Impact of pressure-regulated volume control vs volume-controlled ventilation on respiratory mechanics in pediatric laparoscopic surgery: a randomized controlled trial

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KEY WORDS

carbon dioxide monitoring, laparoscopic surgery, pediatric anesthesia, pressure-regulated volume control, volume-controlled ventilation

ABSTRACT

INTRODUCTION Optimal ventilation during pediatric laparoscopic surgery is a debated issue, as pneumoperitoneum impairs respiratory mechanics and may increase ventilator-induced lung injury.

AIM We aimed to compare pressure-regulated volume control (PRVC) and volume-controlled ventilation (VCV) in young children, focusing on airway pressures and gas exchange.

MATERIALS AND METHODS A total of 120 children aged 1–3 years undergoing elective laparoscopic surgery (≥120 min) were enrolled and assigned to the PRVC or VCV groups. The primary outcome was peak inspiratory pressure (P_{peak}) at 30 minutes after pneumoperitoneum. Secondary outcomes included mean airway (P_{mean}), plateau (P_{plat}), and driving pressures (ΔP), partial pressure of end-tidal carbon dioxide ($PETCO_2$), arterial carbon dioxide partial pressure ($PaCO_2$), hemodynamics, $PaCO_2$-$PETCO_2$ Bland–Altman agreement, and complication rates.

RESULTS At 30 minutes, PRVC produced lower mean (SD) Ppeak than VCV (22.67 [4.18] vs 26.24 [4.51] cm H_2O; $P < 0.001$) and lower mean P_{mean} at multiple time points. However, P_{plat} and ΔP did not differ between the groups. The arterial-to-end-tidal CO_2 gradient was wider with PRVC at 30 minutes and after desufflation. Hemodynamic variables remained stable and similar between the groups. The Bland–Altman analysis showed acceptable agreement between $PaCO_2$ and $PETCO_2$ in both modes, with mean (SD) bias of 3.21 (0.48) in the PRVC and 1.91 (0.82) in the VCV cohorts. The complication rates were similar in both groups.

CONCLUSIONS In young children undergoing prolonged laparoscopic surgery, PRVC lowered P_{peak} and P_{mean} but did not reduce P_{plat} or ΔP, suggesting similar alveolar distention to that occurring in VCV. Both modes maintained adequate ventilation and stable hemodynamics. PRVC may improve airway pressure profiles, but its routine replacement with VCV should not rely on P_{peak} reduction alone.

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Received: April 24, 2026.
Revision accepted: May 26, 2026.
Published online: June 24, 2026.
Wideochir Inne Tech Maloinwazyjne. 2026; 21 (2): 139-147
doi:10.20452/wiitm.2026.18034

INTRODUCTION Minimally-invasive surgical advancements have popularized laparoscopic surgery in clinical practice.[1] For pediatric patients, whose smaller abdominal cavities and limited surgical space present unique challenges, laparoscopy offers significant advantages over traditional open surgery by mitigating issues, such as large incisions or excessive fluid and temperature loss. It is now widely applied in various procedures, including Hirschsprung disease resection, appendectomy, pyloromyotomy, hernia repair, and orchidopexy.[2,3]

The widespread adoption of the Enhanced Recovery After Surgery guidelines has further propelled the use of laparoscopy due to its role in reducing perioperative stress, accelerating recovery, and shortening length of hospital stay.[4] However, laparoscopic surgery is not without challenges. The requisite carbon dioxide (CO_2) pneumoperitoneum increases intra-abdominal pressure,

which elevates the diaphragm, restricts thoracic and pulmonary movement, and, consequently, reduces lung compliance and functional residual capacity. This can lead to ventilation/perfusion (V/Q) imbalances and an increased risk of postoperative pulmonary complications, such as atelectasis and ventilator-induced lung injury (VILI).[5,6] Children are particularly susceptible to such complications, as their relatively large peritoneal surface area-to-body mass ratio enhances CO_2 absorption, predisposing them to hypercapnia and subcutaneous emphysema. Given these physiological challenges, optimizing intraoperative mechanical ventilation is of paramount importance to ensure patient safety.

Volume-controlled ventilation (VCV), a commonly used technique, delivers a constant tidal volume (VT) using a constant (square) inspiratory flow, but can lead to high peak inspiratory pressures (P_{peak}), particularly when lung compliance is poor (eg, during pneumoperitoneum), which increases the theoretical risk of airway trauma. In contrast, pressure-regulated volume control (PRVC) is a pressure-targeted, volume-guaranteed dual-control approach.[7] It delivers a preset VT using a decelerating flow pattern while continuously adjusting the inspiratory pressure limit breath-by-breath based on measured dynamic compliance.[8] However, it is crucial to recognize that VILI is predominantly driven by excessive plateau (P_{plat}) and driving pressures (ΔP), rather than P_{peak}. While PRVC's decelerating flow naturally lowers P_{peak}, its true protective advantage against alveolar overdistension, as compared with VCV, remains a subject of debate in the operating room setting, especially in healthy lungs.[9]

Despite its theoretical benefits, there is a paucity of robust evidence comparing PRVC and VCV, specifically in the context of prolonged pediatric laparoscopic surgery. Furthermore, while end-tidal CO_2 ($PETCO_2$) is a standard noninvasive monitor for ventilation, its agreement with arterial CO_2 partial pressure ($PaCO_2$) can be affected by the V/Q mismatch induced by pneumoperitoneum. Previous studies often erroneously relied on correlation coefficients to assess this relationship, which is statistically inappropriate for evaluating the interchangeability of 2 clinical measurement methods; instead, the Bland–Altman agreement analysis is the methodological gold standard.[10]

AIM The primary objective of this study was to compare the effects of PRVC and VCV on respiratory mechanics in young children undergoing laparoscopic surgery, with P_{peak} as the primary outcome. Secondary objectives included comparisons of alveolar pressures (P_{plat} and ΔP) and other respiratory and hemodynamic parameters, evaluation of the Bland–Altman agreement between $PETCO_2$ and $PaCO_2$ in both ventilation modes, and assessment of perioperative complications.

