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Original Article

The Effect of Flow-Controlled Ventilation on Mechanical Power in Laparoscopic Surgeries: A Comparative Analysis with Pressure Controlled Volume Guaranteed and Volume Controlled Ventilation

Laparoskopik Cerrahilerde Akış Kontrollü Ventilasyonun Mekanik Güç Üzerindeki Etkisi: Basınç Kontrollü Hacim Garantili ve Hacim Kontrollü Ventilasyon ile Karşılaştırmalı Bir Analiz

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ABSTRACT

Objective: To compare mechanical power (MP) levels among flow-controlled ventilation (FCV), volume-controlled ventilation (VCV), and pressure-controlled volume-guaranteed ventilation (PCV-VG) during laparoscopic surgery and to test the hypothesis that the stable flow dynamics of FCV would reduce MP.

Methods: Patients were divided into three groups according to the mechanical ventilation modes applied during laparoscopic surgery: PCV-VG (n=15), VCV (n=14), and FCV (n=15). MP was calculated at four timepoints: baseline (T1), post-induction (T2), during CO_2 insufflation (T3), and post-insufflation (T4). The primary outcome of the study was the comparison of MP in the FCV mode with MP in the other groups during insufflation. Driving pressure (DP), plateau pressure, and peak airway pressure were also analyzed.

Results: Baseline MP was highest in PCV-VG (6.9 J/min vs. 5.0 J/min in VCV and 5.1 J/min in FCV; p=0.002). During insufflation (T3), MP increased to a similar extent across groups (PCV-VG: 9.4 J/min, VCV: 8.7 J/min, FCV: 8.6 J/min), with PCV-VG showing the smallest relative rise (p<0.001). DP and plateau pressures increased during pneumoperitoneum, but Bonferroni-adjusted comparisons revealed that these were not statistically significant. PCV-VG maintained higher positive end-expiratory pressure (5 vs. 4 cmH_2O, p<0.001); however, it did not significantly affect peak pressures.

Conclusions: Contrary to our hypothesis, FCV did not reduce MP more effectively than either VCV or PCV-VG. However, PCV-VG demonstrated better mitigation of insufflation-induced increases in MP, suggesting potential advantages for lung protection during laparoscopy. Further prospective studies are needed to assess clinical outcomes.

Keywords: Respiratory mechanics, mechanical ventilation, laparoscopy, ventilator-induced lung injury

ÖZ

Amaç: Bu çalışmanın amacı, laparoskopik cerrahi sırasında akış kontrollü ventilasyon (FCV), volüm kontrollü ventilasyon (VCV) ve basınç kontrollü volüm garantili ventilasyon (PCV-VG) modları arasındaki mekanik güç (MP) düzeylerini karşılaştırmak ve FCV'nin stabil akış dinamiğinin MP'yi azaltacağı hipotezini test etmektir.

Yöntemler: Laparoskopik cerrahi geçiren 44 hasta uygulanan mekanik ventilasyon modlarına göre üç gruba ayrıldı: PCV-VG (n=15), VCV (n=14) ve FCV (n=15). MP dört zaman noktasında hesaplandı: başlangıç (T1), indüksiyon sonrası (T2), CO_2 insüflasyonu sırasında (T3) ve insüflasyon sonrası (T4). Çalışmanın birincil sonucu, insüflasyon sırasında FCV modundaki MP'nin diğer gruplarla karşılaştırılmasıydı. Sürücü basınç (DP), plato basıncı ve pik hava yolu basınçları da analiz edildi.

Bulgular: Başlangıç MP değeri PCV-VG grubunda en yüksekti (6,9 J/dk vs. VCV: 5.0, FCV: 5.1 J/dk, p=0,002). İnsüflasyon sırasında (T3), MP tüm gruplarda benzer şekilde arttı (PCV-VG: 9,4, VCV: 8,7, FCV: 8,6 J/dk), ancak PCV-VG en düşük relatif artışı gösterdi (p<0,001). DP ve plato basınçları pnömoperitoneum sırasında arttı, ancak Bonferroni düzeltmesi sonrası gruplar arası fark anlamlı değildi. PCV-VG daha yüksek PEEP seviyeleri sağladı (5 vs. 4 cmH_2O, p<0,001), ancak pik basınçları etkilemedi.

Sonuçlar: Hipotezimizin aksine, FCV MP'yi VCV veya PCV-VG'ye göre daha etkili şekilde azaltmadı. Bununla birlikte, PCV-VG'nin insüflasyon kaynaklı MP artışını daha iyi sınırladığı ve laparoskopide akciğer korunumuna katkı sağlayabileceği görüldü. Klinik sonuçları değerlendirmek için ileri prospektif çalışmalara ihtiyaç vardır.

