

Pressure-Controlled versus Volume-Controlled Ventilation in Low-Flow Anesthesia; Intraoperative Respiratory Mechanics and Postoperative Pulmonary Function: A Randomized Controlled Trial

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Abstract

Background

Pressure-controlled ventilation (PCV) and volume-controlled ventilation (VCV) differ in their effects on airway pressure and lung compliance; however, comparative evidence of their effects during low-flow anesthesia is limited. This study aimed to compare the intraoperative respiratory mechanics and early postoperative pulmonary function between PCV and VCV during low-flow anesthesia in ASA I–II adult patients.

Methods

In this single-center, prospective, randomized controlled trial, 40 ASA I–II adult patients scheduled for elective surgery were randomized to receive PCV (n = 20) or VCV (n = 20) under low-flow anesthesia. After induction, the fresh gas flow was reduced to 1 L/min. The primary outcome was the peak inspiratory pressure (Ppeak). Secondary outcomes included mean airway pressure (Pmean), dynamic lung compliance (Cdyn), and pre- versus postoperative pulmonary function measured using Triflo incentive spirometry. Data were analyzed using t-tests, Mann–Whitney U tests, repeated-measures ANOVA, or Friedman tests as appropriate, with significance set at $p < 0.05$.

Results

Demographic and perioperative variables were comparable between the groups. Ppeak was consistently lower in the PCV group than in the VCV group at all time points ($p < 0.001$). Pmean values were similar, although VCV demonstrated a significant reduction after transition to low flow ($p = 0.004$). Cdyn was significantly higher in the PCV group at baseline (62.6 ± 8.5 vs. 48.0 ± 7.4 mL/cmH₂O, $p = 0.001$), but intergroup differences resolved after low-flow initiation. Postoperatively, inspiratory Triflo performance declined significantly in both groups (PCV: $p = 0.025$; VCV: $p = 0.002$), whereas expiratory capacity significantly decreased only in the VCV group ($p = 0.014$). The between-group differences in postoperative spirometry were not significant. Subgroup analyses showed lower Ppeak with PCV in male patients and in both younger and older subgroups, but no significant sex-by-mode or age-by-mode interactions were observed.

Conclusions

Under low-flow anesthesia, PCV provided a significantly lower Ppeak than VCV without compromising mean airway pressure, intraoperative compliance, or early postoperative pulmonary function. These findings support PCV as a preferred strategy when minimizing airway pressure is a clinical priority, while confirming that both modes remain safe and effective options for low-risk patients undergoing low-flow anesthesia.

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1. INTRODUCTION

Low-flow anesthesia, defined as the administration of general anesthesia with a fresh gas flow typically ≤ 1 L/min, continues to gain traction owing to its environmental and clinical advantages, including reduced anesthetic consumption, lower operational costs, conservation of airway heat and humidity, and diminished greenhouse gas emissions. These benefits are well supported by recent literature, emphasizing their dual utility in resource conservation and patient safety [1–3].

In low-flow contexts, the choice of ventilation mode significantly affects respiratory mechanics. Traditionally, mechanical ventilation during anesthesia employs either volume-controlled (VCV) or pressure-controlled ventilation (PCV). VCV ensures a set tidal volume but is associated with higher peak inspiratory pressures, raising concerns of barotrauma, whereas PCV limits inspiratory pressure and generates a decelerating flow pattern, which has been shown to reduce peak airway pressures and optimize compliance [4, 5].

Recent randomized trials comparing VCV and pressure-controlled ventilation–volume-guaranteed (PCV-VG) have demonstrated that PCV-VG offers lower peak pressures and improved compliance and oxygenation compared to VCV, highlighting the potential superiority of pressure-targeted ventilation strategies [6, 7]. Moreover, novel ventilation modalities, such as flow-controlled ventilation (FCV) and automated gas control systems, have further emphasized the role of individualized ventilation in optimizing lung protection [8, 9]. However, robust randomized controlled evidence directly comparing PCV and VCV, specifically under low-flow anesthesia, remains limited.

This randomized controlled trial was designed to compare PCV and VCV under low-flow anesthesia in adult American Society of Anesthesiologists (ASA) I–II surgical patients. The primary objective was to evaluate the difference in peak inspiratory pressure (P_{peak}) between the ventilation modes. The secondary objectives included comparisons of mean airway pressure (P_{mean}), dynamic lung compliance (C_{dyn}), and postoperative pulmonary function using incentive spirometry (Triflo).

2. METHODS

2.1. Study Design, Registration, and Ethical Approval

This was a single-center, prospective, randomized controlled trial conducted at the Hitit University Erol Olcok Training and Research Hospital. The protocol was reviewed and approved by the Hitit University Faculty of Medicine Clinical Research Ethics Committee (Approval No: 2023-64, dated June 14, 2023). All procedures adhered to the principles outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants prior to enrollment. This study was conducted and reported in accordance with the CONSORT 2025 guidelines for randomized controlled trials [10], and the patient flow through screening, randomization, allocation, follow-up, and analysis is summarized in the CONSORT flow diagram (Fig. 1).

2.2. Participants

Fifty-eight adult patients scheduled for elective surgery under general anesthesia between August and December 2023 were screened. The inclusion criteria were age 18–65 years and American Society of Anesthesiologists (ASA) physical status I–II. The exclusion criteria included morbid obesity (BMI > 35 kg/m²), scoliosis or thoracic deformity, restrictive or obstructive lung disease, prior thoracic or upper abdominal surgery, history of major thoracic trauma or congenital chest wall anomaly, active smoking or chronic use of corticosteroids, β -agonists, bronchodilators, or antihistamines, and anticipated difficult airway or severe hypoxemia (SpO₂ < 90%) during induction.

