Comparing Ventilation Modes for Elderly Patients in Prone Spinal Surgery: A Randomized Trial of VCV versus PCV-VG

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Abstract

Background: Pressure-controlled ventilation with volume guarantee (PCV-VG) is a newer ventilation mode that combines the advantages of both pressure and volume control. We performed this study to compare the effect of PCV-VG versus volume-controlled ventilation (VCV) on respiratory function in elderly patients undergoing prone spinal surgery.
Methods: Forty patients aged 65-75 years (ASA II-III, BMI 18.5-25 kg/m^2) undergoing spinal surgery were randomized into PCV-VG group (P, n=20) or VCV group (V, n=20). Measurements were taken at six timepoints: before anesthesia ($\boldsymbol{T_0}$), after intubation ($\boldsymbol{T_1}$), after prone positioning ($\boldsymbol{T_2}$), 60 min in the prone position ($\boldsymbol{T_3}$), after return to supine ($\boldsymbol{T_4}$), and post-extubation ($\boldsymbol{T_5}$). We recorded respiratory mechanics ($\boldsymbol{P}_{\text{peak}}$, $\boldsymbol{P}_{\text{mean}}$, $\boldsymbol{C}_{\text{dyn}}$), hemodynamics (HR, MAP), and blood gas parameters ($PaO_{\mathbf{2}}$, OI, A-a$DO_{\mathbf{2}}$, $\boldsymbol{Q_s/Q_t}$, $PaCO_{\mathbf{2}}$, RI, $\boldsymbol{V_D/V_T}$).
Results: The P group demonstrated significantly higher $\boldsymbol{C}_{\text{dyn}}$ at all timepoints and lower $\boldsymbol{P}_{\text{peak}}$ with higher $\boldsymbol{P}_{\text{mean}}$ at $\boldsymbol{T_3}$ ($\boldsymbol{p < 0.05}$). At $\boldsymbol{T_3}$, the P group showed significantly higher $PaO_{\mathbf{2}}$ and OI values with lower A-a$DO_{\mathbf{2}}$ and $\boldsymbol{Q_s/Q_t}$ compared to V group ($\boldsymbol{p < 0.05}$). No significant differences were observed in hemodynamics, pH, $PaCO_{\mathbf{2}}$, RI, $\boldsymbol{V_D/V_T}$, or postoperative pulmonary complications between groups.
Conclusion: For elderly patients with a row of spine surgery, applying PCV-VG mode is conducive to the optimization of respiratory mechanics and the improvement of respiratory function compared to VCV mode.

Keywords: Elderly, Prone Position Mechanical Ventilation, PCV-VG

Introduction

Aging is characterized by progressive physiological changes throughout the life cycle, particularly affecting the structural integrity and functional capacity of the respiratory system in elderly individuals (López-Otín et al, 2023). Age-related changes in the respiratory system, including reduced lung elasticity, chest wall stiffening, and decreased alveolar surface area, result in impaired pulmonary function characterized by lower vital capacity, higher residual volume, decreased expiratory flow, and ventilation/perfusion mismatch. These physiological changes may elevate the risk of postoperative respiratory complications in elderly patients, particularly when combined with factors like fluid overload, non-physiological surgical positioning, and increased metabolic demands (Olotu, 2021).

Many surgical procedures for elderly patients, such as discectomy and spinal fusion with internal fixation, require prone positioning. While this positioning reduces surgical complexity and potentially improves ventilation/perfusion matching (Aguirre-Bermeo et al, 2018), its non-physiological nature can adversely affect respiratory mechanics and hemodynamics. These effects, combined with age-related respiratory changes, make elderly patients particularly susceptible to ventilator-induced lung injury (VILI) during mechanical ventilation (Kneyber et al, 2014). The incidence of postoperative pulmonary complications (PPCs) caused by VILI in spinal surgery has been increasing, with reports indicating that approximately 43.7% of patients experience lung injury after lumbar fusion surgery (Memtsoudis et al, 2011). This concerning trend has gained attention with the introduction of Enhanced Recovery After Surgery (ERAS) protocols, which emphasize optimizing preoperative patient status, reducing perioperative risks, maintaining the postoperative physiological function, and shortening recovery time (Melnyk et al, 2011). Anesthesiologists play a crucial role in implementing these protocols, with lung-protective ventilation strategies being particularly important. However, determining the optimal approach to reduce lung injury, decrease the incidence and mortality of PPCs, and improve patient prognosis remains a significant clinical challenge (Li et al, 2020).