Anahtar kelimeler: Solunum mekanikleri, mekanik ventilasyon, laparoskopi, ventilatör ilişkili akciğer hasarı

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INTRODUCTION

The primary aims of mechanical ventilation are lung protection, maintenance of adequate gas exchange, and prevention of ventilator-induced lung injury (VILI) caused by barotrauma, volutrauma, atelectrauma, and biotrauma[1]. Significant efforts have been made to identify and minimize factors contributing to VILI[2]. Key triggers include barotrauma (associated with high plateau pressures), volutrauma [related to high tidal volumes (Vt)], and atelectrauma (resulting from cyclic alveolar collapse and reopening)[2]. A novel approach to VILI focuses on the energy dissipated in lung tissue during respiratory cycles as a fundamental mechanism of injury[3]. The energy transferred from the ventilator to the respiratory system appears to be directly related to VILI, and reducing mechanical energy may decrease lung damage[3].

In laparoscopic surgery, pneumoperitoneum increases intra-abdominal pressure (IAP). Cranial displacement of the diaphragm elevates intrathoracic pressure, reduces lung compliance, promotes atelectasis, and impairs gas exchange[4]. To prevent atelectasis and maintain adequate ventilation in the presence of elevated airway pressures, mechanical ventilators must deliver higher energy[4]. Therefore, ventilation modes associated with lower mechanical power (MP) may facilitate lung-protective strategies during laparoscopic procedures[4].

During mechanical ventilation, electrical energy is converted to kinetic and thermal energy to generate pressure for Vt delivery. The energy transferred per breath is termed mechanical energy, while the energy transferred per unit time is defined as MP[5]. Gattinoni et al.[6] developed the formula for calculating MP using ventilator parameters in 2016. Becher et al.[7] later simplified this formula by eliminating the need to measure compliance, resistance, and elastance. The simplified calculation incorporates peak pressure (Ppeak), Vt, and respiratory rate (RR)[7]. Thus, MP serves as a comprehensive variable representing ventilator-induced damaging factors[7]. The relationship between MP and VILI was first demonstrated in a porcine model, establishing 12.1 J/min as the threshold for VILI development[8]. Subsequent animal and human studies have further investigated the role of MP in VILI across various patient populations and procedures[5].

Flow-controlled ventilation (FCV), an innovative strategy developed in 2010, delivers a constant linear flow during both inspiratory and expiratory phases[9]. When implemented via the Evone ventilator (Ventinova Medical BV, Eindhoven, Netherlands), this method minimizes airway resistance through active expiration and reduces intratracheal pressure fluctuations[2]. FCV dynamically optimizes Vt and RR based on preset pressure-flow parameters and demonstrates particular efficacy in high-risk populations (patients with morbid obesity and those undergoing laparoscopic surgery) by reducing atelectasis, hypercapnia, and pressure-related injuries[10]. However, FCV's impact on MP remains insufficiently explored compared to volume-controlled (VCV) and pressure-controlled volume-guaranteed (PCV-VG) modes.

Primary objective: This study compared FCV's MP-reducing efficacy with that of VCV and PCV-VG during laparoscopic surgery to test our hypothesis that FCV's low Vt and stable pressure dynamics would significantly reduce MP. Our primary endpoint was the intermodal MP difference under CO_2 insufflation.

MATERIALS and METHODS

Study Design

The current study was conducted in a tertiary care hospital. Ethical protocol number 2025-79 was received from the University of Health Sciences Türkiye, Kocaeli City Hospital Scientific Research Ethics Committee with protocol no.: 2025-79, date: 10.07.2025. The study was conducted in accordance with the Declaration of Helsinki. VCV and PCV-VG are the ventilation modes most frequently used for laparoscopic procedures in our clinical practice. During the study period (November 2024-February 2025), when FCV was implemented at our institution, we enrolled 44 patients, assigned to three study groups who underwent laparoscopic surgery and had complete intraoperative ventilation data recorded under the three distinct ventilation modalities. Due to the retrospective design, individual patient consent was not obtained.

Patients were divided into three groups according to the applied ventilation modes:

- Group 1: PCV-VG (n=15)

- Group 2: VCV (n=14)

- Group 3: FCV (n=15)

Data Collection and Variables

Information regarding patients' ages, gender, American Society of Anesthesiologists (ASA) scores, height, weight, heart rate (HR), systolic blood pressure, diastolic blood pressure, mean blood pressure, peripheral oxygen saturation (SpO_2), type of surgery, duration of surgery, duration of anesthesia, CO_2 insufflation time, and ventilation mode was recorded. The parameters analyzed

according to ventilation mode included Vt, RR, end-tidal carbon dioxide pressure ($EtCO_2$), positive end-expiratory pressure (PEEP), peak airway pressure (Ppeak), driving pressure (DP), and plateau pressure. MP was calculated from simplified formulas defined in the literature, using these parameters:

Group 1: PCV-VG (PCV-VG) (n=15)

For pressure-controlled ventilation: MP (J/min) = 0.098 × RR (1/min) × Vt (L) × (Peak inspiratory pressure change (ΔPinsp) + PEEP] (cmH_2O)[6,7].