Forty patients met the eligibility criteria and were randomized into two groups (PCV, n = 20; VCV, n = 20). One patient in the VCV group was subsequently excluded because of an intraoperative surgical complication, leaving 39 patients (PCV, n = 20; VCV, n = 19) for the final analysis (Fig. 1). No perioperative anesthetic complications were encountered in any of the patients included in the study. There is no missing data in the study. The reported group sizes throughout the Results, Tables, and Figures reflect this final analytic sample.

2.3. Randomization and Blinding

Randomization was performed using a computer-generated permuted block design (block size: 8) with a 1:1 allocation ratio via Sealed Envelope.com. Group allocation was concealed in sequentially numbered, opaque, sealed envelopes that were opened immediately before induction by a member of the anesthesia team not otherwise involved in outcome assessment. Patients were blinded to group assignment. Anesthesia providers could not be blinded because of the differing ventilator settings required by each mode; however, the postoperative outcome assessors who recorded the Triflo incentive spirometry results were blinded to group allocation.

2.4. Anesthesia Protocol

Patients did not receive any premedication. Standard monitoring (electrocardiography, non-invasive blood pressure, and pulse oximetry) was performed upon arrival. Train-of-four (TOF) monitoring was used to assess neuromuscular function, and anesthetic depth was monitored using entropy.

Induction: propofol 2–3 mg/kg Intravenous (IV), fentanyl 1 μ g/kg IV, midazolam 0.02 mg/kg IV, and rocuronium 0.6 mg/kg IV. After a TOF count of 0–1, tracheal intubation was performed using a cuffed endotracheal tube (internal diameter 8.0 $\pm$ 0.5 mm for male patients and 7.5 $\pm$ 0.5 mm for female patients).

Maintenance: sevoflurane titrated to 1.0 minimum alveolar concentration (MAC) with a remifentanyl infusion (0.02–0.2 μ g/kg/min). Fresh gas flow (FGF) was maintained at 4 L/min until 1.0 MAC was reached and then reduced to 1 L/min (0.5 L/min O₂ + 0.5 L/min air). Sevoflurane concentration was titrated to maintain an entropy value of 40–60. Postoperative analgesia consisted of paracetamol 15

mg/kg IV and tramadol 2 mg/kg IV (maximum 100 mg). Antiemetic prophylaxis was provided with ondansetron 0.15 mg/kg IV (maximum 8 mg).

2.5. Ventilation Strategies

VCV group

volume-controlled mode, tidal volume 8 mL/kg ideal body weight (IBW).

PCV group

pressure-controlled mode, inspiratory pressure titrated to deliver a tidal volume of 8 ± 0.5 mL/kg IBW.

IBW was calculated as follows: male, $50 + 2.3 \times (\text{height in cm} - 152.4)$; female, $45.5 + 2.3 \times (\text{height in cm} - 152.4)$.

The remaining ventilator settings were identical for both groups: respiratory rate, 14 breaths/min; inspiratory: expiratory ratio (I:E), 1:2; FiO_2 , 0.5; and Positive End-Expiratory Pressure (PEEP), 5 cmH₂O. End-tidal CO₂ was maintained at 30–40 mmHg by adjusting the respiratory rate (and inspiratory pressure in the PCV group, if necessary).

2.6. Measurements and Outcomes

Primary outcome

peak inspiratory pressure (P_{peak}).

Secondary outcomes

mean airway pressure (P_{mean}), dynamic lung compliance (C_{dyn}), and Triflo incentive spirometry performance.

Respiratory mechanics measurements

P_{peak}, P_{mean}, and C_{dyn} were recorded at (i) 30 s after intubation (baseline, high flow), (ii) immediately after switching to low flow, and (iii) at 5, 10, 15, and 20 min of low-flow anesthesia.

Pulmonary function

Triflo inspiratory and expiratory performance (number of balls elevated, out of three) was recorded preoperatively and at 6 hours postoperatively.

2.7. Sample Size Calculation

Based on the P_{peak} data reported by Sen et al. (2016), an effect size of 1.25 was estimated for the primary outcome. With $\alpha = 0.05$, power = 0.95, and an allowance of 10% for dropout, a minimum of 20

patients per group was required. Sample size was calculated using G*Power 3.1 [11]. As the calculation was powered for the primary outcome (Ppeak) only, the secondary outcomes – particularly the postoperative Triflo spirometry comparisons – should be regarded as exploratory and may have been underpowered to detect smaller between-group differences.

2.8. Statistical Analysis

Statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Normality of distribution was assessed using the Shapiro–Wilk test. Continuous variables are expressed as mean $\pm$ standard deviation (SD) for normally distributed data or as median [minimum–maximum] for non-normally distributed data. Categorical variables are expressed as n (%). Between-group comparisons were performed using the independent-samples t-test or the Mann–Whitney U test, as appropriate. Within-group repeated measures were analyzed using repeated-measures analysis of variance (ANOVA) or the Friedman test, with Bonferroni correction for multiple comparisons. Categorical data were compared using the chi-square test or Fisher’s exact test. Paired pre- versus postoperative comparisons were analyzed using the Wilcoxon signed-rank test. A two-sided $p < 0.05$ was considered statistically significant.

3. RESULTS

A total of 58 patients were screened for eligibility. Of these, 18 were excluded (16 did not meet the inclusion criteria and 2 declined to participate). Forty patients were enrolled and randomly assigned to the PCV and VCV groups (20 patients each). One patient in the VCV group was subsequently excluded because of an intraoperative complication, leaving 39 patients (PCV, $n = 20$; VCV, $n = 19$) for the final analysis.

