1 ml/kg every 2 minutes until the peak pressure was below 35 cm H_2O before increasing the rate further. If peak airway pressure exceeded 35 cm of H_2O and $PaCO_2$ exceeded 50 mm Hg, PEEP was decreased and the intraabdominal insufflation pressure was reduced to allow the $PaCO_2$ to normalise. If $PaCO_2$ continued to rise, then ventilatory mode was changed and the patient was excluded from the study.

A PEEP of 5 cm of H_20 was set in both groups. Haemodynamic management was as per standard protocols and noradrenaline infusion was begun if the mean arterial pressure was <65 mm Hg.

The alveolar dead space fraction (AVDSF) was calculated by the modified Bohr's equation,[6]

$$AVDSF = \frac{PaCO_2 - ETCO_2}{PaCO_2}$$

The C_{dyn} (ml/cm H2O) was obtained from the machine at the defined time points. The partial pressure of oxygen/fractional inspired oxygen concentration (PaO_2/FiO_2-P/F) ratio was obtained from the machine. The heart rate and blood pressure were noted from the arterial pressure readings at the set time points.

The rest of the anaesthetic management was as per standard protocols with air, oxygen, and sevoflurane. Ringer's lactate was the fluid of choice and restrictive fluid strategy of 2 ml/kg/h was practised. Plasmalyte was added if measured lactate was ≥2 mmol/L. At the end of surgery, neuromuscular blockade was reversed and the trachea was extubated and all patients were shifted to the intensive care unit for postoperative care.

Blood gases were sampled at defined time points during surgery**T0**: Baseline after intubation, **T1:** 10 minutes after the creation of pneumoperitoneum in Trendelenburg position, **T2:** 2 hours into the surgery, **T3:** 4 h of surgery and **Te**: 10 minutes after deflation of the pneumoperitoneum. The P_{aw}, C_{dyn}, P (a-ET)CO_2 gradient and P (A-a) O_2 were also measured at the same time points.

The sample size was calculated from a pilot study of 20 patients with a comparison of *P* (a-ET) CO_2 gradient between PCV and VCV groups, (5.5 ± 1.0) and (7.4 ± 3.1) mm Hg at time point T2. With a 90% power and 95% confidence interval, the minimum sample size was determined to be 25 per group. To compare the mean difference of numerical variables between groups, an independent sample 't' test was applied. To test the association of all categorical variables between the two groups, the Chi-square with Fisher's exact test was applied. A *P* value of <0.05 was considered statistically significant. Statistical analysis was done using International Business Machines Corporation, Statistical Package for the Social Sciences (IBM SPSS) software 20.0 (SPSS Inc, Chicago, USA).

RESULTS

A total of 51 patients were included for randomisation [Figure 1]. The demographics and duration of surgery were comparable between the groups [Table 1]. There were no drop outs after recruitment in the study. The baseline P (a-ET)CO_2 gradient was comparable between the groups. The mean P (a-ET) CO_2 gradients were significantly lower in group PCV at T1, T2, T3 and at Te when compared with group VCV, whereas the $PaCO_2$ was similar at all time points except at T3 when it was lower in the PCV group [Table 2]. The AVDSF was similar at baseline, T1, T2 but was higher in the VCV at 4 h into surgery and at 10 minutes after deflation [Table 2].

The C_{dyn} was higher in the PCV group at T3 and Te, whereas the P_{aw} was significantly lower at T1, T2 and T3 in comparison to the VCV group. The (A-a) DO_2 was comparable between both groups but the P/F ratio was higher in the VCV group at T1 [Table 3]. The minute ventilation in groups VCV and PCV at T0 (5.9 ± 0.9 versus 6.0 ± 0.9), T1 (6.1 ± 1.1 versus 6.4 ± 1.2), T2 (7.0 ± 1.1 versus 7.1 ± 0.9), T3 (7.3 ± 1.1 versus 7.2 ± 1.1) and Te (7.1 ± 1.5 versus 7.0 ± 1.5) was comparable, *P* > 0.05. The heart rate

Table 1: Demographics and duration of surgery

	VCV (*n*=25) Mean±SD	PCV (*n*=26) Mean±SD	*P*
Age (years)	64±8.9	60.8±10.7	0.399
Height (cm)	163.0±2.1	165.0±1.6	0.505
Weight (kg)	67.7±2.4	69.2±1.6	0.608
BMI (kg/m^2)	28.54±1.9	27.7±0.6	0.691
PBW (kg)	59.3±1.9	62.1±1.5	0.133
Duration (min)	233.0±65.8	255.0±65.1	0.221

VCV: Volume controlled ventilation; PCV: Pressure controlled ventilation; SD: Standard deviation; BMI: Body mass index; PBW: Predicted body weight