MATERIALS AND METHODS

Study design and ethics This prospective, single-center, randomized controlled trial was conducted at the Hebei Children's Hospital Affiliated to Hebei Medical University, Shijiazhuang, Hebei, China, between June 2021 and November 2023. The study protocol was approved by the hospital's Ethics Committee (220) and adhered to the provisions set out in the Declaration of Helsinki. The trial was retrospectively registered with the Chinese Clinical Trial Registry (ChiCTR2400093409). Written informed consent was obtained from the legal guardians of all participants before enrollment. The reporting of this trial followed the CONSORT guidelines, endorsed by the Enhancing the Quality and Transparency of Health Research Network.[11]

Patient selection The inclusion criteria were: 1) age between 1 and 3 years; 2) American Society of Anesthesiologists (ASA) physical status I or II; 3) scheduled elective laparoscopic surgery (eg, appendectomy, hydrocelectomy, inguinal hernia repair) with an anticipated duration equal to or greater than 120 minutes; and 4) no pre-existing severe organic, cardiopulmonary, or respiratory diseases (eg, asthma). The exclusion criteria comprised: 1) recent (≤2 weeks) upper respiratory tract infection; 2) known malignant tumors; 3) congenital heart disease or other conditions causing cardiac insufficiency; 4) severe liver or kidney dysfunction; 5) body mass index above 95th percentile for age and sex; 6) known allergy to the anesthetic agents used in the study; 7) intraoperative conversion to open surgery; and 8) a lack of parental consent.

Randomization and blinding The eligible patients were randomly allocated in a 1:1 ratio to either the PRVC or VCV group. Randomization was performed using a computer-generated random number sequence utilizing block randomization with a block size of 4, with allocation concealment maintained through sequentially numbered, opaque, and sealed envelopes. The envelopes were opened in the operating room by an anesthesiologist not involved in patient care or data collection. Due to the nature of the intervention, the attending anesthesiologist administering the ventilation could not be blinded. However, the postoperative data collectors, statisticians, and patients guardians were blinded to group allocation.

Sample size calculation The sample size was calculated based on the primary outcome, P_{peak} at 30 minutes after establishing pneumoperitoneum. Based on a pilot study and previous literature adjustments,[12] we anticipated mean (SD) P_{peak} of 23.5 (4.5) cm H_2O in the PRVC group and 26 (4.5) cm H_2O in the VCV group. To detect this difference with a statistical power (1-β) of 80% and a 2-sided significance level (α) of 0.05, using a 2-sample *t* test, a sample size of 52 patients per group was required. To account for a potential dropout rate of approximately

15%, we aimed to enroll 60 patients in each cohort, for a total of 120 participants. This justified the sample size strictly without exposing pediatric patients to unnecessary interventions.

Anesthesia and ventilation protocol All participants fasted for 6 hours for solids and 2 hours for clear fluids preoperatively. As premedication, Emla cream (Aspen Pharmacare, uMhlanga, Republic of South Africa; 2.5% lidocaine and 2.5% prilocaine) was applied topically to the intended intravenous cannulation site 45 minutes before transfer to the operating room, and oral midazolam (0.5 mg/kg) was administered 30 minutes prior to surgery to minimize preoperative anxiety. On arrival in the operating room, standard noninvasive monitoring was established, including measurements of blood pressure, peripheral oxygen saturation (SpO_2), and nasopharyngeal temperature, using a Primus anesthesia workstation (Dräger, Lübeck, Germany). Electrocardiography was also performed.

Anesthesia was induced intravenously with midazolam (0.1 mg/kg), fentanyl (2 μg/kg), propofol (2–3 mg/kg), and rocuronium (0.6 mg/kg). Following endotracheal intubation using a cuffed endotracheal tube (size calculated according to the formula: age/4 + 3.5 mm, with intracuff pressure maintained at 15–20 cm H_2O to prevent gas leak and aspiration), a 22-gauge radial artery catheter was inserted for invasive arterial blood pressure monitoring and blood gas analysis. This invasive procedure, required for the study's scientific objectives, was explicitly detailed in the informed consent form. Anesthesia was maintained with sevoflurane (1.5%–2.5% end-tidal concentration), a continuous infusion of remifentanil (0.1–0.3 μg/kg/min), and intermittent boluses of rocuronium to maintain deep neuromuscular blockade, guided by train-of-four (TOF) monitoring (aiming for TOF count of 0–1).