Age, sex distribution, body mass index, ASA physical status, time to reach 1 MAC, surgical duration, sevoflurane usage, and total remifentanyl dose were comparable between the groups, with no statistically significant differences (all $p > 0.05$). The baseline demographic and perioperative variables are presented in Table 1.

Table 1
Baseline characteristics of patients in the PCV and VCV groups

Characteristic	PCV Group (n = 20)	VCV Group (n = 19)	p-value †
Age (years)	56.0 ± 11.1	54.2 ± 14.5	0.65 ‡
Sex (F/M)	5 / 15	2 / 17	0.40 §
Body mass index (kg/m ²)	28.0 ± 4.7	27.3 ± 3.9	0.58 ‡
ASA physical status (I/II)	12 / 8	10 / 9	0.75 §
Time to reach 1 MAC (sec)	224 [57–423]	223 [155–364]	0.91 ¶
Surgical duration (min)	41 [19–98]	45 [26–79]	0.47 ¶
Sevoflurane usage (mL)	8 [4–13]	7 [4–19]	0.82 ¶
Total remifentanyl (µg)	91 [16–338]	160 [16–326]	0.06 ¶

Continuous variables are presented as mean ± standard deviation (SD) if normally distributed or as median [minimum–maximum] if non-normally distributed. Categorical data are presented as counts. One patient in the VCV group was excluded from the analysis because of an intraoperative complication, leaving 20 patients in the PCV group and 19 in the VCV group. † Statistical significance for between-group comparisons. ‡ Independent t-test. § Chi-square test (or Fisher's exact test). ¶ Mann–Whitney U test (non-parametric data presented as median [min–max]). ASA, American Society of Anesthesiologists classification; MAC, minimum alveolar concentration.

3.1. Intraoperative Respiratory Mechanics

P_{peak} values were significantly lower in the PCV group than in the VCV group at all time points ($p < 0.001$ for each). Within-group comparisons showed no significant temporal change in the PCV group ($p = 0.80$), whereas the VCV group demonstrated a non-significant trend toward a decrease followed by a return to baseline ($p = 0.06$).

P_{mean} values were similar between the groups at each time point (all $p > 0.05$). Within-group analysis revealed no significant change in the PCV group ($p = 0.47$), whereas the VCV group showed a significant reduction immediately after the transition to low flow ($p = 0.004$).

C_{dyn} was higher in the PCV group at baseline (62.6 ± 8.5 vs. 48.0 ± 7.4 mL/cmH₂O, $p = 0.001$). After initiation of low flow, no significant intergroup differences were observed (all $p > 0.05$). Within-group analysis indicated no significant temporal change in the PCV group ($p = 0.14$), whereas the VCV group showed a significant fluctuation, with an increase after low-flow initiation and a transient reduction at 5 min (overall $p < 0.01$). The intraoperative respiratory mechanics are summarized in Table 2.

Table 2

Intraoperative airway pressures and lung compliance (mean $\pm$ SD) at each time point under low-flow anesthesia in the PCV and VCV groups

Peak inspiratory pressure, P_{peak} (cmH₂O)	PCV	VCV	p
T1 – Baseline (post-intubation)	13.1 $\pm$ 1.1	18.2 $\pm$ 2.8	< 0.001**
T2–0 min low flow	13.2 $\pm$ 1.3	18.0 $\pm$ 2.5	< 0.001**
T3–5 min low flow	13.3 $\pm$ 1.4	17.5 $\pm$ 2.0	< 0.001**
T4–10 min low flow	13.3 $\pm$ 1.5	17.6 $\pm$ 2.1	< 0.001**
T5–15 min low flow	13.2 $\pm$ 1.5	17.8 $\pm$ 2.2	< 0.001**
T6–20 min low flow	13.4 $\pm$ 1.6	18.1 $\pm$ 2.2	< 0.001**
p (time effect within group)	0.80	0.06	–
Mean airway pressure, P_{mean} (cmH₂O)	PCV	VCV	p
T1 – Baseline (post-intubation)	8.4 $\pm$ 1.0	8.9 $\pm$ 0.9	0.08
T2–0 min low flow	8.3 $\pm$ 0.8	8.4 $\pm$ 0.7	0.34
T3–5 min low flow	8.5 $\pm$ 0.9	8.6 $\pm$ 0.8	0.52
T4–10 min low flow	8.4 $\pm$ 0.9	8.7 $\pm$ 0.8	0.27
T5–15 min low flow	8.3 $\pm$ 0.8	8.5 $\pm$ 0.7	0.18
T6–20 min low flow	8.5 $\pm$ 0.8	8.7 $\pm$ 0.7	0.22
p (time effect within group)	0.47	0.004**	–
Dynamic lung compliance, C_{dyn} (mL/cmH₂O)	PCV	VCV	p
T1 – Baseline (post-intubation)	62.6 $\pm$ 8.5	48.0 $\pm$ 7.4	0.001**
T2–0 min low flow	62.8 $\pm$ 7.9	61.3 $\pm$ 8.0	0.74
T3–5 min low flow	60.1 $\pm$ 8.2	56.4 $\pm$ 7.6	0.13
T4–10 min low flow	59.5 $\pm$ 8.9	58.0 $\pm$ 8.5	0.53
T5–15 min low flow	58.9 $\pm$ 9.1	57.2 $\pm$ 8.3	0.46
T6–20 min low flow	58.7 $\pm$ 9.1	57.5 $\pm$ 8.8	0.68
p (time effect within group)	0.14	< 0.01**	–

