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Impact of Ventilatory Mode on Airway Pressures and Hemodynamic Stability During Robotic Pelvic Surgery in Steep Trendelenburg Position.

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Abstract

Background: Robotic pelvic surgeries require prolonged pneumoperitoneum and steep Trendelenburg positioning, which significantly affect respiratory mechanics and cardiovascular physiology. Selection of an optimal ventilatory strategy is crucial to minimize airway pressure elevation and maintain hemodynamic stability. This study aimed to compare pressure-controlled ventilation and volume-controlled ventilation in patients undergoing robotic pelvic surgery. ***Aim:*** To evaluate the impact of ventilatory mode on airway pressures and hemodynamic stability during robotic pelvic surgery in steep Trendelenburg position. ***Materials and Methods:*** This prospective comparative study included 88 patients undergoing elective robotic pelvic surgery, randomly allocated into two groups: PCV (n=44) and VCV (n=44). Standardized general anesthesia was administered to all patients. Respiratory parameters including peak airway pressure, mean airway pressure, and dynamic lung compliance, along with hemodynamic variables such as heart rate and blood pressure, were recorded during pneumoperitoneum in Trendelenburg position. Oxygenation and ventilation parameters were also assessed. Statistical analysis was performed using independent t-test and Chi-square test, with $p < 0.05$ considered statistically significant. ***Results:*** The PCV group demonstrated significantly lower peak airway pressure and mean airway pressure along with higher dynamic lung compliance compared to the VCV group ($p < 0.001$). Hemodynamic parameters including heart rate, systolic blood pressure, and mean arterial pressure were comparable between the groups, while diastolic blood pressure stability was better in the PCV group ($p < 0.001$). Oxygen saturation, end-tidal carbon dioxide, and minute ventilation were maintained within normal ranges in both groups. ***Conclusion:*** Pressure-controlled ventilation provides superior respiratory mechanics with comparable hemodynamic stability and oxygenation when compared to volume-controlled ventilation during robotic pelvic surgery in steep Trendelenburg position. PCV may therefore be considered a preferable ventilation strategy for optimizing intraoperative respiratory management in robotic pelvic procedures.

Keywords: Pressure-Controlled Ventilation. Robotic Pelvic Surgery. Trendelenburg Position.

INTRODUCTION

The advent of minimally invasive and robot-assisted surgical techniques has revolutionized pelvic surgeries by offering superior precision, enhanced dexterity, and improved visualization for surgeons. However, these advantages are accompanied by unique anesthetic challenges, particularly related to respiratory mechanics and cardiovascular stability. Robotic pelvic surgeries typically require prolonged pneumoperitoneum combined with steep Trendelenburg positioning, often up to 45°, which significantly alters pulmonary physiology and hemodynamics. The increased intra-abdominal pressure and cephalad displacement of the diaphragm reduce functional residual capacity, lung compliance, and increase airway pressures, while also affecting venous return and cardiac output. These physiological perturbations necessitate careful selection of ventilation strategies to ensure adequate oxygenation, ventilation, and hemodynamic stability.[1]

Volume-controlled ventilation (VCV) has traditionally been the most commonly used mode of mechanical ventilation in general anesthesia. It ensures delivery of a preset tidal volume irrespective of changes in lung compliance or airway resistance. However, during robotic pelvic procedures, the decreased pulmonary compliance caused by pneumoperitoneum and Trendelenburg positioning often leads to elevated peak airway pressures in VCV mode, thereby increasing the risk of barotrauma and ventilator-induced lung injury.[2]

Pressure-controlled ventilation (PCV), on the other hand, delivers breaths with a preset inspiratory pressure and a decelerating flow pattern. This mode limits peak airway pressure and may improve alveolar recruitment while providing better distribution of ventilation. Several studies have demonstrated that PCV is associated with lower peak airway pressures and improved dynamic lung compliance compared to VCV during laparoscopic and robotic surgeries. Additionally, limiting airway pressure may reduce intrathoracic pressure, improve venous return, and contribute to better cardiovascular stability during prolonged procedures.[3]

Despite these theoretical advantages, the superiority of PCV over VCV in robotic pelvic surgeries remains controversial. While some trials report improved respiratory mechanics with PCV, others have found no significant differences in oxygenation or overall clinical outcomes. Moreover, variations in surgical duration, degree of Trendelenburg tilt, pneumoperitoneum pressure, and patient characteristics further complicate interpretation of existing evidence.[4]

AIM

To compare the impact of pressure-controlled ventilation and volume-controlled ventilation on airway pressures and hemodynamic stability during robotic pelvic surgery in steep Trendelenburg position.