All patients were ventilated using the integrated ventilator of the anesthesia workstation. The initial ventilation settings for both groups were: VT 8 ml/kg of ideal body weight, inspiratory-to-expiratory ratio of 1:2, and an initial respiratory rate (RR) of 18 breaths/min. Positive end-expiratory pressure (PEEP) was set to 5 cm H_2O in all patients to mitigate the development of compression atelectasis caused by the pneumoperitoneum and supine positioning, and the fraction of inspired oxygen was maintained at 0.6 (avoiding 1 to prevent absorption atelectasis) with an air-oxygen mixture. The RR was subsequently adjusted to maintain $PETCO_2$ between 35 and 45 mm Hg.

In the PRVC group, the patients were ventilated in a dual-control mode utilizing pressure-limited, time-cycled breaths, with a decelerating flow to guarantee the preset volume, and the target VT of 8 ml/kg. In the VCV group, the participants were ventilated with the VT set to 8 ml/kg and a constant (square-wave) flow pattern.

Laparoscopic surgery was performed using a standard 3-port technique. Pneumoperitoneum was established and maintained at a constant intra-abdominal pressure of 10–12 mm Hg using a Karl Storz Endoflator device (Tuttlingen, Germany). If Ppeak exceeded 35 cm H_2O, the surgeon was asked to briefly reduce the insufflation pressure, and if $PaCO_2$ rose above 50 mm Hg despite RR adjustments, VT was reduced. No patients were excluded intraoperatively for these reasons. At the end of surgery, residual neuromuscular blockade was reversed with neostigmine (0.05 mg/kg) and atropine (0.02 mg/kg), and the patients were extubated when they met standard criteria (eg, spontaneous breathing, SpO_2 >95% on room air, intact protective reflexes).

Data collection and outcomes Data were collected at 4 time points: T0 (baseline, 5 min after intubation and before establishing pneumoperitoneum), T1 (15 min after establishing pneumoperitoneum), T2 (30 min after establishing pneumoperitoneum), and T3 (10 min after abdominal gas desufflation).

Primary and secondary outcomes The primary outcome was P_{peak} at T2. Secondary outcomes included: 1) hemodynamic indicators: heart rate (HR) and mean arterial pressure (MAP); 2) respiratory indicators: SpO_2, $PaCO_2$, $PETCO_2$, mean airway pressure (P_{mean}), P_{plat}, measured via an inspiratory pause of 10% of the inspiratory cycle (given the short time constants in pediatric lungs, even this brief pause is sufficient for airway pressure to equilibrate and accurately reflect alveolar P_{plat}),[13] ΔP (calculated as P_{plat} – PEEP), RR, and the arterial-to-end-tidal CO_2 gradient (Pa-$ETCO_2$; calculated as $PaCO_2$ – $PETCO_2$); arterial blood gas samples were drawn at each time point; 3) agreement analysis: the clinical agreement between $PETCO_2$ and $PaCO_2$ assessed at T2 in both groups using the Bland–Altman method; and 4) complications: the incidence of postoperative nausea and vomiting, hypotension, bradycardia, atelectasis, pulmonary edema, barotrauma, and pulmonary infection within the first 24 hours. Barotrauma was strictly defined as a new onset of pneumothorax, pneumomediastinum, or subcutaneous emphysema confirmed on postoperative chest X-ray.

Statistical analysis Statistical analysis was performed using SPSS Statistics software, version 26.0 (IBM Corp., Armonk, New York, United States) and GraphPad Prism, version 9.0 (GraphPad Software, San Diego, California, United States). The normality of continuous variables was assessed using the Shapiro–Wilk test and visual inspection of Q-Q plots. Normally distributed continuous data are presented

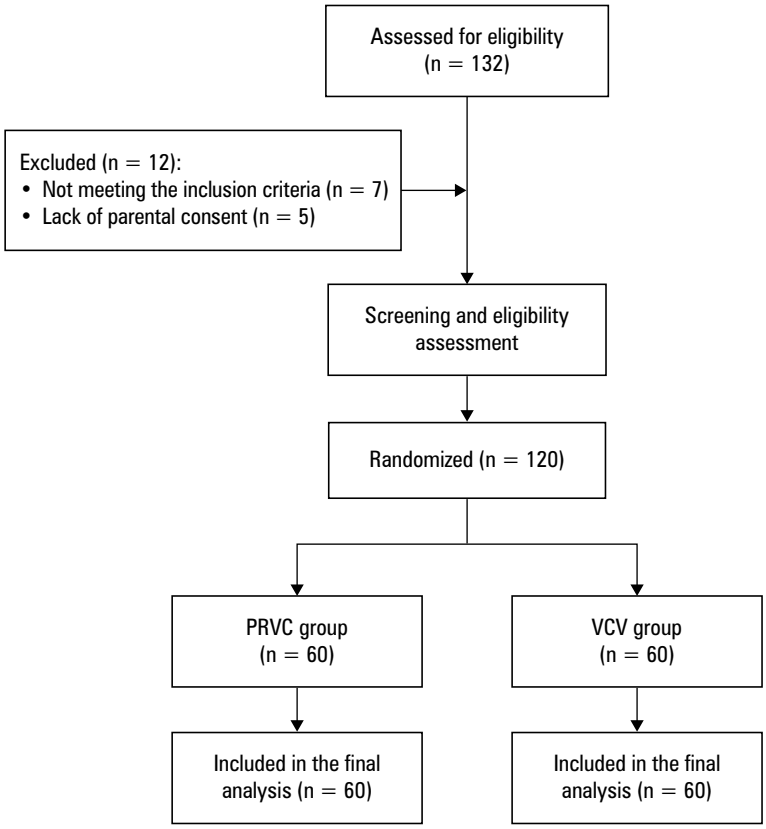

FIGURE 1 2010 CONSORT flow diagram of patient enrollment and allocation

Abbreviations: PRVC, pressure-regulated volume control; VCV, volume-controlled ventilation