Table 2: $PaCO_2$, *P* (a-ET) CO_2 and AVDSF between Groups VCV and Group PCV

Time	$PaCO_2$ mm Hg		*P*	P (a-ET) CO_2 mm Hg		*P*	AVDSF		*P*
	Group VCV Mean±SD	Group PCV Mean±SD		Group VCV Mean±SD	Group PCV Mean±SD		Group VCV Mean±SD	Group PCV Mean±SD	
T0	39.3±2.9	39.0±2.8	0.667	5.8±3.2	5.0±2.3	0.341	0.14±0.08	0.14±0.08	0.986
T1	43.9±3.1	42.2±3.6	0.079	7.7±3.0	5.0±2.6	0.002	0.16±0.09	0.13±0.06	0.108
T2	45.4±3.6	44.0±3.8	0.194	8.5±3.5	6.6±2.2	0.043	0.19±0.09	0.16±0.06	0.195
T3	47.2±2.3	43.8±2.7	0.004	9.5±3.3	6.2±1.7	0.005	0.21±0.07	0.15±0.04	0.029
Te	45.1±3.4	43.4±3.3	0.087	8.7±3.5	5.8±1.7	0.002	0.2.±0.10	0.14±0.07	0.018

$PaCO_2$: Arterial carbon-dioxide; P (a-ET)CO_2: Arterial to end-tidal carbon-dioxide. AVDSF: Alveolar dead space fraction; SD: Standard deviation

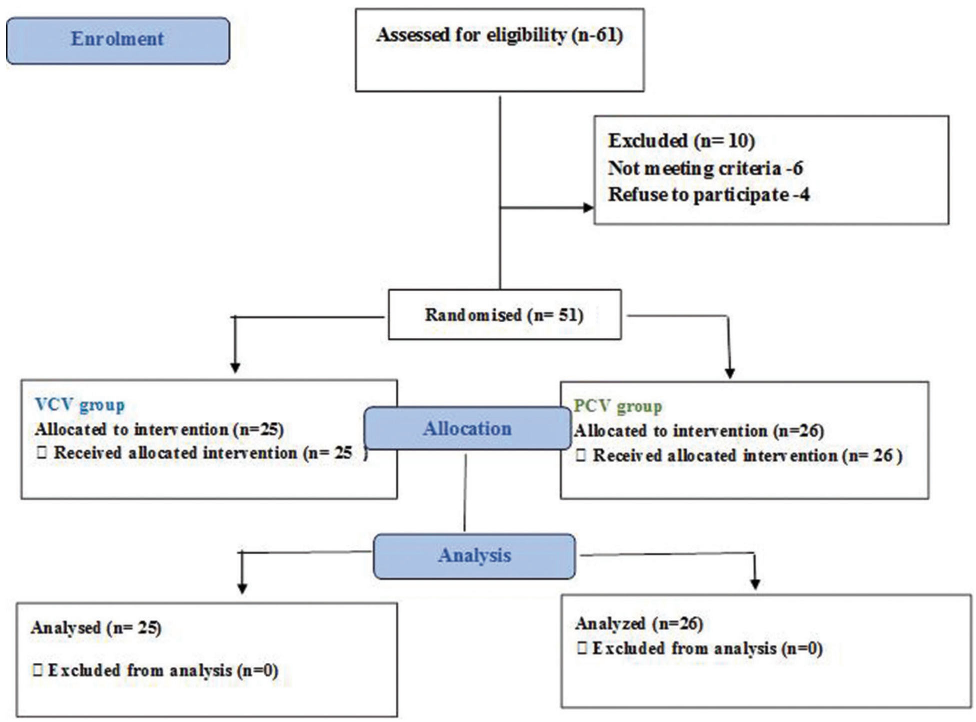

Figure 1: Consolidated standards of reporting trials (CONSORT) diagram

and blood pressure were also comparable between the groups [Figures 2 and 3].

DISCUSSION

Safety of using end-tidal CO_2 as a surrogate of arterial CO_2 and impact of ventilatory modes on the P (a-ET) CO_2 was compared in patients undergoing robotic surgeries in the Trendelenburg position. The P (a-ET) CO_2 gradient was significantly lower in the PCV group throughout the study even while the minute ventilation between both the groups was comparable. The AVDSF showed an increase at 4 hours after pneumoperitoneum and at 10 minutes after the release of pneumoperitoneum in the VCV group suggesting that PCV may reduce the dead space and improve ventilation. The P_{aw} was also lower in the PCV group for the duration of the laparoscopy and C_{dyn} improved at 4 hours and after deflation in the PCV group, highlighting that PCV could be a superior mode in this surgical group.

