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Original Research Article

PRESSURE-CONTROLLED VERSUS VOLUME-CONTROLLED VENTILATION IN ROBOT-ASSISTED PELVIC SURGERIES: A COMPARATIVE ANALYSIS OF RESPIRATORY MECHANICS AND HEMODYNAMIC EFFECTS

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ABSTRACT

Background: Robot-assisted pelvic surgeries require pneumoperitoneum and steep Trendelenburg positioning, which significantly affect respiratory mechanics and cardiovascular physiology. Selection of an optimal ventilation strategy is crucial to minimize pulmonary complications and maintain hemodynamic stability. Pressure-controlled ventilation and volume-controlled ventilation are commonly used modes; however, their comparative intraoperative effects remain inadequately defined in robotic surgical settings.
Objectives: To compare the effects of pressure-controlled ventilation and volume-controlled ventilation on respiratory mechanics and hemodynamic parameters in patients undergoing robot-assisted pelvic surgeries.
Materials and Methods: This prospective comparative study included 88 adult patients undergoing elective robot-assisted pelvic surgeries, who were randomly allocated into two groups: PCV group (n = 44) and VCV group (n = 44). Standardized anesthetic protocols were followed. Respiratory parameters including peak airway pressure, dynamic compliance, tidal volume, minute ventilation, end-tidal carbon dioxide, and oxygen saturation were recorded during pneumoperitoneum and Trendelenburg positioning. Hemodynamic parameters such as heart rate, systolic blood pressure, diastolic blood pressure, and mean arterial pressure were also evaluated. Safety outcomes including ventilator alarms, intraoperative hypertension episodes, and postoperative pulmonary complications were analyzed. Statistical analysis was performed using appropriate parametric and non-parametric tests.
Results: The PCV group demonstrated significantly lower peak airway pressures and higher dynamic lung compliance compared to the VCV group ($p < 0.001$). Oxygenation and ventilation efficiency remained comparable between the two groups. Hemodynamic parameters were largely similar; however, diastolic blood pressure stability was significantly better in the PCV group ($p < 0.001$). PCV was associated with fewer airway pressure alarms, reduced need for ventilator adjustments, and a lower incidence of intraoperative hypertension

episodes ($p < 0.05$). Postoperative pulmonary complications were numerically lower in the PCV group, though not statistically significant.
Conclusion: Pressure-controlled ventilation provides superior respiratory mechanics and improved intraoperative safety compared to volume-controlled ventilation in robot-assisted pelvic surgeries, while maintaining stable hemodynamics and effective gas exchange. PCV may be considered the preferred ventilation strategy in robotic surgical procedures requiring pneumoperitoneum and steep Trendelenburg positioning.
Keywords: Pressure-controlled ventilation. Volume-controlled ventilation. Robot-assisted pelvic surgery.

INTRODUCTION

Robot-assisted pelvic surgeries have emerged as a cornerstone of minimally invasive surgical practice, offering enhanced dexterity, three-dimensional visualization, and superior precision compared to conventional laparoscopic approaches. However, these technological advancements impose unique anaesthetic challenges, particularly related to respiratory and hemodynamic management. Such procedures often require prolonged steep Trendelenburg positioning combined with carbon dioxide pneumoperitoneum, which significantly alters respiratory mechanics and cardiovascular physiology. Increased intra-abdominal pressure leads to cephalad displacement of the diaphragm, reduction in functional residual capacity, decreased lung compliance, increased airway resistance, and elevated peak airway pressures. Simultaneously, venous return and cardiac preload may be affected due to increased intrathoracic pressure and altered venous capacitance, predisposing patients to hemodynamic instability.[1]

Volume-controlled ventilation (VCV) remains the most commonly employed ventilation mode in the operating room because of its ability to deliver a predetermined tidal volume and ensure consistent minute ventilation. However, during robotic pelvic surgeries, reduced pulmonary compliance may result in elevated peak airway pressures, increasing the risk of barotrauma and ventilator-induced lung injury. In contrast, pressure-controlled ventilation (PCV) limits peak inspiratory pressure and delivers gas with a decelerating flow pattern, which may improve alveolar recruitment and reduce airway pressure-related complications. Nevertheless, tidal volume delivery in PCV is dependent on lung compliance and airway resistance, raising concerns regarding potential hypoventilation during dynamic intraoperative physiological changes.[2]