TABLE 1 Demographic and baseline clinical characteristics of the study population

Parameter		PRVC group (n = 60)	VCV group (n = 60)
Sex	Boys	38 (63.3)	36 (60)
	Girls	22 (36.7)	24 (40)
Age, y		2.19 (0.58)	2.26 (0.64)
ASA class	I	45 (75)	47 (78.3)
	II	15 (25)	13 (21.7)
Primary disease	Appendicitis	29 (48.3)	27 (45)
	Hydrocele	17 (28.3)	18 (30)
	Inguinal hernia	14 (23.3)	15 (25)
Operative time, min		203.92 (21.28)	200.92 (19.78)

Data are presented as number (percentage) or mean (SD).

Abbreviations: ASA, American Society of Anesthesiologists; others, see **FIGURE 1**

as mean (SD). Comparisons of patient demographics were performed using the independent *t* test. For repeated measures over time (eg, P_{peak}, P_{mean}, P_{plat}, HR, MAP), a mixed-model analysis of variance (ANOVA) was employed with "time" as the within-subject factor and "group" as the between-subject factor. The Geisser–Greenhouse correction was applied if the sphericity assumption was violated. Post hoc multiple comparisons between the groups at specific time points were adjusted using the Bonferroni correction to minimize type I errors.

Categorical data are presented as numbers (percentages), and were compared using the χ^2 test or the Fisher exact test (when expected cell counts were <5), as appropriate. For the complication analysis, relative risk and the number needed to treat (NNT) were calculated for the total incidence. To appropriately assess the interchangeability of $PaCO_2$ and $PETCO_2$, Bland–Altman plots were generated. Mean bias and 95% limits of agreement (LoAs; calculated as mean bias of 1.96) were reported. Correlation coefficients (*r*) were explicitly avoided for this end point, as correlation measures the strength of a linear relationship, not clinical agreement. A 2-tailed *P* value below 0.05 was considered significant. Given the multiple secondary end points, findings with *P* values between 0.01 and 0.05 were interpreted with caution.

RESULTS **Patient enrollment and baseline characteristics** A total of 132 pediatric patients were assessed for eligibility between June 2021 and November 2023. Twelve patients were excluded due to not meeting the inclusion criteria (n = 7) or a lack of parental consent (n = 5). The remaining 120 patients were randomized into the PRVC group (n = 60) or the VCV group (n = 60). All 120 participants received the allocated intervention and completed the study protocol, and their data were included in the final analysis. The complete patient enrollment and flow process is detailed in the CONSORT diagram in **FIGURE 1**. Baseline characteristics, including sex, age, ASA physical status, primary disease type, and operative time, were comparable between the groups, with no clinically relevant differences observed (**TABLE 1**).

Hemodynamic outcomes At baseline (T0), there were no significant differences in HR or MAP between the groups. A mixed-model ANOVA showed the effect of time on both HR and MAP ($P < 0.001$), reflecting the physiological response to pneumoperitoneum. Following the establishment of pneumoperitoneum, both HR and MAP increased from T0 to T1 and from T1 to T2 in both groups, returning toward baseline at T3. However, there was no significant group-by-time interaction for HR or MAP, and post hoc Bonferroni comparisons confirmed no differences between the PRVC and VCV groups at any individual time point (eg, $P = 0.44$ for HR at T2 and $P = 0.487$ for MAP at T2; **TABLE 2**; **FIGURE 2**).

Respiratory outcomes There were no significant differences in any respiratory parameters at T0. The primary outcome, P_{peak} at T2, was lower in the PRVC than the VCV group (mean [SD], 22.67 [4.18] vs 26.24 [4.51] cm H_2O; adjusted $P < 0.001$). A similar difference was observed at T3 ($P = 0.041$). Furthermore, P_{mean} was markedly lower in the PRVC group at T1, T2, and T3 ($P < 0.001$, $P < 0.001$, and $P = 0.01$, respectively). However, a mixed-model ANOVA demonstrated

TABLE 2 Hemodynamic parameters of the study population

Index	Time point	PRVC group (n = 60)	VCV group (n = 60)	Group-by-time interaction *P* value	Post hoc *P* value[a]
Heart rate, bpm	T0	74.77 (11.47)	73.88 (11.29)	0.67	0.67
	T1	74.97 (11.32)	75.98 (11.67)		0.62
	T2	74.89 (11.94)	76.51 (11.09)		0.44
	T3	74.36 (11.76)	73.67 (11.17)		0.74
Mean arterial pressure, mm Hg	T0	76.87 (8.83)	77.91 (8.09)	0.51	0.5
	T1	84.03 (8.67)	85.54 (9.09)		0.35
	T2	83.87 (8.56)	84.99 (9.16)		0.49
	T3	77.46 (8.32)	78.76 (9.07)		0.42

Data are presented as mean (SD).

a Post hoc multiple comparisons were adjusted using the Bonferroni correction.