Values are shown at six time points: T1 = 30 s after intubation (high-flow baseline), and T2–T6 = 0, 5, 10, 15, and 20 min after the transition to low fresh gas flow. The p-values in the table refer to between-group comparisons at each time point (independent t-tests). Within-group p-values reflect the significance of changes over time (repeated-measures ANOVA or Friedman test, as appropriate). Bold p-values indicate

statistical significance at $\alpha = 0.05$. Under low-flow anesthesia, PCV maintained markedly lower P_{peak} at all time points, whereas P_{mean} remained similar between modes. C_{dyn} was initially higher with PCV but equalized after the initiation of low flow, with no significant intergroup differences from T2 onward (all $p > 0.05$). Both P_{peak} and C_{dyn} were stable over time within the PCV group, whereas the VCV group showed a minor, non-significant decline in P_{peak} and a significant but transient change in C_{dyn} (a dip at 5 min). P_{peak} , peak inspiratory pressure; P_{mean} , mean airway pressure; C_{dyn} , dynamic compliance.

3.2. Postoperative Pulmonary Function

Inspiratory Triflo capacity decreased significantly postoperatively in both the PCV ($p = 0.025$) and VCV ($p = 0.002$) groups compared with preoperative values. Expiratory capacity showed no significant change in the PCV group ($p = 0.16$) but declined significantly in the VCV group ($p = 0.014$). Between-group comparisons demonstrated no statistically significant differences in inspiratory or expiratory Triflo results ($p > 0.05$). The Triflo performance results are presented in Table 3.

Table 3

Preoperative versus postoperative Triflo® incentive spirometry performance in the PCV and VCV groups

Triflo Performance	PCV Group (n = 20)	VCV Group (n = 19)	p-value (within-group)	p-value (between-groups)
Inspiratory (balls)				
– Preoperative	3 (2–3)	3 (2–3)	–	0.48
– Postoperative (6 h)	2 (1–3)	2 (1–3)	0.025 (PCV) ‡ 0.002 (VCV) ‡	0.88
Expiratory (balls)				
– Preoperative	2 (2–2)	2 (2–2)	–	1.00
– Postoperative (6 h)	2 (1–2)	1 (1–2)	0.16 (PCV) ‡ 0.014 (VCV) ‡	0.12

Inspiratory and expiratory Triflo capacity (number of balls elevated, out of three) was measured before surgery and at 6 hours after extubation. Wilcoxon signed-rank tests were used for paired pre- versus postoperative comparisons within each group, and Mann–Whitney U tests were used for between-group comparisons. Triflo, incentive spirometry device; SD, standard deviation.

At 20 min of low-flow anesthesia, P_{peak} remained significantly lower with PCV than with VCV among male patients ($p < 0.001$) and in both the younger (≤ 58 years, $p = 0.002$) and older (> 58 years, $p < 0.001$) subgroups. No significant difference was found among female patients ($p = 0.12$), likely reflecting the small sample size in this subgroup. No significant sex-by-mode or age-by-mode interactions were observed. These subgroup analyses are exploratory, were not pre-specified in the sample size

calculation, and should be interpreted as hypothesis-generating rather than confirmatory. The subgroup analyses are presented in Table 4.

Table 4

Subgroup analyses of the effect of ventilation mode on peak inspiratory pressure (Ppeak) by sex and age

Subgroup	Ppeak @ 20 min – PCV (cmH ₂ O)	Ppeak @ 20 min – VCV (cmH ₂ O)	p-value
Male patients (n = 33)	13.3 ± 1.4	18.2 ± 2.8	< 0.001
Female patients (n = 7)	13.6 ± 2.3	18.0 ± 1.4	0.12
Age ≤ 58 years (n = 20)	13.4 ± 1.8	18.1 ± 3.2	0.002
Age > 58 years (n = 20)	13.3 ± 1.4	18.2 ± 2.0	< 0.001

Values are mean ± SD of peak inspiratory pressure at 20 min of low-flow anesthesia within each subgroup. p-values by unpaired t-test (for male and age subgroups, which showed approximately normal distributions) or Mann–Whitney U test (for the female subgroup, owing to the small n). Ppeak, peak inspiratory pressure; SD, standard deviation.

Two-way ANOVA with repeated measures indicated a significant effect of ventilation mode on Ppeak ($\eta^2 = 0.04$, $p < 0.001$). Mode had no significant effect on Pmean ($\eta^2 = 0.002$, $p = 0.29$) and a small but significant effect on Cdyn ($\eta^2 = 0.03$, $p < 0.001$). Time had moderate-to-large effects on Pmean ($\eta^2 = 0.10$, $p < 0.01$) and Cdyn ($\eta^2 = 0.15$, $p < 0.001$), but only a small effect on Ppeak ($\eta^2 = 0.06$, $p = 0.03$). No mode × time interaction effects reached statistical significance (Supplementary Table 1).