Group 2: VCV (n=14)

For VCV: MP (J/min) =0.098 × RR (1/min) × VT (L) × [ΔPinsp - ½ (Plateau Pressure - PEEP)] (cmH_2O)[11]. Group 3: FCV (n=15)

For FCV, MP (J/min) =0.098 × RR (1/min) × VT (L) × ½ × (Plateau Pressure - PEEP) (cmH_2O)[6,11].

Inclusion criteria were adults (≥18 years of age) undergoing elective laparoscopic surgery under general anesthesia and ventilated in continuous mode for at least 15 minutes.

Exclusion criteria included conversion to open surgery, intraoperative ventilation mode changes due to hemodynamic instability or hypoxemia, missing ventilation data, emergency surgical interventions, and pregnant women. Additionally, patients with preoperative pulmonary diseases (chronic obstructive pulmonary disease, interstitial lung disease) or severe cardiovascular pathologies (ejection fraction <30%, pulmonary hypertension) were excluded from the study.

The study screened a total of 80 patients; 28 had incomplete data and 8 were excluded due to conversion to open surgery. As a result, data from 44 patients were analyzed. These strict exclusion criteria ensured the comparability of ventilation parameters between study groups and maintained data homogeneity.

To compare variables, four different time periods were determined during the mechanical ventilation process:

T1: The point at which mechanical ventilation was initiated after anesthesia induction

T2: 15 minutes of mechanical ventilation after anesthesia induction

T3: 15 minutes of CO_2 insufflation

T4: 15 minutes after CO_2 insufflation was discontinued

Primary and Secondary Outcome Measure

The primary endpoint of the study was the difference in MP between ventilation modes during CO_2 insufflation. The secondary outcomes were comparisons of MP values measured during the anaesthesia induction phase of mechanical ventilation in the perioperative period, at the 15th minute of mechanical ventilation prior to pneumoperitoneum, and at the 15th minute after completion of pneumoperitoneum.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 27.0. Descriptive statistics were presented as median (minimum-maximum) or mean ± standard deviation for continuous variables, and as frequency and percentage (n, %) for categorical variables. The distribution of numerical variables was assessed using the Shapiro-Wilk test. For independent numerical variables that were not normally distributed, the Kruskal-Wallis test was used, and results were expressed as median (minimum-maximum). For normally distributed variables, one-way analysis of variance was applied, and values were presented as mean ± standard deviation. To assess the independence of categorical variables, Fisher's exact test was used. A p-value <0.05 was considered statistically significant.

For within-group comparisons across multiple time points, the Friedman test was used. If a significant difference was found, Dunn's test was performed for post-hoc multiple comparisons. For between-group comparisons at each time point, the Kruskal-Wallis test was applied, followed by Dunn's post-hoc test when appropriate.

To control for type I error, Bonferroni correction was applied. For variables measured at four time points, a significance threshold of p<0.007 was used; for those measured at five time points, a significance threshold of p<0.006 was used.

RESULTS

During the study period, a total of 80 patients underwent laparoscopic procedures. After applying the exclusion criteria —28 patients with missing data and 8 patients who converted to open procedures — data from 44 patients who met the study criteria were included in the analysis. According to our patient data, no perioperative mortality or intraoperative complications were reported.

The perioperative mechanical ventilation targets were similar for all patients in terms of saturation, $EtCO_2$, and Ppeak. Any ad hoc adjustments to mechanical ventilation made during surgery were excluded from the analysis. Instead, MP values were calculated based on data from specified time intervals.

Evaluation of the demographic data of the study patients revealed no difference between the groups in gender distribution (p=1.000). The PCV-VG, VCV, and FCV groups included 11 (73.4%), 11 (78.6%), and 12 (80.0%) female patients, respectively. The mean age in the PCV-VG group was significantly higher (61.9±10.7 years; p=0.039). The mean ages in the VCV and FCV groups were 49.4±17.4 years and 48.7±16.8 years, respectively. No significant differences were observed between the groups with respect to height and weight (Table 1).

A significant difference in ASA scores among the groups was observed (p=0.003). In the PCV-VG group, no patients were classified as ASA I, while 53.3% were ASA II and 46.7% were ASA III. In the VCV group, 14.3% of patients were ASA I, 78.7% were ASA II, and 7.1% were ASA III. In the FCV group, 13.3% were ASA I and 86.7% were ASA II, with no ASA III patients (Table 1).