Abbreviations: see **FIGURE 1**

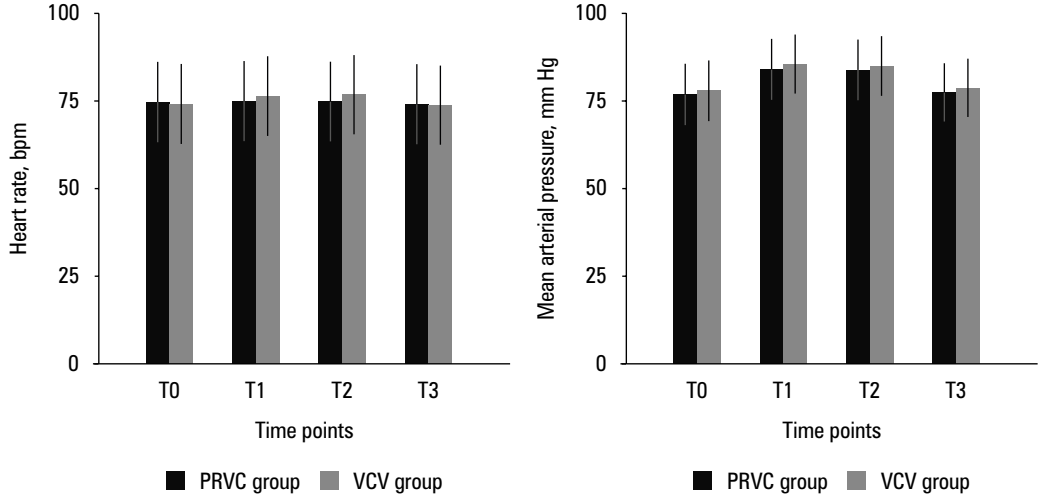

FIGURE 2
Hemodynamic parameters (heart rate and mean arterial pressure) in the pressure-regulated volume control and volume-controlled ventilation groups at different time points. Data are presented as mean (SD).

Abbreviations: see **FIGURE 1**

no differences in P_{plat} between the 2 groups at T2 (mean [SD], 18.12 [2.34] vs 18.55 [2.51] cm H_2O; P = 0.34) or any other time point. Consequently, ΔP, was also comparable between the groups throughout the surgery (T2, mean [SD] 13.12 [2.34] vs 13.55 [2.51] cm H_2O; P = 0.34).

$PETCO_2$ was considerably lower in the PRVC group at T2 and T3 (P <0.001). Conversely, Pa-$ETCO_2$ gradient was higher in the PRVC cohort at T2 and T3 (P <0.001 and P = 0.002, respectively). SpO_2, $PaCO_2$, and the adjusted RR did not differ between the groups at any time point (eg, P = 0.35 to 0.81; **TABLE 3**; **FIGURE 3**).

Agreement between partial pressure of end-tidal carbon dioxide and arterial carbon dioxide partial pressure To appropriately assess the interchangeability of $PETCO_2$ and $PaCO_2$, a Bland–Altman analysis was conducted at T2. In the PRVC group, mean (SD) bias between $PaCO_2$ and $PETCO_2$ was 3.21 (0.48) mm Hg, with 95% LoA ranging from –1.1 to 7.5 mm Hg (**FIGURE 4**). In the VCV group, mean (SD) bias was slightly lower at 1.91 (0.82) mm Hg, with 95% LoA ranging from –1.5 to 5.3 mm Hg (**FIGURE 5**). Both modes demonstrated clinically acceptable agreement, as the vast majority of data points fell within the 95% LoA, although the PRVC cohort exhibited a slightly wider bias and LoA during pneumoperitoneum than the VCVgroup.

Complications The overall incidence of postoperative complications was lower in the PRVC group (3.33%), as compared with the VCV cohort (10%), but this difference was insignificant. The relative risk for developing a complication in the VCV group, in comparison with the PRVC group, was 3 (95% CI, 0.64–14), with an NNT of 15 to prevent 1 additional complication by using PRVC. Notably, 2 cases of barotrauma (subcutaneous emphysema) occurred in the VCV group, while none occurred in the PRVC cohort; this difference was not significant due to the low event rate (**TABLE 4**).

DISCUSSION This randomized controlled trial demonstrated that, in young children undergoing prolonged laparoscopic surgery, PRVC resulted in significantly lower P_{peak} and P_{mean}, as compared with traditional VCV. However, our newly added analyses showed that P_{plat} and ΔP remained unchanged in both modes. Furthermore, a rigorous Bland–Altman analysis confirmed that both techniques provide clinically acceptable agreement between $PETCO_2$ and $PaCO_2$, although a slightly