Researchers have extensively studied various lung-protective strategies for elderly patients undergoing spinal surgery, with mechanical ventilation modes being a key focus (Young et al, 2019). Two primary ventilation modes are commonly used in clinical practice: Volume-Controlled Ventilation (VCV) and Pressure-Controlled Ventilation (PCV). VCV operates by gradually increasing airflow and airway pressure, but its effectiveness depends heavily on local lung compliance (Figueroa-Casas and Montoya, 2017). In areas of low compliance, VCV can lead to inadequate ventilation, resulting in increased shunting, ventilation/perfusion mismatch, and potential mechanical lung injury from high airway pressures (Jaju et al, 2017). PCV, on the other hand, uses preset pressure with decelerating inspiratory flow to deliver tidal volume. This approach typically achieves adequate ventilation at lower peak pressures and can improve oxygenation through its initial high flow rate (Kothari and Baskaran, 2018). However, PCV has its own limitations - the high initial flow may cause lung tissue damage (Maeda et al, 2004), and variations in lung compliance can result in unstable ventilation, risking both hypo- and hyperventilation (White, 2020).

Pressure-controlled ventilation with volume guarantee (PCV-VG) was developed to combine the benefits of both VCV and PCV modes. This intelligent ventilation mode integrates time-limited pressure, decelerating airflow, and volume control. While maintaining PCV's efficiency and clinical advantages, it automatically adjusts to changes in lung compliance to ensure consistent tidal volumes. PCV-VG has gained widespread clinical adoption across various surgical procedures due to its ability to maintain low airway pressures and high lung compliance (Kim et al, 2018; Bristle et al, 2014; Coisel et al, 2014). Studies have demonstrated its superiority over VCV, with Lin et al. (Lin et al, 2015) showing improved arterial oxygenation and reduced inspiratory pressures in thoracic surgery patients. Additional research has confirmed PCV-VG's lung-protective effects through reduced inflammatory markers and indicators of lung injury compared to VCV (Sari et al, 2024; Vlaar et al, 2010).

The PCV-VG ventilation mode, being an intelligent mode that combines the advantages of volume control and pressure control, has been widely studied, and its effects are well-established. However, most related studies have focused on non-elderly patients, and the impact of the PCV-VG ventilation mode on respiratory function in elderly patients undergoing prone spinal surgery remains to be explored. Therefore, this study aims to observe the effects of the PCV-VG ventilation mode on respiratory mechanics and respiratory function in elderly patients undergoing spinal surgery in the prone position under general anesthesia.

Materials and Methods

Study design, setting, and participants

This study was conducted at Ningxia Medical University General Hospital between 2020 to 2021. The study protocol was approved by the hospital's Ethics Committee (IRB number), and written informed consent was obtained from all participants. The following inclusion criteria were implemented: (1) age between 65 to 75 years; (2) body mass index [BMI, calculated by weight (kg)/height (m)2] between 18.2 and 25; (3) patients that have normal cardiac, pulmonary, hepatic, and renal function; (4) classified by the American Society of Anaesthesia (ASA) physical status as class II or III; (5) patients that were scheduled for posterior lumbar interbody fusion surgery under general anesthesia in the prone position; and (6) expected surgery duration between 2-5 hours;

Patients with preoperative hypoxemia ($PaO_2 < 60$ mmHg or $SpO_2 < 90\%$), history of asthma or COPD ($FEV_1/FVC < 70\%$), mechanical ventilation within one month, anesthesia within one year, preoperative anemia (hemoglobin $<$ 120 g/L for males, $<$ 110 g/L for females), or those refusing to participate were excluded from the study. Additionally, patients were withdrawn if they experienced difficult airway preventing successful intubation, intraoperative blood loss $>$ 400 mL, severe hypotension (SBP $<$ 100 mmHg), frequent changes in surgical position, persistent hypoxemia (SpO $<$ 90% for $>$ 10 minutes), hypercapnia ($PaO_2 > 45$ mmHg), or required postoperative ICU admission.