The median anesthesia durations were 150 minutes (range, 60-400) in the PCV-VG group, 122.5 minutes (range, 70-300) in the VCV group, and 125 minutes (range, 90-310) in the FCV group (p=0.672). Surgical durations were 120 (50-375), 102.5 (45-280), and 105 (50-300) minutes, respectively (p=0.837). CO_2 insufflation times were also similar across groups: 75 (15-300) minutes in PCV-VG, 75 (30-240) minutes in VCV, and 85 (40-255) minutes in FCV (p=0.976). The insufflation pressure showed comparable median values of 13 mmHg across all groups (p=0.934). No statistically significant differences were observed among the three ventilation modes regarding anesthesia duration, surgical duration, CO_2 insufflation time, or insufflation pressure at the 15-minute mark (Table 2).

MP Values: In our study, baseline (T1) MP was significantly higher in the PCV-VG group [6.9 (4.8-11.3) J/min] compared with VCV [5.0 (4.2-8.1) J/min] and FCV [5.1 (3.5-9.4) J/min] (p=0.002). However, this difference diminished over time. At 15 minutes post-CO_2 insufflation (T3), MP increased in all groups: PCV-VG [9.4 (6.0-13.1)], VCV [8.7 (4.6-13.6)], and FCV [8.6 (0.8-13.6)]. Following insufflation termination (T4), MP returned to baseline levels in all groups. In the VCV and FCV groups, the rise in MP at T2 and T3 time points was statistically significant (p<0.001), whereas in PCV-VG the T3 increase was also statistically significant (p=0.008) (Table 3).

DP and plateau pressure dynamics; All ventilation modes demonstrated significant increases in DP during

Table 1. Patients' demographic and clinical characteristics.

	PCV-VG	VCV	FCV	p-value*
Sex				
Female	11 (73.4)	11 (78.6)	12 (80)	1.000[a]
Male	4 (26.7)	3 (21.4)	3 (20)	
Age (years)	61.9±10.7[a]	49.4±17.4[b]	48.7±16.8[c]	**0.039[a]***
Height (cm)	161.7±8.2	163.5±6.5	163.5±6.2	0.712[a]
Weight (kg)	81.5±11.9	74.8±9.9	73.9±9.3	0.110[a]
ASA score				
ASA I	0 (0)	2 (14.3)	2 (13.3)	**0.003*[z]**
ASA II	8 (53.3)	11 (78.7)	13 (86.7)	
ASA III	7 (46.7)	1 (7.1)	0 (0)	
Type of surgery				
Laparoscopic hysterectomy	8 (53.3)	8 (57.1)	7 (46.7)	0.114[z]
Ovarian cyst	0 (0)	1 (7.1)	5 (33.3)	
Laparoscopic colon tumor	3 (20)	3 (21.4)	0 (0)	
Other	4 (26.7)	2 (14.3)	3 (20)	

Data are presented as number (%) or mean ± standard deviation. [a-c]: Groups with different letters are statistically significantly different.

[a]: One-way ANOVA test; [z]: Fisher's exact test. p*<0.05 was considered statistically significant, PCV-VG: pressure-controlled volume-guaranteed ventilation, VCV: volume-controlled ventilation, FCV: Flow-controlled ventilation, ASA: American Society of Anesthesiologists

Table 2. Operative time parameters and insufflation pressure data across groups.				
	PCV-VG	**VCV**	**FCV**	**p-value**
Anesthesia duration (minute)	150 (60-400)	122.5 (70-300)	125 (90-310)	0.672[1]
Surgical duration (minute)	120 (50-375)	102.5 (45-280)	105 (50-300)	0.837[1]
CO_2 insufflation duration (minute)	75 (15-300)	75 (30-240)	85 (40-255)	0.976[1]
Insufflation pressure at 15th minute	13 (8-15)	13 (7-18)	13 (7-15)	0.934[1]
Data are presented as median (minimum-maximum). [1]Kruskal Wallis test. PCV-VG: Pressure-controlled volume-guaranteed ventilation, VCV: Volume-controlled ventilation, FCV: Flow-controlled ventilation				

pneumoperitoneum at T3 (p<0.001). The PCV-VG group exhibited the most pronounced elevation, with DP rising from 14 (6-26) cmH_2O at baseline (T1) to 22 (13-29) cmH_2O during insufflation. The VCV and FCV groups showed more moderate increases, to 17.5 (13-26) and 16 (13-26) cmH_2O, respectively. Plateau pressure followed a similar trend, with PCV-VG reaching significantly higher values [26 (17-33) cmH_2O] than VCV [20.5 (17-29) cmH_2O) and FCV [19 (17-30) cmH_2O]. While initial analysis suggested intergroup differences at T3 (p=0.034), Bonferroni-adjusted comparisons revealed that these differences were not statistically significant (adjusted p>0.007), indicating that the observed variations may reflect physiological variability rather than mode-dependent effects (Table 3).