OBJECTIVES

1. To compare peak airway pressures and dynamic lung compliance between PCV and VCV modes.
2. To evaluate intraoperative hemodynamic parameters including heart rate and blood pressure in both ventilation modes.
3. To assess oxygenation and ventilation parameters during pneumoperitoneum and Trendelenburg positioning.

MATERIALS AND METHODS

Source of Data

Data were collected from patients undergoing elective robotic-assisted pelvic surgeries under general anesthesia in the Department of Anaesthesiology at a tertiary care teaching hospital.

Study Design

This study was conducted as a prospective, randomized, comparative observational study.

Study Location

The study was carried out in the operation theatres of a tertiary care center equipped with robotic surgical facilities.

Study Duration

The study was conducted over a period of 24 months.

Sample Size

A total of 88 patients were included in the study. Patients were equally divided into two groups:

- Pressure-Controlled Ventilation Group (PCV): 44 patients
- Volume-Controlled Ventilation Group (VCV): 44 patients

Inclusion Criteria

- Patients aged between 20 and 70 years
- American Society of Anesthesiologists (ASA) physical status I and II
- Patients scheduled for elective robotic pelvic surgery under general anesthesia
- Patients who provided written informed consent

Exclusion Criteria

- Patients refusing participation
- ASA physical status III and IV
- Patients with chronic obstructive pulmonary disease, bronchial asthma, restrictive lung disease, or significant

cardiopulmonary disease

- Morbid obesity and difficult airway cases

Procedure and Methodology

Institutional ethical committee approval was obtained prior to initiation of the study. Eligible patients were randomly allocated into PCV and VCV groups using computer-generated random numbers. Standard preoperative fasting and premedication protocols were followed.

After induction of general anesthesia and endotracheal intubation, patients were ventilated according to their allocated group. In the VCV group, tidal volume was set at 8 mL/kg of predicted body weight with an inspiratory to expiratory ratio of 1:2 and positive end-expiratory pressure of 4 cm H_2O. In the PCV group, inspiratory pressure was adjusted to achieve a similar tidal volume while maintaining identical respiratory rate, FiO_2, and I:E ratio.

All patients were positioned in steep Trendelenburg position and pneumoperitoneum was established as per surgical requirement. Hemodynamic and respiratory parameters were recorded at predefined time intervals: after induction, after establishment of pneumoperitoneum and Trendelenburg position, intraoperatively at fixed intervals, and at the end of surgery. At the conclusion of the procedure, neuromuscular blockade was reversed and patients were extubated following standard protocols.

Sample Processing

All physiological parameters were recorded in structured case record forms. Data were cross-verified for completeness and accuracy before statistical analysis.

Statistical Methods

Data were entered into Microsoft Excel and analyzed using SPSS statistical software. Continuous variables were expressed as mean ± standard deviation and categorical variables as percentages. Independent t-test was used for comparison of continuous variables and Chi-square test for categorical data. A p-value less than 0.05 was considered statistically significant.

Data Collection

Demographic variables, respiratory parameters (peak airway pressure, dynamic compliance, tidal volume, end-tidal CO_2, oxygen saturation), and hemodynamic variables (heart rate, systolic and diastolic blood pressure, mean arterial pressure) were systematically recorded at predefined intraoperative time points for analysis.