Several clinical studies have demonstrated that PCV may provide lower peak airway pressures and improved dynamic lung compliance compared to VCV during laparoscopic and robotic surgeries, particularly in the steep Trendelenburg position. Furthermore, PCV has been associated with improved ventilation-perfusion matching and reduced intrathoracic pressure, potentially contributing to better hemodynamic stability. Despite these advantages, evidence remains inconclusive, and the optimal ventilation strategy for robot-assisted pelvic surgeries continues to be debated.[3]

Hemodynamic fluctuations during robotic pelvic surgeries are influenced by multiple factors, including pneumoperitoneum-induced increases in systemic vascular resistance, vagal stimulation, and altered venous return. Ventilation strategies may further modulate these effects by altering intrathoracic pressures and right ventricular afterload. Therefore, understanding the comparative impact of PCV and VCV on both respiratory mechanics and hemodynamic parameters is clinically relevant to optimize intraoperative patient safety and postoperative outcomes.[4]

Aim

To compare the effects of pressure-controlled ventilation and volume-controlled ventilation on respiratory mechanics and hemodynamic parameters in patients undergoing robot-assisted pelvic surgeries.

Objectives

1. To evaluate and compare intraoperative respiratory mechanics between pressure-controlled and volume-controlled ventilation modes.
2. To assess and compare hemodynamic changes associated with both ventilation strategies.
3. To analyze the overall safety and efficacy of both ventilation modes during robotic pelvic procedures.

MATERIALS AND METHODS

Source of Data: Data were collected from patients undergoing elective robot-assisted pelvic surgeries in the Department of Anaesthesiology and Pain Relief at a tertiary care teaching hospital.

Study Design: This study was conducted as a prospective comparative interventional study.

Study Location: The study was carried out in the operation theatres of a tertiary care referral hospital 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 enrolled in the study. Patients were equally allocated into two groups:

- **PCV Group:** 44 patients
- **VCV Group:** 44 patients

Sample size was calculated based on previous studies with a power of 80% and a significance level of 5%.

Inclusion Criteria

- Patients aged between 20 and 70 years
- American Society of Anesthesiologists (ASA) physical status I and II
- Patients scheduled for elective robot-assisted pelvic surgeries under general anaesthesia
- Body mass index between 18.5 and 24.9 kg/m²
- Patients who provided written informed consent

Exclusion Criteria

- Patient refusal to participate
- ASA physical status III and IV
- History of chronic obstructive pulmonary disease, bronchial asthma, or restrictive lung disease
- Known cardiovascular instability
- Morbid obesity

Procedure and Methodology

Institutional ethical committee approval was obtained prior to initiation of the study. Eligible patients were explained about the study protocol and written informed consent was obtained. Patients were randomly allocated into two groups using computer-generated random numbers.

Standard fasting guidelines were followed. Pre-anaesthetic evaluation was conducted on the previous day. In the operating room, standard monitoring including ECG, non-invasive blood pressure, pulse oximetry, and capnography was applied. Intravenous access was secured.

Anaesthesia was induced using intravenous midazolam, fentanyl, and propofol, followed by neuromuscular blockade with succinylcholine to facilitate endotracheal intubation. Anaesthesia was maintained using inhalational agents and intermittent doses of muscle relaxants.

Patients in the VCV group were ventilated with a tidal volume of 8 ml/kg, respiratory rate adjusted to maintain end-tidal CO_2 between 35–40 mmHg, inspiratory to expiratory ratio of 1:2, and PEEP of 4 cm H_2O. Patients in the PCV group were ventilated with inspiratory pressure adjusted to achieve similar tidal volume, with respiratory rate and PEEP maintained similarly.

All patients were placed in steep Trendelenburg position and pneumoperitoneum was established. Respiratory and hemodynamic parameters were recorded at predefined intervals: after induction, after establishment of pneumoperitoneum, during surgery, and at skin closure.

At the end of surgery, neuromuscular blockade was reversed and patients were extubated once adequate spontaneous respiration was established. Patients were shifted to the recovery area for postoperative monitoring.

Sample Processing

Collected data were entered into a structured case record form and subsequently transferred to Microsoft Excel spreadsheets for analysis. Data were cross-verified for accuracy before statistical processing.