TABLE 3 Respiratory parameters in the study groups

Index	Time point	PRVC group (n = 60)	VCV group (n = 60)	Group-by-time interaction *P* value	Post hoc *P* value[a]
P_{peak}, cm H_2O	T0	13.48 (2.32)	13.04 (2.41)	<0.001	0.31
	T1	20.67 (5.34)	22.37 (5.45)		0.09
	T2	22.67 (4.18)	26.24 (4.51)		<0.001
	T3	14.29 (2.09)	15.08 (2.02)		0.04
P_{plat}, cm H_2O	T0	12.21 (1.45)	12.18 (1.52)	0.43	0.91
	T1	17.55 (2.11)	17.82 (2.25)		0.49
	T2	18.12 (2.34)	18.55 (2.51)		0.34
	T3	12.45 (1.67)	12.61 (1.72)		0.61
ΔP, cm H_2O	T0	7.21 (1.45)	7.18 (1.52)	0.43	0.91
	T1	12.55 (2.11)	12.82 (2.25)		0.49
	T2	13.12 (2.34)	13.55 (2.51)		0.34
	T3	7.45 (1.67)	7.61 (1.72)		0.61
P_{mean}, cm H_2O	T0	6.81 (1.02)	6.95 (1.15)	<0.001	0.48
	T1	8.54 (1.55)	9.89 (1.82)		<0.001
	T2	9.12 (1.68)	11.45 (2.01)		<0.001
	T3	7.03 (1.21)	7.64 (1.33)		0.01
$PETCO_2$, mm Hg	T0	36.21 (2.12)	35.98 (2.61)	<0.001	0.6
	T1	38.23 (2.03)	38.83 (2.34)		0.14
	T2	38.38 (1.91)	40.19 (2.41)		<0.001
	T3	37.23 (1.36)	38.98 (1.67)		<0.001
$PaCO_2$, mm Hg	T0	2.52 (0.26)	2.41 (0.38)	<0.001	0.07
	T1	2.34 (0.38)	2.59 (1.11)		0.1
	T2	3.21 (0.48)	1.91 (0.82)		<0.001
	T3	2.14 (1.29)	1.26 (1.7)		0.002

Data are presented as mean (SD).

a Post hoc multiple comparisons were adjusted using the Bonferroni correction.

Abbreviations: ΔP, driving pressure; $PaCO_2$, arterial carbon dioxide partial pressure; $PETCO_2$, partial pressure of end-tidal carbon dioxide; P_{mean}, mean airway pressure; P_{peak}, peak inspiratory pressure P_{plat}, plateau pressure; others, see **FIGURE 1**

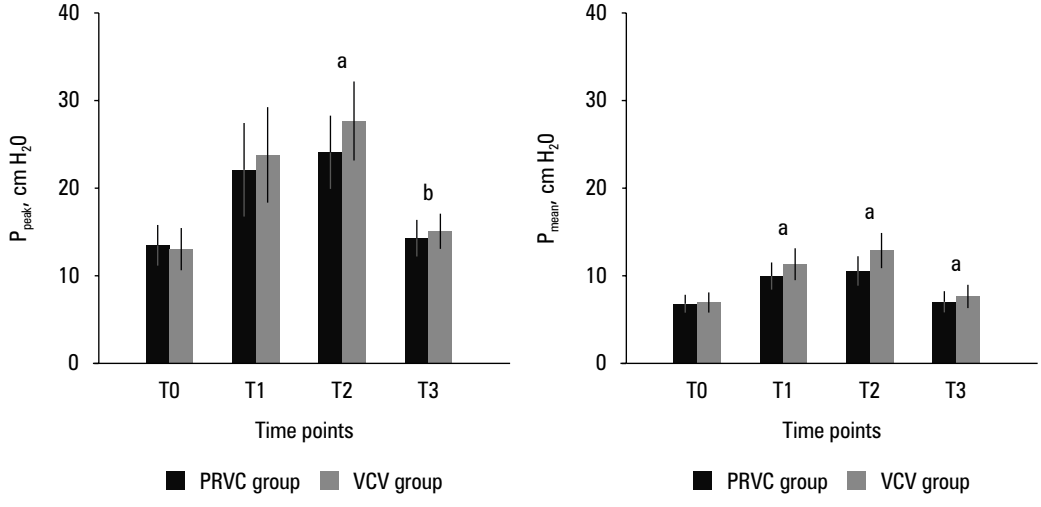

FIGURE 3 Key respiratory mechanics parameters (P_{peak} and P_{mean}) in the study groups. Pressure-regulated volume control resulted in significantly lower P_{peak} and P_{mean} during pneumoperitoneum, but P_{plat} and ΔP remained identical in both groups. Data are presented as mean (SD).

a $P < 0.01$

b $P < 0.05$

Abbreviations: see **FIGURE 1** and **TABLE 3**

wider bias was observed during PRVC. This primary finding suggests that, while PRVC alters the flow dynamics and peak resistive pressures, its direct superiority over VCV in preventing alveolar overdistension in healthy pediatric lungs may be overstated.

The reduction in P_{peak} observed in the PRVC group is a predictable consequence of its flow delivery algorithm. It is a common misconception to label PRVC as an "intelligent" mode that mimics lung physiology; rather, it is fundamentally a pressure-targeted, time-cycled mode with a volume guarantee. PRVC delivers target tidal volume with a decelerating flow pattern, which distributes gas more evenly and avoids the high resistive pressures that can occur with the constant