Supplementary Table 1. Effect-size measures for ventilation mode and time factors on key intraoperative outcomes

Outcome	Partial η^2 (Effect of Mode)	Partial η^2 (Effect of Time)
Peak inspiratory pressure	0.04 ($p < 0.001$)	0.06 ($p = 0.03$)
Mean airway pressure	0.002 ($p = 0.29$)	0.10 ($p < 0.01$)
Dynamic lung compliance	0.03 ($p < 0.001$)	0.15 ($p < 0.001$)

Partial η^2 = partial eta-squared from two-way repeated-measures ANOVA (factor A: ventilation mode; factor B: time). Higher values indicate a larger effect size for that factor on the outcome; p-values for the factor effects are given in parentheses. Interpretation: ventilation mode had a significant effect on Ppeak (PCV vs. VCV, $\eta^2 = 0.04$, $p < 0.001$), indicating that mode explained 4% of the total variance in peak pressure — a meaningful effect given the large between-subject variability typical of repeated-measures designs. Mode had only a trivial effect on Pmean (0.2% of variance, $p = 0.29$), consistent with the absence

of significant Pmean differences. For Cdyn, mode explained 3% of variance ($p < 0.001$), reflecting the initial compliance difference that equalized over time. Time had moderate-to-large effects on Pmean and Cdyn but only a small effect on Ppeak.

4. DISCUSSION

The primary finding of this randomized trial was that, under low-flow anesthesia, PCV resulted in a significantly lower Ppeak than VCV at equivalent tidal volumes. This finding aligns with numerous studies reporting reduced airway pressures with PCV in various surgical settings [12]. A lower Ppeak is clinically desirable because it reduces alveolar overdistension and the risk of barotrauma, a core principle of lung-protective ventilation. Notably, meta-analyses of surgical patients have found that PCV (or pressure-targeted modes) consistently lower Ppeak by 4–6 cmH₂O relative to VCV without compromising gas exchange [12–14]. Our results indicate that this benefit extends to low-flow anesthesia in healthy adult patients: even with a reduced fresh gas flow, PCV achieved the target minute ventilation with a markedly lower peak-pressure burden on the airways.

The Pmean values in our study were comparable between modes, indicating similar overall ventilatory support despite different inspiratory dynamics. Interestingly, PCV tended to produce slightly lower Pmean than VCV at most time points. This finding contrasts with some reports under high fresh gas flow, in which the decelerating flow pattern of PCV led to higher mean pressures and improved oxygenation [15]. In our low-flow setting, however, both modes maintained a modest Pmean (8–9 cmH₂O) and stable oxygenation, likely reflecting the relatively compliant lungs of our ASA I–II patients and the use of 5 cmH₂O PEEP in both groups. The comparable Pmean suggests that VCV and PCV provided a similar mean distending pressure to the lungs under these conditions, which may explain the absence of a difference in oxygenation outcomes reported in previous studies [12]. In essence, aside from peak pressures, the overall ventilatory profiles were equivalent between PCV and VCV during low-flow anesthesia.

Cdyn was initially higher in the PCV group, but this difference was transient. Immediately after intubation under high flow, PCV was associated with significantly better compliance than VCV, consistent with more homogeneous lung inflation arising from the decelerating inspiratory flow pattern of PCV [16]. Improved compliance with PCV has been noted in multiple randomized studies, particularly when lung mechanics are challenged by patient positioning or pneumoperitoneum [12]. In our trial, once low-flow anesthesia was initiated, compliance in the VCV group improved markedly, and the intergroup difference disappeared. One possible explanation is that the transition to low flow, with its associated conservation of heat and humidity, may have helped recruit or stabilize alveoli in the VCV group, thereby normalizing compliance; low fresh gas flow is known to preserve respiratory moisture and temperature, factors that can enhance mucociliary function and potentially lung compliance. Additionally, as anesthetic depth and PEEP were maintained constant, both modes likely achieved similar alveolar recruitment over time. Under these steady-state low-flow conditions, Cdyn equilibrated between groups, suggesting that in patients with healthy lungs, either mode can eventually achieve comparable compliance with appropriate

ventilatory management. We acknowledge, however, that this explanation is post hoc and was not directly tested; future studies incorporating direct measures of alveolar recruitment (e.g., lung ultrasound or electrical impedance tomography) would be needed to confirm this mechanism.

Despite the clear differences in intraoperative airway pressures, our data showed no significant difference in early postoperative pulmonary function between the PCV and VCV groups. All patients experienced a decline in incentive spirometry performance at 6 hours after extubation, an expected finding after general anesthesia attributable to factors such as residual anesthetic effects, pain, and recumbency. Median inspiratory Triflo capacity fell from 3 balls preoperatively to 2 balls postoperatively in both groups, with no significant intergroup difference, indicating that the choice of ventilation mode did not measurably affect immediate inspiratory recovery. Both groups showed a similar mild reduction in their ability to take deep breaths, reflecting a degree of atelectasis or respiratory muscle weakness common even in healthy individuals after anesthesia. Our findings are consistent with those of Liao et al., who reported that although PCV improved intraoperative mechanics, it conferred no advantage in postoperative recovery indices compared with VCV [16]. Likewise, a recent large randomized controlled trial in thoracic surgery found no difference in postoperative pulmonary complication rates among VCV, PCV, or hybrid modes when protective ventilation protocols were applied uniformly [17, 18]. These reports support the notion that, when modern protective ventilation strategies are used, the intraoperative mode alone may not substantially influence early postoperative pulmonary outcomes in relatively low-risk patients.

In our study, the VCV group showed a significant decline in expiratory Triflo performance postoperatively, whereas the decline in the PCV group did not reach statistical significance. Although the between-group difference in postoperative expiratory performance was not itself statistically significant, this within-group pattern raises the possibility that PCV may be associated with somewhat better-preserved expiratory muscle function or cough effort. One could speculate that the lower peak pressures, and possibly more homogeneous ventilation, associated with PCV led to less microatelectasis or airway irritation, allowing patients to generate near-baseline expiratory force. Given the lack of a significant between-group difference, the absence of a significant within-group change in inspiratory spirometry for either group beyond the expected decline, and the multifactorial nature of postoperative pulmonary function, this observation should be interpreted with caution and considered hypothesis-generating. Patient effort, analgesia adequacy, and surgical factors likely had a greater influence on postoperative spirometry than the intraoperative ventilator mode in our sample of healthy adults.