RESULTS

Table 1: Baseline Demographic and Clinical Characteristics (PCV vs VCV)

Parameter	PCV (n=44) Mean ± SD / n(%)	VCV (n=44) Mean ± SD / n(%)	Mean Difference / χ^2	95% CI	Test of Significance	p-value
Age (years)	57.4 ± 4.4	57.7 ± 4.8	−0.3	−2.1 to 1.5	Independent t-test	0.50
BMI (kg/m²)	22.8 ± 4.0	23.0 ± 4.6	−0.2	−1.9 to 1.4	Independent t-test	0.21
Male gender	19 (43.2%)	25 (56.8%)	1.60	—	Chi-square test	0.20
Female gender	25 (56.8%)	19 (43.2%)	—	—	Chi-square test	—
ASA I	28 (63.6%)	26 (59.1%)	0.18	—	Chi-square test	0.67
ASA II	16 (36.4%)	18 (40.9%)	—	—	Chi-square test	—

Table 1 presents the baseline demographic and clinical characteristics of patients in the PCV and VCV groups. The mean age was comparable between the two groups (57.4 ± 4.4 years in PCV versus 57.7 ± 4.8 years in VCV), with no statistically significant difference (p = 0.50). Similarly, the mean BMI was 22.8 ± 4.0 kg/m² in the PCV group and 23.0 ± 4.6 kg/m² in the VCV group, showing no significant intergroup variation (p = 0.21). Gender distribution was also well matched, with males constituting 43.2% of the PCV group and 56.8% of the VCV group (p = 0.20), while females comprised 56.8% and 43.2% of the PCV and VCV groups respectively. With respect to ASA physical status, the proportion of ASA I patients was 63.6% in the PCV group and 59.1% in the VCV group, whereas ASA II patients accounted for 36.4% and 40.9% respectively, with no statistically significant difference between the groups (p = 0.67).

Table 2: Respiratory Mechanics Comparison During Pneumoperitoneum (T2)

Parameter	PCV (n=44) Mean ± SD	VCV (n=44) Mean ± SD	Mean Difference	95% CI	Test of Significance	p-value
Peak Airway Pressure (cmH_2O)	27.9 ± 1.2	32.0 ± 1.3	−4.1	−4.7 to −3.5	Independent t-test	<0.0001
Dynamic Compliance (mL/cmH_2O)	42.3 ± 4.1	36.8 ± 3.8	5.5	3.9 to 7.1	Independent t-test	<0.0001
Mean Airway Pressure (cmH_2O)	16.8 ± 1.1	18.6 ± 1.3	−1.8	−2.3 to −1.2	Independent t-test	<0.001

Table 2 compares respiratory mechanics between the two ventilation strategies during pneumoperitoneum (T2). The peak airway pressure was significantly lower in the PCV group (27.9 ± 1.2 cmH_2O) compared to the VCV group (32.0 ± 1.3 cmH_2O), with a mean difference of −4.1 cmH_2O (95% CI: −4.7 to −3.5; $p < 0.0001$). Dynamic lung compliance was significantly higher in patients ventilated with PCV (42.3 ± 4.1 mL/cmH_2O) than those receiving VCV (36.8 ± 3.8 mL/cmH_2O), demonstrating a mean improvement of 5.5 mL/cmH_2O (95% CI: 3.9 to 7.1; $p < 0.0001$). In addition, mean airway pressure was significantly lower in the PCV group (16.8 ± 1.1 cmH_2O) compared to the VCV group (18.6 ± 1.3 cmH_2O), with a mean difference of −1.8 cmH_2O (95% CI: −2.3 to −1.2; $p < 0.001$).

Table 3: Hemodynamic Parameters Comparison During Pneumoperitoneum (T2)

Parameter	PCV (n=44) Mean ± SD	VCV (n=44) Mean ± SD	Mean Difference	95% CI	Test of Significance	p-value
Heart Rate (beats/min)	65.2 ± 5.9	64.0 ± 5.7	1.2	−1.4 to 3.8	Independent t-test	0.31
Systolic BP (mmHg)	124.6 ± 8.9	126.6 ± 9.2	−2.0	−5.7 to 1.6	Independent t-test	0.20
Diastolic BP (mmHg)	92.8 ± 1.7	90.5 ± 3.3	2.3	1.3 to 3.4	Independent t-test	<0.001
MAP (mmHg)	103.4 ± 3.5	102.5 ± 3.4	0.9	−0.5 to 2.3	Independent t-test	0.18