Randomization and Blinding

Forty eligible patients were randomized using a random number table into two groups: Group P (PCV-VG mode) and Group V (VCV mode). All patients were mechanically ventilated using the GE Healthcare Avance CS2 anesthesia machine. Identical ventilation parameters were maintained across both groups except for the ventilation mode, with settings as follows: (1) Fraction of Inspired Oxygen (FiO_2) of 0.8, (2) fresh gas flow of 2 L/min, (3) tidal volume of 6 mL/kg predicted body weight (PBW), (4) Positive End-Expiratory Pressure (PEEP) of 5 cmH_2O, (5) Inspiratory to Expiratory Ratio (I:E) is set to 1:2, (6) respiratory rate adjusted to maintain end-tidal carbon dioxide ($P_{ET}CO_2$) between 35-45 mmHg, and (7) maximum airway pressure limit of 40 cmH_2O. Noted that Predicted body weight (PBW) was calculated as follows: $\text{PBW} = 50.0 + 0.91 \times (\text{height} - 152.4)$ for males and $\text{PBW} = 45.5 + 0.91 \times (\text{height} - 152.4)$ for females, where height is in centimeters.

Anesthetic Protocol

Anesthetic Preparation

We conduct preoperative patient evaluation and develop an appropriate anesthesia protocol based on relevant preoperative laboratory tests and examinations. We inform patients of anesthesia-related risks and obtain signed anesthesia informed consent and trial research notification forms. Following Enhanced Recovery After Surgery (ERAS) protocols, we instruct patients on standard fasting guidelines (6 hours for solids and 2 hours for clear liquids). Upon admission to the operating room, standard monitoring of vital signs was established, including heart rate (HR), non-invasive blood pressure, peripheral oxygen saturation (SpO2), electrocardiogram (ECG), and bispectral index (BIS). Following peripheral venous access establishment, an Allen test was performed. In patients with negative Allen test results, left radial artery catheterization was performed under local anesthesia for invasive arterial blood pressure monitoring.

Anesthesia Induction

Both groups underwent total intravenous anesthesia. All patients received intravenous sufentanil (0.3-0.5 μg/kg), etomidate (0.1-0.3 mg/kg), and rocuronium (0.6-0.9 mg/kg). After complete neuromuscular blockade was achieved, topical anesthesia was applied to the epiglottis root. Under direct laryngoscopy guidance, a reinforced endotracheal tube (size 7# for females, 7.5# for males) was inserted. Following successful intubation, proper tube positioning was confirmed via fiberoptic bronchoscopy. After secure fixation, the tube was connected to the anesthesia machine for mechanical ventilation.

Anesthesia Maintenance

Both groups received a continuous infusion of propofol (4-6 mg/kg/h) and remifentanil hydrochloride (0.2-0.5 μg/kg/min) to maintain BIS values between 40-60. Anesthetic drug dosages were adjusted according to heart rate, invasive arterial blood pressure, and BIS values. When fluctuations in heart rate and invasive blood pressure occurred, the cause was analyzed and symptomatic treatment with vasoactive drugs such as ephedrine, urapidil, and esmolol was administered as indicated.

Anesthesia Recovery

Following surgery completion and return to the supine position, propofol and remifentanil hydrochloride infusions were discontinued. Residual neuromuscular blockade was routinely antagonized with atropine and neostigmine. Before extubation, thorough suctioning was performed. After confirmation of stable vital signs, patients were transferred to the post-anesthesia care unit (PACU) for continued monitoring and treatment. Postoperative analgesia was managed via patient-controlled intravenous analgesia (PCIA), with the analgesic pump formulation consisting of sufentanil 1.5 μg/kg diluted to 100 ml with normal saline. Rescue analgesia with intravenous dezocine 5 mg was administered when numerical rating scale (NRS) scores were ≥ 4.