From a clinical standpoint, our results indicate that under low-flow anesthesia, both PCV and VCV are effective and safe; however, PCV offers mechanical advantages that may be relevant in certain contexts. The approximately 25–30% reduction in P_{peak} observed with PCV may be particularly relevant in scenarios in which high airway pressures are a concern — for example, in patients with reduced lung compliance, steep Trendelenburg positioning, obesity, or laparoscopic surgery with pneumoperitoneum. Although these conditions were not directly evaluated in our ASA I–II cohort, the existing literature has consistently shown that PCV, or pressure-controlled volume-guaranteed modes, mitigate increases in

airway pressure in such higher-risk situations, potentially improving safety margins [12]. In our low-flow setting, PCV achieved the set tidal volume with a lower driving pressure, reflecting more efficient lung inflation. This suggests that anesthesiologists may select PCV to take advantage of lower peak pressures without compromising ventilation, even as fresh gas flow is minimized for environmental and physiological benefit. On the other hand, VCV did not result in worse outcomes in our uncomplicated cases — a reassuring finding for practitioners who prefer volume control for its guaranteed minute ventilation. The absence of differences in early postoperative spirometry suggests that, for ASA I–II patients, the choice of ventilator mode may reasonably be guided by intraoperative priorities rather than concerns about postoperative pulmonary function. Both groups in our study received lung-protective ventilation (low tidal volume and PEEP), which likely contributed to the overall low incidence of pulmonary issues and to the equivalence in postoperative recovery; under such protective conditions, the ventilatory mode itself appears to become a secondary factor in determining patient outcomes, consistent with recent controlled trials [17].

4.1. Strengths

This study has several methodological strengths. First, to our knowledge, it is among the first randomized controlled trials to directly compare PCV and VCV specifically under low-flow (1 L/min) anesthesia, a setting in which respiratory mechanics may behave differently from the high-flow conditions evaluated in most prior comparisons. Second, the trial was designed and reported in accordance with the CONSORT 2025 guidelines, with computer-generated permuted-block randomization, concealed allocation, and blinding of postoperative outcome assessors, which minimizes detection bias for the secondary pulmonary function outcomes. Third, respiratory mechanics were assessed serially at multiple, closely spaced intraoperative time points (baseline and five low-flow time points), allowing both between-group and within-group temporal comparisons and the calculation of effect sizes (partial η^2) for mode, time, and their interaction. Fourth, the inclusion of both intraoperative respiratory mechanics and early postoperative pulmonary function (via incentive spirometry) provides a more complete picture of the clinical relevance of intraoperative ventilatory choices than intraoperative data alone. Finally, the sample size was prospectively calculated for the primary outcome using an established method (G*Power 3.1), and the achieved sample closely matched the planned sample, supporting the validity of the primary comparison.

4.2. Limitations

This study has several limitations that should be considered when interpreting the findings. First, it was conducted at a single center with a relatively small sample size calculated to detect a difference in the primary outcome (Ppeak) only; the secondary and subgroup analyses, including the comparisons of postoperative Triflo performance and the sex- and age-based subgroups, were therefore exploratory and likely underpowered to detect smaller between-group differences, and their results should be interpreted as hypothesis-generating rather than confirmatory. Second, the study population consisted exclusively of ASA I–II patients without major comorbidities and with relatively short surgical durations (median

approximately 41–45 min); the findings may not be directly generalizable to higher-risk populations, such as patients with obesity, chronic pulmonary disease, or those undergoing longer or more complex surgical procedures, or procedures requiring pneumoperitoneum or steep positioning, in which the pressure-related advantages of PCV may be of greater clinical importance. Third, blinding of the anesthesia team to the ventilation mode was not feasible because of inherent differences in ventilator settings between PCV and VCV, which may have introduced performance bias; we attempted to mitigate this by blinding the postoperative outcome assessors. Fourth, postoperative pulmonary function was assessed using incentive spirometry (Triflo) alone at a single postoperative time point (6 hours); this is a simple, effort-dependent, and relatively coarse measure, and additional objective assessments (e.g., spirometric forced vital capacity, arterial blood gas analysis, chest imaging, or longer-term follow-up for pulmonary complications) were not performed and might have revealed differences not captured by Triflo scores. Finally, the unequal final group sizes (PCV, $n = 20$; VCV, $n = 19$) resulting from a single intraoperative exclusion are unlikely to have materially affected the results given the magnitude of the observed Ppeak differences, but they represent a minor deviation from the originally planned 1:1 allocation.

5. CONCLUSIONS

This randomized controlled trial demonstrated that, under low-flow anesthesia, PCV provided significantly lower peak inspiratory pressures than VCV while maintaining comparable mean airway pressures and dynamic compliance during the maintenance phase. Both ventilation modes resulted in similar early postoperative pulmonary function, as assessed by incentive spirometry, with no significant intergroup differences.

These findings indicate that PCV can enhance lung-protective ventilation by reducing peak airway pressure, an effect that may be particularly relevant in patients or procedures associated with elevated airway pressures, although this was not directly tested in our ASA I–II cohort. In otherwise healthy surgical patients, both PCV and VCV were safe and effective when combined with protective ventilatory strategies, including appropriate tidal volume and PEEP settings.