Table 3 summarizes the intraoperative hemodynamic parameters during pneumoperitoneum (T2). Heart rate was comparable between the PCV and VCV groups (65.2 ± 5.9 beats/min versus 64.0 ± 5.7 beats/min; $p = 0.31$). Similarly, systolic blood pressure did not differ significantly between groups (124.6 ± 8.9 mmHg in PCV and 126.6 ± 9.2 mmHg in VCV; $p = 0.20$). However, diastolic blood pressure was significantly higher and more stable in the PCV group (92.8 ± 1.7 mmHg) compared to the VCV group (90.5 ± 3.3 mmHg), with a mean difference of 2.3 mmHg (95% CI: 1.3 to 3.4; $p < 0.001$). Mean arterial pressure remained comparable between the two groups (103.4 ± 3.5 mmHg in PCV versus 102.5 ± 3.4 mmHg in VCV; $p = 0.18$).

Table 4: Oxygenation and Ventilation Parameters During Pneumoperitoneum (T2)

Parameter	PCV (n=44) Mean ± SD	VCV (n=44) Mean ± SD	Mean Difference	95% CI	Test of Significance	p-value
SpO_2 (%)	99.02 ± 0.85	98.93 ± 0.87	0.09	−0.21 to 0.39	Independent t-test	0.60
$EtCO_2$ (mmHg)	28.7 ± 2.6	28.3 ± 5.1	0.4	−1.3 to 2.1	Independent t-test	0.59
Respiratory Rate (/min)	16.2 ± 1.5	14.4 ± 1.2	1.8	1.2 to 2.4	Independent t-test	<0.0001
Minute Ventilation (mL/min)	5945 ± 555	6041 ± 537	−96	−321 to 129	Independent t-test	0.40

Table 4 depicts the oxygenation and ventilation parameters during pneumoperitoneum (T2). Peripheral oxygen saturation remained high and comparable in both groups (99.02 ± 0.85% in PCV and 98.93 ± 0.87% in VCV; $p = 0.60$). End-tidal carbon dioxide levels were also similar between the PCV and VCV groups (28.7 ± 2.6 mmHg versus 28.3 ± 5.1 mmHg; $p = 0.59$), indicating adequate ventilation in both modes. The respiratory rate was significantly higher in the PCV group (16.2 ± 1.5 breaths/min) compared to the VCV group (14.4 ± 1.2 breaths/min), with a mean difference of 1.8 breaths/min (95% CI: 1.2 to 2.4; $p < 0.0001$). Despite this difference, minute ventilation was comparable between the groups (5945 ± 555 mL/min in PCV and 6041 ± 537 mL/min in VCV; $p = 0.40$).

DISCUSSION

With regard to baseline demographic and clinical characteristics (Table 1), the absence of statistically significant differences between the PCV and VCV groups in terms of age, BMI, gender distribution, and ASA physical status ensured homogeneity of study populations and minimized confounding bias. Similar baseline comparability has been reported by Tontu F et al. (2025)[5] in robotic prostatectomy cohorts, where both ventilation groups were well matched for demographic and perioperative risk factors. Likewise, Xue S et al. (2024)[6] reported no significant intergroup differences in age and ASA status in patients undergoing laparoscopic gynecological surgeries, supporting the methodological robustness of randomized ventilation mode comparisons.

The respiratory mechanics findings (Table 2) demonstrated significantly lower peak airway pressure and mean airway pressure, along with higher dynamic lung compliance in the PCV group compared to the VCV group during pneumoperitoneum. These results are in strong agreement with the study by Lee JM et al. (2020)[7], who reported a significant reduction in peak inspiratory pressure and improved dynamic compliance with PCV during robotic-assisted laparoscopic prostatectomy. Similarly, Tan HS et al. (2025)[8] in their meta-analysis concluded that PCV was associated with lower peak airway pressures and better respiratory compliance during laparoscopic surgery. The physiological explanation for this benefit is attributed to the decelerating inspiratory flow pattern of PCV, which promotes more uniform alveolar ventilation and reduces airway resistance, particularly under conditions of reduced lung compliance caused by pneumoperitoneum and Trendelenburg positioning. Comparable improvements in lung mechanics with PCV were also described by Tontu F et al. (2025)[5] during laparoscopic cholecystectomy, reinforcing the consistency of these findings across different surgical populations.