Patient Positioning in Prone Position

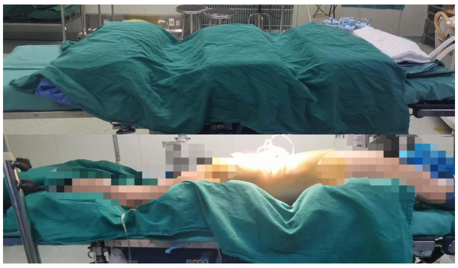

Fig. 1 Patient Positioning in Prone Position

After induction, patients were carefully turned to the prone position using the Jackson table, as shown in Figure 1. The standard positioning protocol was followed: Positioning pads were placed at three key levels - from shoulders to the xiphoid process, from the anterior superior iliac spine to pubic symphysis, and from the anterior tibia to the ankle joint. The head, neck, and chest were maintained in axial alignment while ensuring cervical spine protection with appropriate support. The abdomen was suspended to allow free movement. Additionally, toes were elevated to prevent dorsiflexion-induced foot strain, and a horseshoe-shaped gel pad supported the forehead and chin to avoid compression of facial structures and eyes. All positioning was performed under the direct supervision of the anesthesiologist to ensure proper alignment and prevent pressure points.

Outcomes and Measurements

Measurements were obtained at six predefined time points: 10 minutes before anesthesia induction (T0), 10 minutes after endotracheal intubation in supine position (T1), 10 minutes after prone positioning (T2), 60 minutes in prone position (T3), 10 minutes after return to supine position (T4), and 30 minutes after extubation in PACU (T5).

The primary outcomes consisted of respiratory function indices and respiratory mechanics parameters measured for each patient throughout the intraoperative period. Respiratory function was evaluated through arterial blood gas analysis at all time points, examining both oxygenation and ventilation parameters. Oxygenation was assessed via arterial oxygen tension (PaO_2), oxygenation index (OI), alveolar-arterial oxygen difference ($A\text{-}aDO_2$), and pulmonary shunt fraction (Q_s/Q_t). Ventilation parameters included arterial carbon dioxide tension ($PaCO_2$), respiratory index (RI), and dead space fraction (V_D/V_T). Respiratory mechanics parameters were recorded from T1 through T4. These included peak airway pressure (P_{peak}), mean airway pressure (P_{mean}), and dynamic lung compliance (C_{dyn}). Additionally, clinical outcomes such as length of hospital stay and the incidence of postoperative pulmonary complications were also documented.

We also measured baseline characteristics, perioperative variables, and hemodynamic parameters between the two groups. Demographic data included age, sex, body mass index (BMI), predicted body weight (PBW), and American Society of Anesthesiologists (ASA) physical status classification. Surgical and anesthetic parameters comprised number of operative segments, duration of anesthesia, mechanical ventilation time, prone position ventilation time, operative time, perioperative fluid balance, and intraoperative blood loss. We also follow up the hospital length of day (LOS) and incidence of postoperative pulmonary complications (PPCs) for each patients.

Statistical Analysis

The statistical analysis in this study was performed using the R statistical software. This randomized controlled trial used P_{peak} as the primary outcome measure. The sample size was calculated based on literature review and pilot data showing a 10% mean difference in P_{peak} between groups ($\alpha = 0.05$, power=80%, effect size= 1.007). Assuming a 20% dropout rate, 20 patients per group were required. We use independent t-tests or rank-sum tests for baseline characteristics, repeated measures ANOVA for quantitative variables (presented as mean and SD), and chi-square or Fisher's exact test for categorical data (presented as percentages). For all analyses, two-sided $p < 0.05$ were considered to indicate the statistically significant difference between groups.