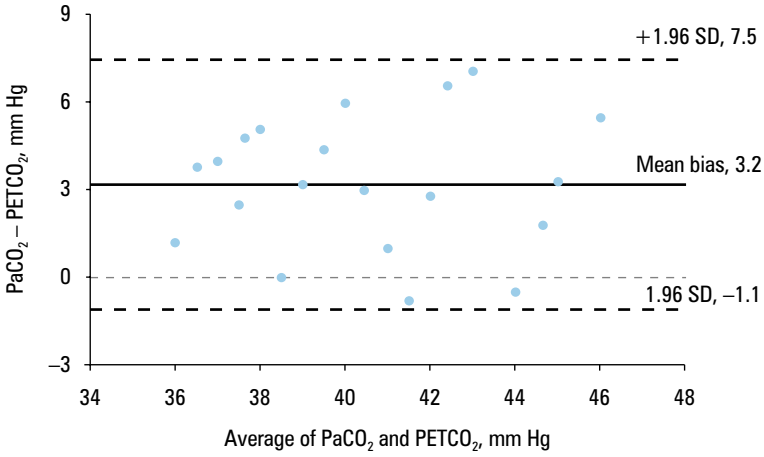

FIGURE 4 Bland–Altman plot assessing the agreement between $PaCO_2$ and $PETCO_2$ in the pressure-regulated volume control group during pneumoperitoneum (T2). The solid line represents mean bias (3.2 mm Hg), the dashed lines correspond to the 95% limits of agreement (–1.1 to 7.5 mm Hg), and the dots represent individual patient measurements.

Abbreviations: $PaCO_2$, arterial carbon dioxide partial pressure; $PETCO_2$, partial pressure of end-tidal carbon dioxide

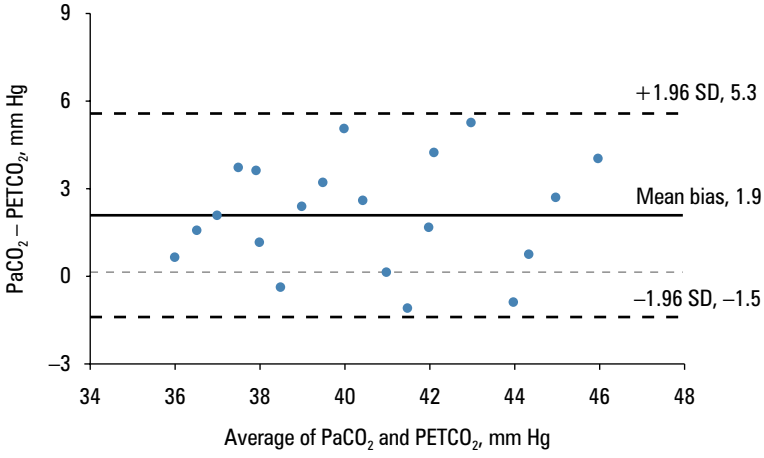

FIGURE 5 Bland–Altman plot assessing the agreement between $PaCO_2$ and $PETCO_2$ in the volume-controlled ventilation group during pneumoperitoneum (T2). The solid line represents mean bias (1.9 mm Hg), the dashed lines correspond to the 95% limits of agreement (–1.5 to 5.3 mm Hg), and the dots represent individual patient measurements.

Abbreviations: see **FIGURE 4**

(square-wave) flow in VCV, especially when lung compliance is reduced by pneumoperitoneum.[8,14] However, elevated Ppeak primarily reflects overcoming the resistance of the endotracheal tube and proximal airways, not the static stress placed on the alveoli. The true driver of VILI and barotrauma is excessive alveolar distension, which is best estimated by P_{plat} and ΔP.[9,15] Our findings explicitly show that P_{plat} and ΔP did not differ between PRVC and VCV. Since both modes delivered identical tidal volumes against the same intra-abdominal pressure, the elastic recoil of the respiratory system—and thus the alveolar stretch—were identical. Therefore, the isolated reduction in P_{peak} does not inherently translate into superior lung protection, corroborating recent physiological evidence in operating room settings.[16,17]

The concurrent reduction in P_{mean} in the PRVC group is also noteworthy. While lower P_{mean} can sometimes compromise oxygenation, in our study, SpO_2 remained clinically acceptable and did not differ between the groups, indicating that lower pressures did not negatively impact oxygenation. This finding supports PRVC's capability of achieving adequate gas exchange without sacrificing ventilation adequacy.[18]

An interesting secondary finding was the wider Pa-$ETCO_2$ gradient and the corresponding larger mean bias in the Bland–Altman analysis in the PRVC group during pneumoperitoneum (at T2 and T3). A wider gradient typically signifies an increase in physiological dead space or a greater V/Q mismatch, as alveolar dead space expansion and ventilation–perfusion imbalance directly contribute to this divergence.[19,20] In the context of laparoscopy, CO_2 absorption from the peritoneum increases $PaCO_2$, while diaphragmatic elevation causes atelectasis that exacerbates V/Q mismatch, thereby affecting $PETCO_2$ accuracy.[21] The wider gradient observed in the PRVC group—despite lower airway pressures—suggests a complex interaction: although PRVC reduces P_{peak}, its decelerating flow pattern may alter regional gas distribution, as compared with VCV, potentially amplifying V/Q heterogeneity under pneumoperitoneum-specific conditions.[22] It is plausible that the decelerating flow profile of PRVC, while reducing dynamic airway resistance, might subtly increase the shunt fraction or derecruitment in dependent lung regions in comparison with the constant flow and higher Pmean associated with VCV. This indicates that the Pa-$ETCO_2$ gradient is influenced multifactorially and should be interpreted cautiously.[23,24]

Previous analyses assessing the relationship between $PETCO_2$ and $PaCO_2$ frequently relied on correlation coefficients (r), which fundamentally misrepresents the data by assessing linear relationship rather than clinical agreement. Addressing this critical methodological flaw, we utilized the Bland–Altman analysis. Our results demonstrated a mean bias of 3.2 mm Hg in the PRVC group and 1.9 mm Hg in the VCV group, with acceptable limits of agreement. This indicates that, while $PETCO_2$ systematically underestimates $PaCO_2$, the difference is predictable and clinically acceptable for continuous monitoring in healthy children undergoing laparoscopy.[10] Importantly, the ventilation mode did not disrupt clinical reliability of capnography, though providers should be mindful of the slightly larger discrepancy when using PRVC.