Statistical Methods

Statistical analysis was performed using SPSS software version 26.0. Continuous variables were expressed as mean ± standard deviation and compared using independent sample t-tests. Categorical variables were expressed as percentages and analyzed using Chi-square tests. A p-value of less than 0.05 was considered statistically significant.

Data Collection

Demographic details, intraoperative respiratory parameters (peak airway pressure, tidal volume, dynamic compliance, end-tidal CO_2), and hemodynamic parameters (heart rate, systolic blood pressure, diastolic blood pressure, mean arterial pressure) were recorded at predefined time points using standardized monitoring equipment and anaesthesia workstation displays.

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	0.52
BMI (kg/m²)	22.8 ± 4.0	23.0 ± 4.6	−0.2	−1.9 to 1.4	Independent t-test	0.61
Male gender	19 (43.2%)	25 (56.8%)	—	—	Chi-square test	0.20
ASA I	26 (59.1%)	24 (54.5%)	—	—	Chi-square test	0.67
ASA II	18 (40.9%)	20 (45.5%)	—	—	Chi-square test	0.67
Duration of surgery (min)	176 ± 22	179 ± 24	−3	−12 to 6	Independent t-test	0.48

Table 1 summarizes the baseline demographic and clinical characteristics of patients in the PCV and VCV groups and demonstrates good comparability between the two study arms. The mean age of patients in the PCV group (57.4 ± 4.4 years) was similar to that of the VCV group (57.7 ± 4.8 years), with no statistically significant difference (p = 0.52). Likewise, body mass index was comparable

between groups, measuring 22.8 ± 4.0 kg/m² in the PCV group and 23.0 ± 4.6 kg/m² in the VCV group ($p = 0.61$). Gender distribution also showed no significant variation, with males constituting 43.2% of the PCV group and 56.8% of the VCV group ($p = 0.20$). The American Society of Anesthesiologists (ASA) physical status distribution was similar across both groups, with ASA I comprising 59.1% in the PCV group and 54.5% in the VCV group, and ASA II accounting for 40.9% and 45.5%, respectively ($p = 0.67$). Additionally, the duration of surgery was comparable between the groups, with mean values of 176 ± 22 minutes in the PCV group and 179 ± 24 minutes in the VCV group ($p = 0.48$).

Table 2: Comparison of Intraoperative Respiratory Mechanics

Parameter	PCV (n=44) Mean ± SD	VCV (n=44) Mean ± SD	Mean Difference	95% CI	Test Used	p-value
Peak airway pressure (cmH_2O)	27.9 ± 1.2	32.0 ± 1.3	−4.1	−4.6 to −3.5	Independent t-test	<0.001
Dynamic compliance (ml/cmH_2O)	38.7 ± 4.8	32.5 ± 4.2	+6.2	4.3 to 8.1	Independent t-test	<0.001
Tidal volume (ml)	368 ± 12	418 ± 11	−50	−55 to −45	Independent t-test	<0.001
Minute ventilation (ml/min)	5945 ± 555	6041 ± 537	−96	−302 to 110	Independent t-test	0.37
$EtCO_2$ (mmHg)	28.7 ± 2.6	28.3 ± 5.1	+0.4	−1.4 to 2.2	Independent t-test	0.61
SpO_2 (%)	99.0 ± 0.8	98.9 ± 0.9	+0.1	−0.2 to 0.4	Independent t-test	0.54

Table 2 presents the comparison of intraoperative respiratory mechanics measured during pneumoperitoneum and steep Trendelenburg positioning. A significant reduction in peak airway pressure was observed 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 ($p < 0.001$). Dynamic lung compliance was significantly higher in the PCV group (38.7 ± 4.8 ml/cmH_2O) than in the VCV group (32.5 ± 4.2 ml/cmH_2O), indicating improved pulmonary mechanics with pressure-controlled ventilation ($p < 0.001$). Although tidal volume was lower in the PCV group (368 ± 12 ml) compared to the VCV group (418 ± 11 ml), this difference was statistically significant ($p < 0.001$) and reflected the pressure-limited delivery pattern of PCV. However, minute ventilation did not differ significantly between groups ($p = 0.37$), suggesting that adequate ventilation was maintained in both modes. Similarly, end-tidal carbon dioxide levels and oxygen saturation remained comparable, with no statistically significant differences observed ($p > 0.05$).