Results

A total of 49 patients were initially selected. Five patients were excluded based on preoperative exclusion criteria, leaving 44 patients enrolled in the study (23 in Group P and 21 in Group V). In Group P, three patients were subsequently excluded: one due to severe acidosis, one due to blood loss exceeding 400 ml, and one requiring unplanned ICU admission. In Group V, one patient was excluded due to persistent postoperative hypotension. Ultimately, 20 patients in each group completed the study and were included in the final data analysis. (See Figure 2). The patient characteristics between the two groups were comparable, as seen in Table 1. There were no statistically significant differences between the two groups in terms of age, gender, BMI, PBW, ASA classification, number of surgical segments, duration of anesthesia, prone position ventilation time, operative time, perioperative fluid balance, and intraoperative blood loss (all p value $>$ 0.05).We also compare the hemodynamic parameters (HR and MAP) between the two groups. The results show no statistically significant differences at any time point (all p value > 0.05), as shown in Table 2.

Comparison of Respiratory Mechanics Outcomes

The respiratory mechanics outcomes comparison between the two groups is presented in Table 3. Our analysis encompassed both the temporal changes in respiratory mechanics within each group and the between-group differences at corresponding time points.

Temporal comparison: Both groups demonstrated significant temporal variations in respiratory mechanics

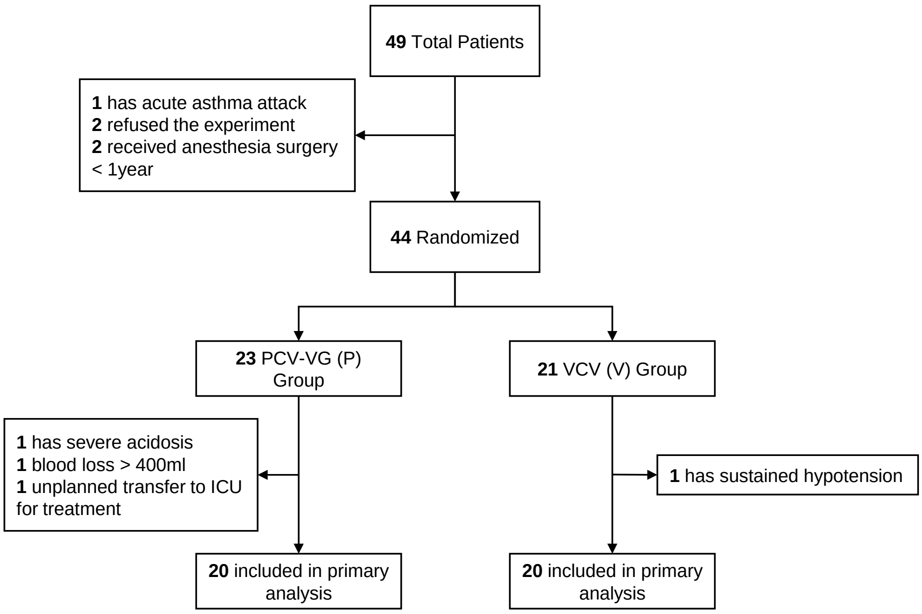

Fig. 2 Flow Chart

Table 1 Baseline Characteristics

Variable	V Group	P Group	t/χ^2 value	P-value
Age	78.55 ± 3.78	78.60 ± 4.12	-0.04	0.97
Male/Female	9/11	8/12	0.10	0.75
BMI (kg/m2)	23.52 ± 1.41	23.89 ± 1.18	-0.89	0.38
PBW (kg)	$61,78 \pm 6.15$	61.57 ± 3.85	0.13	0.90
ASA (II/III)	7/13	8/12	0.11	0.74
Surgical Segments (1/2/3)	13/6/1	12/7/1	0.12	0.94
Anesthesia Duration (min)	191.75 ± 36.36	192.55 ± 37.66	0.07	0.95
PPV Duration (min)	170.10 ± 35.12	172.00 ± 35.32	0.17	0.87
Operation Time (min)	162.20 ± 34.27	160.55 ± 35.74	-0.15	0.88
Fluid Input (ml)	1646.50 ± 202.57	1648.50 ± 243.77	0.03	0.98
Blood Loss (ml)	327.50 ± 34.32	328.50 ± 42.71	0.08	0.94
Urine output (ml)	508.50 ± 142.69	494.00 ± 161.13	-0.30	0.77

parameters across all time points ($P_{time} \leq 0.001$ for time effect by repeated measures ANOVA). The significant time effect confirms that positional changes during the procedure substantially altered respiratory mechanics. Peak airway pressure (P_{peak}), mean airway pressure (P_{mean}), and dynamic