Ventilatory Pressure Characteristics; The PCV-VG strategy consistently maintained higher PEEP levels [5 (4-6) cmH_2O] throughout the procedure compared with VCV and FCV [4 (3-5) cmH_2O, p<0.001], reflecting its distinct algorithmic approach to lung protection. Ppeak during pneumoperitoneum showed mode-dependent variation, with PCV-VG generating the highest pressures [27 (18-34) cmH_2O], followed by VCV [21.5 (18-30) cmH_2O] and FCV [20 (18-31) cmH_2O] (Table 3).

Haemodynamic data; Significant decreases in mean arterial pressure (MAP) (p*<0.001) and HR (p*=0.001) were observed in the PCV group. In the VCV and FCV groups, however, changes in MAP and HR were not found to be significant (p*=0.035 and 0.048 for MAP, and p*=0.009 and 0.006 for HR; values correspond to VCV and FCV, respectively). Although SpO_2 increased in all groups, this change was not statistically significant (p>0.006). Intergroup comparisons revealed differences only in measurements of MAP-2, MAP-3, and MAP-4 (p<0.006) (Table 4).

DISCUSSION

This study compared the effects of PCV-VG, VCV, and FCV ventilation modes on MP during laparoscopic surgery. The mechanical ventilation process was evaluated at four distinct time points, analyzing both within-group changes and between-group differences. Our findings show that, contrary to our hypothesis, FCV yields MP values similar to those of PCV-VG and VCV during CO_2 insufflation for laparoscopic surgery. The most notable finding of the study is that the PCV-VG mode limits the increase in MP during laparoscopy more effectively than other ventilation modes.

The concept of MP, defined by Gattinoni et al.[6], is a critical parameter in the pathogenesis of VILI. Essentially, it is the time-normalized expression of the energy transmitted to the lung parenchyma and is calculated by the following formula: MP=0.098× RR (1/min) × VT (L) × (ΔPinsp + PEEP) (cmH_2O)[6]. In our study, the initially observed high MP values in the PCV-VG group (T1) may be associated with this mode's requirement for higher PEEP and higher plateau pressure. However, the significantly lower rate of MP increase after CO_2 insufflation (T3) compared with other groups suggests physiological advantages of PCV-VG. Specifically, the adaptive flow profile (initially high and gradually decreasing) may optimize gas distribution under conditions of increased IAP, thereby ensuring a more homogeneous distribution of mechanical stresses. Additionally, its autoregulatory capacity, which dynamically adjusts pressure limits while maintaining Vt, enhances this adaptation[12].

Laparoscopic surgery is widely preferred because it is minimally invasive, results in shorter hospital stays, and yields favorable cosmetic outcomes[13]. However, pneumoperitoneum and the Trendelenburg position increase IAP, restrict diaphragmatic movement, elevate mechanical stress in the lungs, and raise the risk of atelectasis[13]. Pozzi et al.[14] reported that MP increased across different PEEP levels during pneumoperitoneum. Consistent with Pozzi[14]'s findings, our study also observed increased MP values during insufflation, independent of ventilation mode. Similar MP values were observed across all three ventilation modes during insufflation; however, the PCV-VG mode significantly attenuated the increase