Clinically, these results support the preferential use of PCV during low-flow anesthesia when minimizing airway pressure is a priority, while confirming that both modes are viable options with respect to short-term pulmonary outcomes in low-risk patients. Larger, multicenter trials including higher-risk surgical populations and more comprehensive pulmonary outcome measures are warranted to confirm and extend these findings.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the principles of the Declaration of Helsinki. The protocol was reviewed and approved by the Clinical Research Ethics Committee of the Hitit University Faculty of Medicine (Approval No: 2023-64, dated June 14, 2023). Written informed consent was obtained from all participants prior to enrollment.

Consent for publication

Not applicable, as no individual patient data or identifiable information is included in this manuscript.

Competing interests

The authors declare that they have no competing interests related to this study.

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Author Contribution

SO: Study conception and design, anesthesia procedures, data acquisition, manuscript drafting, clinical supervision, critical review. HT: Patient recruitment, intraoperative monitoring, data collection. BMC: Data analysis, interpretation of results, critical revision of the manuscript. MY: Study conception and design, patient management, clinical supervision, critical review. All authors read and approved the final manuscript. The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information. The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

References

1. Doger C, Kahveci K, Ornek D, But A, Aksoy M, Gokcinar D, Katar D. Effects of Low-Flow Sevoflurane Anesthesia on Pulmonary Functions in Patients Undergoing Laparoscopic Abdominal Surgery. *Biomed Res Int*. 2016;2016:3068467. 10.1155/2016/3068467.
2. Samad K, Yousuf MS, Ullah H, Ahmed SS, Siddiqui KM, Latif A. Anesthesia and its environmental impact: approaches to minimize exposure to anesthetic gases and reduce waste. *Med Gas Res*. 2025;15(1):101–9. 10.4103/mgr.MEDGASRES-D-23-00059.
3. Ayanoglu Tas B, Sanli Karip C, Abitagaoglu S, Ozturk MC, Erdogan Ari D. Comparison of minimal-flow sevoflurane versus desflurane anesthesia: randomized clinical trial. *Braz J Anesthesiol*. 2022;72(1):77–82. 10.1016/j.bjane.2021.05.012.
4. Cadi P, Guenoun T, Journois D, Chevallier JM, Diehl JL, Safran D. Pressure-controlled ventilation improves oxygenation during laparoscopic obesity surgery compared with volume-controlled ventilation. *Br J Anaesth*. 2008;100(5):709–16. 10.1093/bja/aen067.
5. Griva P, Talliou C, Soulioti E, Millionis O, Sidiropoulou T. The role of the tidal volume challenge test in volume responsiveness assessment: a narrative review. *J Anesth Analg Crit Care*. 2025;5(1):37. 10.1186/s44158-025-00256-9.
6. Schick V, Dusse F, Eckardt R, Kerkhoff S, Commotio S, Hinkelbein J, Mathes A. Comparison of Volume-Guaranteed or -Targeted, Pressure-Controlled Ventilation with Volume-Controlled Ventilation during Elective Surgery: A Systematic Review and Meta-Analysis. *J Clin Med*. 2021;10(6). 10.3390/jcm10061276.
7. Kim MS, Soh S, Kim SY, Song MS, Park JH. Comparisons of Pressure-controlled Ventilation with Volume Guarantee and Volume-controlled 1:1 Equal Ratio Ventilation on Oxygenation and Respiratory Mechanics during Robot-assisted Laparoscopic Radical Prostatectomy: a Randomized-controlled Trial. *Int J Med Sci*. 2018;15(13):1522–9. 10.7150/ijms.28442.
8. Lagier D, Zeng C, Fernandez-Bustamante A, Vidal Melo MF. Perioperative Pulmonary Atelectasis: Part II. Clinical Implications. *Anesthesiology*. 2022;136(1):206–36. 10.1097/ALN.0000000000004009.
9. Bialka S, Palaczynski P, Szuldrzynski K, Wichary P, Kowalski D, van der Hoorn JWA, Bottinger L, Misiolek H. Flow-controlled ventilation - a new and promising method of ventilation presented with a review of the literature. *Anaesthesiol Intensive Ther*. 2022;54(1):62–70. 10.5114/ait.2022.112889.
10. Hopewell S, Chan AW, Collins GS, Hrobjartsson A, Moher D, Schulz KF, Tunn R, Aggarwal R, Berkwits M, Berlin JA, et al. CONSORT 2025 statement: updated guideline for reporting randomised trials. *BMJ*. 2025;389:e081123. 10.1136/bmj-2024-081123.
11. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–91. 10.3758/bf03193146.