Table 2 Hemodynamic Outcomes

	V Group	P Group	t-value
MAP (mmHg)			
T0	79.85 ± 4.18	79.65 ± 4.28	0.15
T1	76.75 ± 5.11	76.85 ± 4.96	-0.06
T2	74.70 ± 5.08	74.35 ± 4.22	0.24
T3	72.70 ± 4.95	72.85 ± 4.82	-0.10
T4	72.45 ± 4.42	72.55 ± 4.35	-0.07
T5	78.25 ± 4.60	78.15 ± 4.63	0.07
Heart Rate			
T0	76.75 ± 6.15	77.00 ± 5.89	-0.13
T1	70.20 ± 4.66	70.30 ± 4.61	-0.06
T2	68.40 ± 4.88	69.20 ± 4.73	-0.52
T3	66.05 ± 7.10	66.25 ± 7.19	-0.09
T4	62.85 ± 5.27	63.00 ± 5.24	-0.09
T5	69.60 ± 5.52	69.80 ± 5.48	-0.11

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

compliance (C_{dyn}) all showed statistically significant changes throughout the different phases of the procedure in both groups, highlighting the dynamic nature of respiratory mechanics in response to positioning.

Intergroup differences: The P group exhibited significantly higher C_{dyn} values and lower P_{peak} measurements compared to the V group at corresponding time points ($P < 0.05$). Mean airway pressure (P_{mean}) was notably elevated in the P group at T3, showing statistical significance ($P < 0.05$).

Table 3 Respiratory Mechanics Outcomes

	V Group	P Group	t-value
$\mathbf{P_{peak}}$			
T1	14.20 ± 1.24	13.30 ± 1.38	2.16^{*}
T2	18.15 ± 1.69	14.90 ± 1.33	6.76^{***}
T3	19.50 ± 1.43	16.05 ± 1.54	7.34^{***}
T4	14.30 ± 1.42	13.20 ± 1.06	2.78^{**}
P_{time}	< 0.001	< 0.001	
$\mathbf{P_{mean}}$			
T1	5.95 ± 0.69	6.00 ± 0.65	-0.24
T2	7.60 ± 0.60	7.75 ± 0.64	-0.76
T3	7.20 ± 0.83	8.70 ± 0.57	-6.66^{***}
T4	6.10 ± 0.64	6.15 ± 0.59	-0.26
P_{time}	< 0.001	< 0.001	
$\mathbf{C_{dyn}}$			
T1	33.45 ± 2.82	38.90 ± 2.73	-6.21^{***}
T2	25.70 ± 2.30	32.45 ± 2.93	-8.10^{***}
T3	25.95 ± 1.88	32.70 ± 2.87	-8.80^{***}
T4	30.35 ± 2.30	36.40 ± 3.55	-6.40^{***}
P_{time}	< 0.001	< 0.001	

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Comparison of Respiratory Functions Outcomes

The respiratory function outcomes comparison between the two groups is presented in Table 4. Similarly, our analysis encompassed both the temporal changes in respiratory function within each group and the between-group differences at corresponding time points.

Temporal comparison: No statistically significant differences were observed in $PaCO_2$ levels across all time points for both groups (repeated measures ANOVA, $P_{time} > 0.05$). Statistically significant differences were observed in pH, PaO_2, oxygenation index (OI), alveolar-arterial oxygen difference (A-aDO_2), pulmonary shunt fraction (Q_s/Q_t) and respiratory index (RI) across all time points ($P_{time} < 0.05$). Especially, both groups demonstrated significantly elevated PaO_2, OI, and A-aDO_2 at T_3-T_4 compared to T_0, while pulmonary shunt fraction (Q_s/Q_t)

and respiratory index (RI) were significantly lower than T_0.