Table 3. Mechanical ventilation values of the groups in the T1, T2, T3, T4 time periods.					
Groups	**MP-1**	**MP-2**	**MP-3**	**MP-4**	**p*-value***
PCV-VG	6.9 (4.8-11.3)^{A}	7.1 (4.5-10.4)	9.4 (6-13.1)	7.5 (4.7-9.5)	0.008[1]
VCV	5 (4.2-8.1)^{Ba}	8 (4.9-11.9)^{b}	8.7 (4.6-13.6)^{b}	6.5 (3.4-11.2)^{a}	**<0.001[1]***
FCV	5.1 (3.5-9.4)^{Ba}	7.9 (5.1-12.3)^{b}	8.6 (0.8-13.6)^{b}	6.4 (3-10)^{a}	**<0.001[1]***
p-value*	**0.002[2]***	**0.109[2]**	**0.976[2]**	**0.415[2]**	
Groups	**DP-1**	**DP-2**	**DP-3**	**DP-4**	**p*-value**
PCV-VG	14 (6-26)^{a}	13 (7-26)^{b}	22 (13-29)^{b}	13 (9-20)^{a}	**<0.001[1]***
VCV	10.5 (5-25)^{a}	15.5 (11-27)^{b}	17.5 (13-26)^{b}	12 (3-16)^{a}	**<0.001[1]***
FCV	11 (5-9)^{a}	14 (12-27)^{b}	16 (13-26)^{b}	12 (3-22)^{a}	**<0.001[1]***
p-value*	0.204[2]	0.060[2]	0.970[2]	0.171[2]	
Groups	**PEEP-1**	**PEEP-2**	**PEEP-3**	**PEEP-4**	**p-value**
PCV-VG	5 (4-6)^{A}	5 (5-5)^{A}	5 (5-7)^{A}	5 (5-7)^{A}	0.112[1]
VCV	4 (3-5)^{B}	4 (3-5)^{B}	4 (4-5)^{B}	4.5 (3-5)^{B}	0.466[1]
FCV	4 (3-5)^{B}	4 (3-5)^{B}	4 (4-5)^{B}	5 (3-5)^{B}	0.091[1]
p-value*	**0.002[2]***	**<0.001[2]***	**<0.001[2]***	**<0.001[2]***	
Groups	**PLATO-1**	**PLATO-2**	**PLATO-3**	**PLATO-4**	**p*-value**
PCV-VG	18 (11-30)^{a}	17 (11-30)^{a}	26 (17-33)^{b}	17 (13-26)^{a}	**<0.001[1]***
VCV	13 (9-27)^{a}	19 (14-30)^{b}	20.5 (17-29)^{b}	15.5 (6-19)^{a}	**<0.001[1]***
FCV	15 (7-23)^{a}	18 (14-30)^{b}	19 (17-30)^{b}	16 (6-25)^{a}	**<0.001[1]***
p-value	0.082[2]	0.244[2]	0.034[2]	0.083[2]	
Groups	**PEAK-1**	**PEAK-2**	**PEAK-3**	**PEAK-4**	**p-value***
PCV-VG	19 (12-31)^{a}	18 (12-31)^{a}	27 (18-34)^{b}	18 (14-27)^{a}	**<0.001[1]***
VCV	14 (10-28)^{a}	20 (15-31)^{b}	21.5 (18-30)^{b}	16.5 (7-20)^{a}	**<0.001[1]***
FCV	16 (8-24)^{a}	19 (15-31)^{b}	20 (18-31)^{b}	17 (7-26)^{a}	**<0.001[1]***
p-value	0.082[2]	0.244[2]	0.034[2]	0.083[2]	
Groups	**RR-1**	**RR-2**	**RR-3**	**RR-4**	**p-value***
PCV-VG	12 (10-14)	12 (10-20)^{A}	12 (10-16)^{A}	12 (10-16)	0.408[1]
VCV	12 (10-14)^{b}	18 (13-30)^{Ba}	17 (13-28)^{Ba}	14 (9-24)^{ab}	**<0.001[1]***
FCV	12 (10-14)^{c}	17 (13-30)^{Bb}	17 (13-28)^{Bb}	13 (10-20)^{a}	**<0.001[1]***
p-value*	0.996[2]	**<0.001[2]***	**<0.001[2]***	0.148[2]	
Groups	**VT-1**	**VT-2**	**VT-3**	**VT-4**	**p-value***
PCV-VG	0.5 (0.4-0.6)	0.5 (0.4-0.5)^{A}	0.5 (0.4-0.6)^{A}	0.5 (0.4-0.6)	0.197[1]
VCV	0.5 (0.4-0.5)^{b}	0.4 (0.2-0.5)^{Ba}	0.4 (0.3-0.5)^{Ba}	0.5 (0.4-0.5)^{ab}	**0.001[1]***
FCV	0.5 (0.4-0.5)^{b}	0.4 (0.2-0.5)^{Bab}	0.4 (0-0.5)^{Ba}	0.4 (0.4-0.5)^{ab}	**0.007[1]***
p-value*	0.033[2]	**<0.001[2]***	**0.006[2]***	0.450[2]	
Groups	**$ETCO_2$-1**	**$ETCO_2$-2**	**$ETCO_2$-3**	**$ETCO_2$-4**	**p-value***
PCV-VG	14 (26-30.5)	14 (27-34)^{A}	14 (30-35.5)	14 (29-33)	0.780[1]
VCV	15 (26-32)^{b}	15 (28-35)^{Ba}	15 (30-37)^{a}	15 (29-35)^{ab}	**0.002[1]***
FCV	44 (23-30.5)^{b}	44 (27-32.5)^{Bab}	44 (24-34)^{a}	44 (27-33)^{ab}	**0.002[1]***
p-value*	0.507[2]	0.0072*	0.094[2]	0.033[2]	

Data are presented as median (minimum-maximum) *p<0.007 was considered statistically significant. [1]Friedman test, [2]Kruskal Wallis test. $^{A-C}$: For each parameter within columns, groups sharing the same letter are not significantly different (Dunn's test). $^{a-c}$: For each parameter within rows, groups sharing the same letter are not significantly different (Dunn's test).