Laparoscopic surgery in the Trendelenberg position causes changes in respiratory mechanics during surgery. The primary objective of the study was to compare the relationship between P (a-ET) CO_2 between two ventilatory modes and ventilatory changes were made to ensure standardisation in management. The P (a-ET) CO_2 was higher in the VCV group for the same target of $ETCO_2$ with adjusted ventilation. The $PaCO_2$ during laparoscopic surgery is an end measure of minute ventilation and the corresponding $ETCO_2$ represents phase III of the capnograph.[7] In children, a negative gradient can occur at particular times such as deflation of pneumoperitoneum following laparoscopic surgery when excessive alveolar ventilation ensues with the sudden increase in lung compliance.

Table 3: Respiratory variables between Group VCV versus Group PCV

C_{dyn} ml/cm H_2O				(A-a) DO_2 mm Hg			*P*
Time	Group VCV Mean±SD	Group PCV Mean±SD	*P*	Time	Group VCV Mean±SD	Group PCV Mean±SD	
T0	36.4±14.0	34.2±9.9	0.503	T0	111.8±25.6	111.0±21.8	0.903
T1	21.5±6.4	20.3±5.3	0.467	T1	149.6±35.9	167±33.0	0.068
T2	18.4±4.9	17.1±2.7	0.395	T2	165.9±29.7	174.6±22.1	0.259
T3	16.6±4.6	22.7±5.9	0.011	T3	166.9±35.0	169.3±29.0	0.862
Te	30.1±5.5	35.4±7.01	0.005	Te	159.3±30.0	162.7±28.5	0.677
P_{aw} cmH_2O				P/F ratio			
Time	Group VCV Mean±SD	Group PCV Mean±SD	*P*	Time	Group VCV Mean±SD	Group PCV Mean±SD	*P*
T0	16.4±2.1	18.1±4.3	0.068	T0	399.7±39.0	393.7±44.0	0.614
T1	28.1±3.7	26.0±3.4	0.043	T1	348.1±36.0	279.7±74.3	0.001
T2	30.4±3.2	26.1±4.1	<0.001	T2	269.5±53.0	250.3±47.8	0.200
T3	30.5±2.8	26.1±2.8	0.001	T3	262.4±63.2	262.9±59.0	0.982
Te	19.3±2.8	18.9±2.7	0.607	Te	290.7±59.5	276.7±50.9	0.369

C_{dyn}: Dynamic compliance. (A-a) DO_2: Alveolar to arterial oxygen gradient. P_{aw}: Peak airway pressure. P/F: PaO_2/FiO_2 SD: Standard deviation

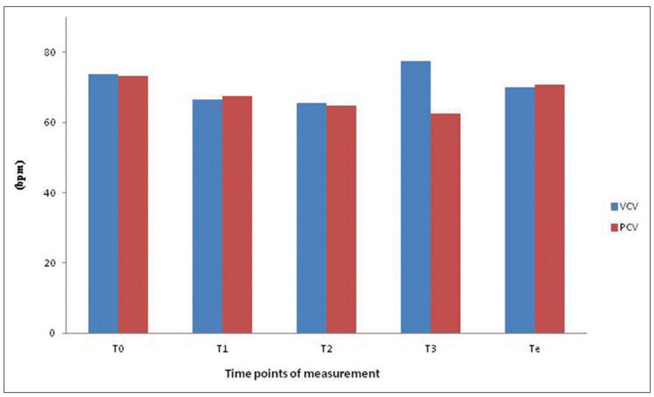

Figure 2: Heart rate between PCV and VCV groups

Although the impact of PCV versus VCV on other respiratory variables has been extensively studied,[8,9] little is known of the impact on alveolar ventilation and thereby P (a-ET)CO_2. PCV is a time-cycled mode with decelerating flow and a square wave pattern of ventilation that can provide effective alveolar ventilation which explain our findings.

Increasing age has been shown to increase the P (a-ET)CO_2 in the supine position but in our study, the groups were comparable in age.[10] In a study of respiratory variables in robotic prostatectomy, PCV showed a decrease in P (a-ET) CO2 gradient in comparison to the VCV group after pneumoperitoneum.[11] A study in laparoscopic colonic surgery[3] concluded that there was no reliable correlation between P (a-ET) CO_2 amongst forty patients using uniform ventilatory strategies. This is contrary to a study comparing the P (a-ET)CO_2 in laparoscopic nephrectomy where the authors could establish a trend between end-tidal CO_2 and $PaCO_2$.[12]