12. Wen C, Qi Y, Xiang Y, Pang Q, Xiao J, An R. Effect of pressure-controlled ventilation and volume-controlled ventilation for laparoscopic surgery in the Trendelenburg position: a systematic review and meta-analysis. *Perioper Med (Lond)*. 2025;14(1):56. 10.1186/s13741-025-00540-w:.
13. Turan Civraz AZ, Saracoglu A, Saracoglu KT. Evaluation of the Effect of Pressure-Controlled Ventilation-Volume Guaranteed Mode vs. Volume-Controlled Ventilation Mode on Atelectasis in Patients Undergoing Laparoscopic Surgery: A Randomized Controlled Clinical Trial. *Med (Kaunas)*. 2023;59(10). 10.3390/medicina59101783.
14. Li X, Xu Y, Wang Z, Wang W, Luo Q, Yi Q, Yu H. Effect of ventilation mode on postoperative pulmonary complications among intermediate- to high-risk patients undergoing abdominal surgery: A randomized controlled trial. *Anaesth Crit Care Pain Med*. 2024;43(6):101423. 10.1016/j.accpm.2024.101423.
15. Lee JM, Lee SK, Rhim CC, Seo KH, Han M, Kim SY, Park EY. Comparison of volume-controlled, pressure-controlled, and pressure-controlled volume-guaranteed ventilation during robot-assisted laparoscopic gynecologic surgery in the Trendelenburg position. *Int J Med Sci*. 2020;17(17):2728–34. 10.7150/ijms.49253.
16. Liao CC, Kau YC, Ting PC, Tsai SC, Wang CJ. The Effects of Volume-Controlled and Pressure-Controlled Ventilation on Lung Mechanics, Oxidative Stress, and Recovery in Gynecologic Laparoscopic Surgery. *J Minim Invasive Gynecol*. 2016;23(3):410–7. 10.1016/j.jmig.2015.12.015.
17. Li XF, Jin L, Yang JM, Luo QS, Liu HM, Yu H. Effect of ventilation mode on postoperative pulmonary complications following lung resection surgery: a randomised controlled trial. *Anaesthesia*. 2022;77(11):1219–27. 10.1111/anae.15848.
18. Piccioni F, Langiano N, Bignami E, Guarnieri M, Proto P, D'Andrea R, Mazzoli CA, Riccardi I, Bacuzzi A, Guzzetti L, et al. One-Lung Ventilation and Postoperative Pulmonary Complications After Major Lung Resection Surgery. A Multicenter Randomized Controlled Trial. *J Cardiothorac Vasc Anesth*. 2023;37(12):2561–71. 10.1053/j.jvca.2023.04.029.

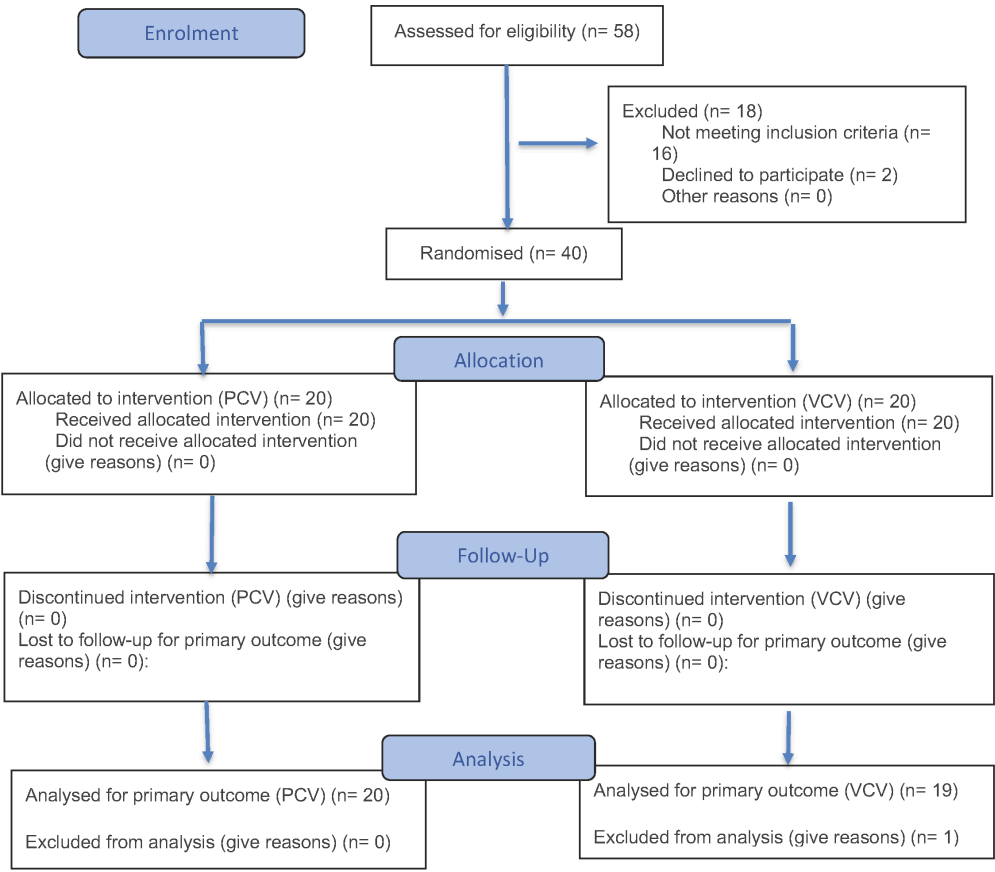
Abbreviations

ANOVA: one-way analysis of variance, ASA: American Society of Anesthesiologists; BMI: Body Mass Index; Cdyn: Dynamic Lung Compliance; FCV: Flow-Controlled Ventilation; FGF: Fresh Gas Flow; IBW: Ideal Body Weight; I:E: Inspiratory-to-Expiratory Ratio; IV: Intravenous; MAC: Minimum Alveolar Concentration; PCV: Pressure-Controlled Ventilation; PCV-VG: Pressure-Controlled Ventilation – Volume Guaranteed; PEEP: Positive End-Expiratory Pressure; Pmean: Mean Airway Pressure; Ppeak: Peak Inspiratory Pressure; TOF: Train-of-Four; VCV: Volume-Controlled Ventilation.

Figures

Figure 1: CONSORT 2025 Flow Diagram

Flow diagram of the progress through the phases of a randomised trial of two groups (that is, enrolment, intervention allocation, follow-up, and data analysis)



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Figure 1

See image above for figure legend.

Supplementary Files

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