MP: Mechanical power (cmH_2O J/min), DP: Driving pressure (cmH_2O), PEEP: Positive end-expiratory pressure (cmH_2O), PLATO: Plateau pressure (cmH_2O), PEAK: Peak inspiratory pressure (cmH_2O), RR: Respiratory rate (breaths per minute), Vt: Tidal volume (L), $ETCO_2$: End-tidal carbon dioxide (mmHg)

Table 4. Comparisons of MAP, SPO_2, and HR across groups at different time periods.

Groups	MAP-0	MAP-1	MAP-2	MAP-3	MAP-4	p*-value
PCV	98 (81-123)^{b}	67 (57-93)^{a}	68 (58-92)^{Aa}	82 (65-111)^{Aab}	76 (59-103)^{Aa}	**<0.001[1]***
VCV	99.8 (75.3-114.7)	85.8 (57.3-106.7)	103.3 (83.3-116)^{B}	96.2 (67.7-177)^{B}	97.2 (69.7-121.3)^{B}	0.035[1]
FCV	99.7 (82.3-119)	87 (60.7-114.3)	104.3 (79-125.3)^{B}	99.3 (76.7-114.7)^{B}	94 (81-131.3)^{B}	0.048[1]
p*-value	0.907[2]	0.026[2]	**<0.001[2]***	**0.006[2]***	**0.001[2]***	
Groups	**SPO_2-0**	**SPO_2-1**	**SPO_2-2**	**SPO_2-3**	**SPO_2-4**	**p*-value**
PCV	98 (96-100)	100 (98-100)	99 (97-100)	99 (96-100)	100 (95-100)	0.0120[1]
VCV	98 (95-100)^{b}	99.5 (98-100)^{ab}	99.5 (97-100)^{ab}	100 (98-100)^{ab}	100 (99-100)^{a}	**<0.001[1]***
FCV	98 (95-100)^{b}	100 (98-100)^{ab}	100 (96-100)^{ab}	100 (98-100)^{ab}	100 (99-100)^{a}	**<0.001[1]***
p-value	0.806[2]	0.445[2]	0.100[2]	0.255[2]	0.068[2]	
Groups	**HR-0**	**HR-1**	**HR-2**	**HR-3**	**HR-4**	**p*-value**
PCV	80 (55-115)^{b}	79 (54-91)^{b}	72 (53-117)^{ab}	64 (53-87)^{a}	67 (54-91)^{ab}	**0.001[1]***
VCV	79.5 (47-96)	74 (54-111)	67 (51-94)	71 (57-89)	68.5 (49-95)	0.009[1]
FCV	79 (47-104)^{b}	70 (54-111)^{ab}	68 (50-103)^{b}	70 (57-89)^{ab}	73 (53-95)^{ab}	**0.006[1]***
p-value	0.812[2]	0.991[2]	0.765[2]	0.168[2]	0.727[2]	

Data are presented as median (minimum-maximum). [1]Friedman test, [2]Kruskal Wallis test. p*<0.006 was considered statistically significant. $^{A-C}$: For each parameter within columns, groups sharing the same letter are not significantly different (Dunn's test). $^{a-c}$: For each parameter within rows, groups sharing the same letter are not significantly different (Dunn's test).

MAP: Mean arterial pressure (mmHg), SpO_2: Peripheral capillary oxygen saturation (%), HR: Heart rate (beats per minute, bpm), FCV: Flow-controlled ventilation, PCV: Pressure-controlled volume

in MP. Accordingly, PCV-VG's variable flow profile and dynamic pressure regulation allow better adaptation to increased IAP. Additionally, the lower rate of MP increase observed in the PCV-VG group between T1 and T3 may offer clinically significant advantages. First, a smaller increase in MP in the early stages of surgery may reduce the cumulative mechanical energy load transmitted to the lungs throughout the procedure, thus minimizing the risk of VILI during prolonged surgeries. Second, PCV-VG's more effective prevention of alveolar distortion in the pre-insufflation phase may enhance lung compensation during surgical stress, preserve pulmonary reserve, and increase the patient's tolerance to surgical stress. Therefore, although the final MP values were similar, this dynamic adaptation provided by PCV-VG may offer a clinically meaningful advantage, particularly in high-risk patients who have limited pulmonary reserve, who are obese, or who are undergoing prolonged surgery. However, prospective studies evaluating postoperative pulmonary complications and long-term outcomes are needed to confirm this hypothesis.