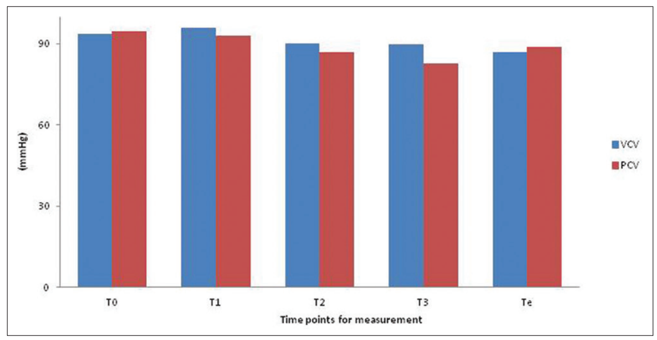

Figure 3: Blood pressure between groups PCV and VCV

The study amongst colorectal patients[3] suggested that the differences could increase with a duration of laparoscopy beyond 250 minutes but confounding influences of hypoxic pulmonary vasoconstrictive responses to inhalational agents and alterations of dead space to tidal volume ratios could affect the relationship.

Several studies have shown that PCV improved lung compliance and oxygenation in comparison to VCV.[13-18] An additional finding in the colorectal study was an increase in the inflammatory markers sRAGE and S100A12 leading to a higher incidence of postoperative complications.[18] We did not follow the outcomes of the patients in the intensive care unit and this may have led to more insights into the impact of ventilatory strategies.

Studies show that the haemodynamic and pulmonary parameters remained within normal limits during the surgery indicating that the Trendelenburg position and CO_2 pneumoperitoneum are well tolerated.[14,17] Haemodynamic changes that occur with pneumoperitoneum include an increase in systemic vascular resistance, a decrease in cardiac output and an increase in pulmonary artery pressures and wedge pressures.[19] As patients with compromised cardiac status were not included, we did not encounter cardiovascular instability in our study group. Our observations with haemodynamic parameters showed comparable changes between the two groups. An evaluation of respiratory variables and supportive haemodynamic monitoring on transitioning from VCV to PCV during urologic laparoscopy showed that PCV improved inspiratory flow, dynamic compliance and reduced airway pressures without affecting cardiac function.[20]

Although few have reported facial puffiness at the end of surgery, Trendelenburg position has been tolerated even in obese patients undergoing robotic gynaecological surgery without any overt evidence of increased intracranial pressure.[21] Restrictive fluid strategies are shown to be safe and do not affect lactates or renal function in colorectal surgery.[22] The role of the endothelial glycocalyx in maintaining vascular integrity has been increasingly recognised and conservative fluids help in its preservation.[23] We did not encounter facial puffiness perhaps with a combination of minimal head down, exclusion of obese patients, use of restrictive fluids, management of peak airway and intra-abdominal pressures.

Most studies evaluating PCV versus VCV during surgery have documented improved oxygenation in the PCV group.[24] PCV has a decelerating flow that opens the alveoli early during inspiration and minimises the pressure difference between the conducting airway and alveoli. The subsequent decelerating flow maintains the alveoli open, preventing their collapse. Nevertheless, the PCV group in our study did not have an improvement in P/F ratio which was higher at T1 in the VCV group.

Our results suggest that the use of PCV amongst patients undergoing laparoscopic robotic surgery in the Trendelenburg position can provide better alveolar ventilation, more accurate representation of $PaCO_2$, improved C_{dyn} and P_{aw} with its decelerating flow and square pattern. The reduction in AVDSF could perhaps contribute to the reduced P (a-ET) CO_2. There were no haemodynamic differences between the ventilatory modes and the Trendelenburg position was well tolerated in both modes.

There were limitations in our study. The readings for comparison were taken at specified time points. Variations in P_{aw} and intra-abdominal pressures with surgical movements could have occurred at some measurement points. The plateau pressure was not included during measurement and only the peak airway pressure between the modes was compared. Baseline differences in pulmonary function amongst the elderly could have introduced some differences in our readings. Due to constraints in surgical numbers during the pandemic, we included all robotic surgeries in Trendelenburg including gynaecological, urological and gastro intestinal surgery to obtain adequate sample size. This resulted in heterogeneity amongst surgical types. Variations in pulmonary blood flow and use of PEEP could have affected the alveolar dead space. For the safety of patients, the methodology involved an adjustment of ventilation to maintain the $ETCO_2$ in the desired range during this surgery. This may have contributed to variations in the P (a-ET) CO_2 during measurement.

A prospective study comparing a dual ventilatory mode versus VCV in a homogenous surgical group and cross over from one mode to the other in the same patient may provide insights into ventilatory changes in robotic surgery.

CONCLUSION

PCV reduces P (a-ET)CO_2 gradient throughout surgery, reduces the P_{aw} and improves C_{dyn} but does not affect P (A-a)O_2 or haemodynamics in comparison to VCV in laparoscopic assisted robotic surgery in the Trendelenburg position.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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