From a hemodynamic perspective, both ventilation modes were well tolerated, with no significant differences in HR or MAP. This is consistent with the fact that no dramatically different mean

TABLE 4 Postoperative complications in the study population[a]

Complication	PRVC group (n = 60)	VCV group (n = 60)	*P* value
Nausea and vomiting	1 (1.67)	1 (1.67)	>0.99
Hypotension	0	1 (1.67)	>0.99
Bradycardia	1 (1.67)	1 (1.67)	>0.99
Atelectasis	0	0	–
Barotrauma	0	2 (3.33)	0.495
Pulmonary infection	0	1 (1.67)	>0.99
Total incidence	2 (3.33)	6 (10)	0.14

Data are presented as number (percentage).

a The rates were calculated using the Fisher exact test.

Abbreviations: see **FIGURE 1**

intrathoracic pressures that would impair venous return were applied in any of the 2 modes. However, our findings also showed lower, though nonsignificant, complication rates in the PRVC group, including 2 cases of barotrauma (subcutaneous emphysema) in the VCV group and none in the PRVC cohort. While the study was not powered to detect differences in rare complications, this observation is mechanistically plausible but must be interpreted with extreme caution given the identical P_{plat} values. Subcutaneous emphysema during laparoscopy is more frequently related to surgical technique (eg, retroperitoneal CO_2 tracking from port sites) rather than alveolar rupture from mechanical ventilation.

Limitations This study has several limitations that must be acknowledged. First, it was conducted in a single center with a relatively small sample size, which limits the generalizability of our findings and the statistical power to detect differences in less common outcomes (complications). Second, due to the nature of the intervention, the attending anesthesiologist could not be blinded to the ventilation mode, which could introduce performance bias, although data collectors and analysts were blinded. Third, while we standardized many aspects of anesthesia, the adjustment of RR to target a $PETCO_2$ range may have introduced variability. Reporting the final RR as an outcome helps mitigate this, but it remains a potential confounder. Fourth, the ethical considerations of placing an invasive arterial line in all patients for a study, even with consent, must be recognized; this practice is not routine for all such surgeries. Fifth, although we derived P_{plat} and ΔP, continuous monitoring via esophageal manometry to measure transpulmonary pressure was not feasible, limiting our assessment of true lung stress. Sixth, a notable limitation was the use of a fixed PEEP of 5 cm H_2O for all patients. Since optimal PEEP can vary based on individual lung mechanics during pneumoperitoneum, using a standardized rather than individualized PEEP titration could theoretically influence ΔP calculations and overall respiratory mechanics.[11] Moreover, our observation period for complications was limited to the first 24 postoperative hours. This timeframe may not be sufficiently long to capture delayed postoperative pulmonary complications, such as late-onset atelectasis or pneumonia. As highlighted by recent comprehensive reviews on perioperative respiratory outcomes, these complications often manifest several days after surgery, with most standardized assessments necessitating an observation window of at least 7 to 30 days to ensure accurate detection.[25] Finally, the trial was registered retrospectively, which is a deviation from ideal trial conduct standards.

CONCLUSIONS In conclusion, for young children aged 1–3 years undergoing prolonged laparoscopic surgery, PRVC provides a significant advantage over VCV by reducing both peak and mean airway pressures due to its decelerating flow pattern. However, PRVC does not lower P_{plat} and ΔP, suggesting its capability to mitigate alveolar stretch and VILI is comparable to VCV. Furthermore, the Bland–Altman analysis confirmed that capnography reliably reflects arterial CO_2 trends in both modes, despite a marginally wider bias during PRVC. Both techniques are safe and effective, and their selection should be tailored to individual clinical scenarios rather than assumed generalized superiority of PRVC. Larger, multicenter trials powered for clinical outcomes are warranted to confirm these findings.

ARTICLE INFORMATION

ACKNOWLEDGMENTS None.

FUNDING This study was supported by the Medical Science Research Project of Hebei (No. 202115245; to JS).

CONTRIBUTION STATEMENT JS and WB: conception and design of the study. WC and XL: data acquisition. LS and HW: statistical analysis. JS: writing. WB and WC: revision. All authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST None declared.

AI STATEMENT Artificial intelligence was not used in the preparation of this manuscript.

HOW TO CITE Jing S, Wenjuan B, Wenjing C, et al. Impact of pressure-regulated volume control vs volume-controlled ventilation on respiratory mechanics in pediatric laparoscopic surgery: a randomized controlled trial. Wideochir Inne Tech Maloinwazyjne. 2026; 21: 139-147. doi:10.20452/wiitm.2026.18034

JOURNAL INFORMATION

Videosurgery and Other Miniinvasive Techniques is an official journal of the Videosurgery Foundation.

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