Table 3. Comparison of Hemodynamic Parameters

Parameter	PCV Mean ± SD	VCV Mean ± SD	Mean Difference	95% CI	Statistical Test	p-value
Heart rate (beats/min)	65.2 ± 5.9	64.0 ± 5.7	+1.2	−1.1 to 3.5	Independent t-test	0.31
SBP (mmHg)	124.6 ± 8.9	126.6 ± 9.1	−2.0	−5.8 to 1.8	Independent t-test	0.29
DBP (mmHg)	92.8 ± 1.7	90.5 ± 3.3	+2.3	1.1 to 3.4	Independent t-test	<0.001
MAP (mmHg)	103.4 ± 3.5	102.5 ± 3.4	+0.9	−0.6 to 2.4	Independent t-test	0.24

Table 3 compares the hemodynamic parameters between the two ventilation strategies during the pneumoperitoneum phase. Heart rate was similar between the PCV and VCV groups (65.2 ± 5.9 vs. 64.0 ± 5.7 beats/min; $p = 0.31$), indicating no significant chronotropic effect attributable to ventilation mode. Systolic blood pressure also showed no significant difference between groups (124.6 ± 8.9 mmHg in PCV vs. 126.6 ± 9.1 mmHg in VCV; $p = 0.29$). However, diastolic blood pressure was significantly higher in the PCV group (92.8 ± 1.7 mmHg) compared to the VCV group (90.5 ± 3.3 mmHg), with a statistically significant mean difference of 2.3 mmHg ($p < 0.001$), suggesting better diastolic stability with PCV. Mean arterial pressure remained comparable between groups ($p = 0.24$), indicating that overall perfusion pressure was adequately maintained with both ventilation modes. These results highlight the hemodynamic stability associated with pressure-controlled ventilation without inducing tachycardia or hypotension.

Table 4: Overall Safety and Clinical Efficacy Outcomes

Outcome Parameter	PCV (n=44) n (%)	VCV (n=44) n (%)	Risk Difference	95% CI	Test	p-value
Intraoperative hypertension episodes	3 (6.8%)	10 (22.7%)	−15.9%	−30.2 to −1.6	Chi-square	0.03
High airway pressure alarm events	2 (4.5%)	11 (25.0%)	−20.5%	−35.4 to −5.6	Chi-square	0.006
Desaturation episodes	1 (2.3%)	2 (4.5%)	−2.2%	−9.8 to 5.4	Fisher's Exact	0.56

Need for ventilator adjustment	4 (9.1%)	13 (29.5%)	−20.4%	−37.8 to −3.1	Chi-square	0.02
Post-operative pulmonary complications	1 (2.3%)	4 (9.1%)	−6.8%	−18.2 to 4.6	Fisher's Exact	0.17

Table 4 outlines the overall safety and clinical efficacy outcomes between the PCV and VCV groups. The incidence of intraoperative hypertension episodes was significantly lower in the PCV group (6.8%) compared to the VCV group (22.7%) ($p = 0.03$). Similarly, high airway pressure alarm events were markedly reduced in the PCV group (4.5%) compared to the VCV group (25.0%), demonstrating a statistically significant difference ($p = 0.006$). The need for ventilator adjustments was also significantly less frequent in the PCV group (9.1%) compared to the VCV group (29.5%) ($p = 0.02$), reflecting better ventilatory stability with PCV. Although desaturation episodes and postoperative pulmonary complications were numerically lower in the PCV group, these differences did not reach statistical significance ($p > 0.05$).

DISCUSSION

The mean age and BMI values in both groups were comparable to those reported by Kim MS et al. (2018),[5] who studied ventilatory strategies during laparoscopic and robotic procedures and similarly observed no statistically significant differences in baseline patient profiles. Comparable ASA physical status distribution in both groups further aligns with findings reported by Jo YY et al. (2023),[6] emphasizing that homogeneous baseline characteristics are essential to isolate the true effects of ventilation modes on respiratory and hemodynamic outcomes. Additionally, the similarity in surgical duration between groups in the present study mirrors observations by Wang JP et al. (2015),[7] who highlighted that procedure length itself does not significantly influence ventilatory outcomes when standardized anesthetic protocols are followed.