In terms of hemodynamic parameters (Table 3), the present study demonstrated comparable heart rate, systolic blood pressure, and mean arterial pressure between PCV and VCV groups, while diastolic blood pressure was significantly more stable in the PCV group. Similar hemodynamic neutrality between ventilation modes has been reported by Xue S et al. (2024)[6], who observed no clinically significant differences in heart rate or mean arterial pressure between PCV and VCV during prolonged laparoscopic surgeries. The slightly improved diastolic stability observed in the PCV group in the present study may be related to lower intrathoracic pressures and reduced impedance to venous return, a mechanism also suggested by Shoaib M et al. (2023)[9], who emphasized the cardiovascular benefits of lung-protective ventilation strategies with controlled airway pressures.

Regarding oxygenation and ventilation parameters (Table 4), both PCV and VCV maintained comparable oxygen saturation and end-tidal carbon dioxide levels, indicating effective gas exchange with both modes. These findings are consistent with those reported by Cortese G et al. (2025)[10], who demonstrated no significant difference in oxygenation indices between PCV and VCV during laparoscopic procedures. However, the higher respiratory rate required in the PCV group to maintain similar minute ventilation observed in the present study has also been reported by Gao L et al. (2025)[11], suggesting that PCV may require compensatory adjustments in ventilatory settings to achieve target carbon dioxide elimination.

CONCLUSION

The present study demonstrates that the choice of ventilatory mode significantly influences intraoperative respiratory mechanics during robotic pelvic surgeries performed in steep Trendelenburg position with pneumoperitoneum. Pressure-controlled ventilation was associated with significantly lower peak and mean airway pressures and superior dynamic lung compliance compared to volume-controlled ventilation, highlighting its mechanical advantage in conditions of reduced pulmonary compliance. These findings suggest that PCV offers better protection against elevated airway pressures and potential ventilator-induced lung injury during prolonged robotic procedures.

Hemodynamic parameters such as heart rate, systolic blood pressure, and mean arterial pressure remained comparable between both ventilation strategies, indicating that neither mode adversely affected overall cardiovascular stability. However, the observed improvement in diastolic blood pressure stability in the PCV group suggests a potential hemodynamic benefit related to reduced intrathoracic pressure and improved venous return. Importantly, oxygenation and ventilation parameters including oxygen saturation, end-tidal carbon dioxide levels, and minute ventilation were maintained within physiological limits in both groups, confirming the safety and adequacy of gas exchange with both ventilatory approaches.

Overall, the findings of this study support the preferential use of pressure-controlled ventilation during robotic pelvic surgeries requiring steep Trendelenburg positioning, as it provides superior respiratory mechanics without compromising hemodynamic stability or oxygenation. Incorporation of PCV into routine anesthetic practice for robotic pelvic procedures may contribute to improved intraoperative safety and optimized perioperative respiratory management.

LIMITATIONS OF THE STUDY

1. The study was conducted at a single tertiary care center, which may limit the generalizability of the results to other institutions and surgical settings.

2. The sample size, although adequate for detecting significant differences in respiratory mechanics, may not have been sufficiently powered to detect rare perioperative respiratory or cardiovascular complications.
3. Only intraoperative parameters were evaluated, and postoperative pulmonary outcomes such as atelectasis, oxygen requirement, and length of hospital stay were not assessed.
4. Advanced respiratory parameters such as arterial blood gas analysis, driving pressure, and lung ultrasound findings were not included, which could have provided additional insight into ventilation efficiency.
5. The study did not evaluate long-term clinical outcomes or patient-centered endpoints such as postoperative respiratory morbidity or quality of recovery.
6. Variations in surgical duration and degree of Trendelenburg tilt among patients may have influenced respiratory and hemodynamic parameters despite standardized anesthetic management.

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