FCV is a strategy that controls gas flow during both inspiration and expiration, and it has been shown to be a safe ventilation method in various experimental and clinical studies[15]. In FCV, MP is a parameter comprising pressure, volume, and frequency components that are transmitted to the lungs. For MP calculation, integration of the pressure-volume curve is considered the gold standard[16]. Since inspiratory and expiratory flows are constant, the pressure waveform approximates a triangular profile. In a triangular pressure profile, the pressure-volume integral is approximately halved; thus, MP can be calculated using a simplified formula with a conversion factor of 0.49 instead of 0.98. This approach can be particularly useful for the rapid estimation of MP during FCV in clinical practice[6,11]. In our study, the integral method was not used for MP calculation during FCV; instead, MP was calculated using the formula advocated by Giosa et al.[11] A modified VCV formula was used for this calculation, as there is no universally accepted formula for FCV in the literature. Wittenstein et al.[17] reported, in a porcine model, that FCV reduced MP compared with VCV during one-lung ventilation. Abram et al.[18] reported, in human studies, that FCV reduced MP compared to PCV and improved oxygenation. Weber et al.[10] demonstrated in morbidly obese patients that, compared with VCV, FCV reduced the risk of atelectasis by minimizing lung collapse during expiration. Bialka et al.[2], in their literature review on FCV, suggested that FCV may be beneficial for patient groups at increased risk of compression atelectasis, such as those undergoing laparoscopy or surgery in the Trendelenburg position.

Although MP measured during CO_2 insufflation in the FCV group was lower than in other groups in our study (8.6 J/min; PCV-VG: 9.4 J/min, VCV: 8.7 J/min), the difference was not statistically significant. Additionally, insufflation led to a noticeable increase in MP compared with baseline. These findings suggest that FCV does not provide a significant advantage in laparoscopic surgeries; however, because data in the literature are limited, no definitive conclusion can be drawn.

The main limitation of our study is the small sample size. This is perhaps an inevitable issue of a cross-sectional retrospective analysis. Since FCV cannot be performed with standard anesthesia machines and requires additional equipment, its routine use in clinical practice is limited. This may explain the small sample sizes observed both in our study and in the existing literature. Nevertheless, we believe that our study contributes to the development of new strategies aimed at reducing the MP associated with mechanical ventilation during laparoscopic surgery. Another limitation is that postoperative outcomes associated with the ventilation modes were not assessed because our current dataset was not suitable for analyzing this relationship. The lack of adequate follow-up and postoperative data makes it difficult to objectively track postoperative complications based on retrospective records. Numerous confounding factors —such as the definition of postoperative pulmonary complications and the timing of their assessment— render the acquisition and interpretation of these parameters challenging. We believe that prospective studies with larger sample sizes focusing specifically on postoperative clinical outcomes are necessary to evaluate this issue. An additional limitation is that MP was calculated using simplified formulas because of the study's retrospective design. Although the accuracy of these formulas has been demonstrated in previous studies, the simplified formula has not been sufficiently or specifically tested for FCV. This may represent both a limitation of our study and a contribution to the literature. Our hypothesis was that FCV might be associated with lower MP during insufflation in laparoscopic surgery. However, FCV produced MP values similar to those of other modes. Therefore, we were not able to confirm our hypothesis. Nonetheless, new prospective randomized studies may help further develop this hypothesis. Moreover, no ventilation mode has yet been identified in either adult or pediatric laparoscopic surgery that has been proven to reduce complications or to be superior in terms of MP[19]. For this reason, we believe that our study will also contribute to the development of mechanical ventilation strategies in laparoscopic procedures.

CONCLUSION

This study demonstrates that PCV-VG, VCV, and FCV modes achieve similar MP levels during laparoscopic surgery; however, PCV-VG more effectively limits insufflation-induced increases in MP than the other modes. This feature may be clinically significant, particularly in high-risk patients with limited pulmonary reserve, with obesity, or scheduled for prolonged surgery. Our findings may contribute to clinical decisions regarding the optimization of ventilation strategies. However, prospective studies with larger sample sizes, including postoperative outcome assessments, are needed.

Ethics

Ethics Committee Approval: Ethical approval was received from the Scientific Research Ethics Committee of University of Health Sciences Türkiye, Kocaeli City Hospital Scientific Research Ethics Committee with protocol no: 2025-79, date: 10.07.2025.

Informed Consent: Due to the retrospective design individual patient consent waived.

Footnotes

Author Contributions

Surgical and Medical Practices: A.S., N.D., B.G., A.Y., Concept: A.S., N.D., A.Y., Design: A.S., N.D., A.Y., Data Collection and/or Processing: A.S., N.D., A.Y., Analysis or Interpretation:B.G., A.Y., Literature Search: A.S., A.Y., Writing: A.S., N.D., B.G., A.Y.

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