With regard to respiratory mechanics, the current study demonstrated significantly lower peak airway pressures and improved dynamic lung compliance in the PCV group compared to the VCV group during pneumoperitoneum and steep Trendelenburg positioning. These findings are consistent with those reported by Jaju R et al. (2017),[1] who observed a significant reduction in peak inspiratory pressures and improved pulmonary compliance with PCV during robot-assisted prostatectomy. Similarly, Choi EM et al. (2011),[4] reported superior compliance and reduced airway pressure with PCV in patients undergoing laparoscopic abdominal surgeries, attributing these improvements to the decelerating inspiratory flow pattern and better alveolar recruitment associated with pressure-controlled modes. The comparable end-tidal CO_2 and oxygen saturation levels between the two groups in the present study are in agreement with the observations of Chiumello D et al. (2023),[3] who reported equivalent gas exchange efficiency between PCV and VCV despite differences in airway pressure dynamics. This suggests that PCV can achieve effective ventilation while simultaneously minimizing airway stress.

Hemodynamic analysis revealed no significant differences in heart rate, systolic blood pressure, or mean arterial pressure between the two groups, indicating overall cardiovascular stability with both ventilation strategies. However, a significantly higher diastolic blood pressure was observed in the PCV group, suggesting improved diastolic stability during pneumoperitoneum. These findings are supported by Choi EM et al. (2011),[4] who reported that PCV may exert lower intrathoracic pressure fluctuations, thereby preserving venous return and maintaining stable cardiac output. Similarly, Chowdhury S et al. (2023),[8] observed that pressure-controlled ventilation was associated with improved hemodynamic tolerance during laparoscopic procedures, particularly in prolonged surgeries requiring steep Trendelenburg positioning.

Analysis of safety and clinical efficacy outcomes demonstrated a significantly lower incidence of intraoperative hypertension, fewer high airway pressure alarms, and reduced need for ventilator adjustments in the PCV group. These results correlate with findings by Peng Z et al. (2021),[9] who reported fewer ventilator-related alarms and better intraoperative stability with PCV during minimally invasive surgeries. Although postoperative pulmonary complications and desaturation episodes were numerically lower in the PCV group in the present study, the differences did not reach statistical significance. Similar trends were observed by Lian M et al. (2017),[10] who reported reduced postoperative respiratory morbidity with PCV, although statistical significance varied depending on sample size and patient selection.

CONCLUSION

This prospective comparative study demonstrated that pressure-controlled ventilation (PCV) offers significant advantages over volume-controlled ventilation (VCV) in patients undergoing robot-assisted pelvic surgeries, particularly during periods of pneumoperitoneum and steep Trendelenburg positioning. PCV was associated with significantly lower peak airway pressures and improved dynamic lung compliance, indicating better preservation of respiratory mechanics and reduced risk of ventilator-induced lung injury. Despite lower delivered tidal volumes in the PCV group, effective ventilation and oxygenation were maintained, as reflected by comparable end-tidal carbon dioxide levels and arterial oxygen saturation between the two groups.

Hemodynamic stability was preserved with both ventilation strategies; however, PCV showed superior diastolic blood pressure stability without inducing tachycardia or hypotension, suggesting a favorable cardiovascular profile during the physiologically stressful intraoperative phase. Furthermore, PCV demonstrated a superior safety profile with fewer intraoperative hypertension episodes, reduced airway pressure alarm events, and a lower requirement for ventilator adjustments compared to VCV.

Limitations of The Study

1. The study was conducted at a single tertiary care center, which may limit the generalizability of the findings to other institutions and surgical settings.
2. The sample size, although adequately powered for primary outcomes, may not have been sufficient to detect differences in rare postoperative pulmonary complications.
3. Long-term postoperative respiratory outcomes were not evaluated, restricting the assessment to immediate intraoperative and early postoperative parameters.
4. The study population included only ASA physical status I and II patients, thereby excluding high-risk populations who may exhibit different physiological responses.
5. Advanced hemodynamic monitoring parameters such as cardiac output and stroke volume variation were not included.
6. The influence of different robotic pelvic procedures and variations in surgical duration on respiratory and hemodynamic outcomes was not separately analyzed.

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