Intergroup differences: At T_3, the P group demonstrated significantly higher PaO_2 along with lower A-aDO_2 and Q_s/Q_t compared to the V group ($P < 0.05$). No statistically significant differences were observed between groups in pH, $PaCO_2$, RI, and physiological dead space ratio (V_D/V_T).

Discussion

Age-related respiratory system deterioration poses significant challenges in elderly patients undergoing prone spinal surgery, necessitating careful ventilation strategies that balance the benefits of prone positioning against potential complications through evidence-based approaches like low tidal volumes with appropriate PEEP. Recent advancements in mechanical ventilation technology have led to significant innovations in lung-protective strategies. Among these, pressure-controlled ventilation with volume guarantee (PCV-VG) has emerged as a promising approach that combines the benefits of both pressure and volume control methodologies.

In this study, we investigated the efficacy of PCV-VG mode compared to volume-controlled ventilation (VCV) in elderly patients undergoing prone-position spinal surgery under general anesthesia. All participants received standardized ventilation parameters (tidal volume 6 mL/kg PBW, PEEP 5 cmH_2O), differing only in ventilation mode. To minimize confounding factors, we utilized a specialized prone positioning pad similar to the Jackson surgical table to reduce the influence of intra-abdominal pressure variations to C_{dyn} (Palmon et al, 1998), established strict exclusion criteria for high-risk patients, and employed advanced monitoring techniques. Statistical analysis confirmed comparable baseline characteristics between groups across all demographic and clinical parameters, reducing potential confounding effects on study outcomes.

Our primary findings demonstrated that PCV-VG significantly optimized respiratory mechanics with lower peak airway pressures and higher dynamic lung compliance while improving arterial oxygenation parameters and reducing pulmonary shunt fraction during prone positioning. These results align with previous research evidencing the advantages of PCV-VG across various surgical settings, including laparoscopic cholecystectomy (Kothari and Baskaran, 2018), prone-position lumbar surgery (Lee et al, 2020), robot-assisted gynecological procedures (Yılmaz et al, 2022), thoracotomy with one-lung ventilation (Song et al, 2014), and general adult mechanical ventilation (Wang et al, 2021), wherein this intelligent ventilation mode demonstrated significant benefits over conventional volume-controlled ventilation (Figueroa-Casas and Montoya, 2017) through reduced peak airway pressure, enhanced dynamic compliance, improved oxygenation, and superior pulmonary protection.

We want to discuss several points from our results. Firstly, from the results of this study, we found hemodynamic parameters such as heart rate (HR) and mean arterial pressure (MAP) showed no statistically significant differences between groups at any time point ($P > 0.05$), indicating that both VCV and PCV-VG modes with fixed 5 cmH_2O PEEP ventilation maintain stable hemodynamics. While research indicates that

Table 4 Respiratory Function Outcomes

	V Group	P Group	t-value		V Group	P Group	t-value
pH				**PaCO$_2$**			
T0	7.40 ± 0.03	7.42 ± 0.03	-2.11*	T0	36.62 ± 3.15	37.88 ± 3.35	-1.23
T1	7.41 ± 0.03	7.40 ± 0.05	0.77	T1	36.28 ± 3.94	35.89 ± 2.54	0.37
T2	7.39 ± 0.04	7.40 ± 0.03	-0.89	T2	36.52 ± 2.85	37.49 ± 3.23	-1.01
T3	7.37 ± 0.04	7.39 ± 0.04	-1.58	T3	37.24 ± 3.75	35.98 ± 1.79	1.36
T4	7.39 ± 0.02	7.40 ± 0.03	-1.24	T4	36.62 ± 3.46	36.18 ± 2.25	0.48
T5	7.39 ± 0.02	7.39 ± 0.05	0.00	T5	36.71 ± 4.72	37.46 ± 2.65	-0.62
P_{time}	< 0.001	0.02		P_{time}	0.87	0.002	
PaO$_2$				**OI**			
T0	72 ± 2.56	72 ± 4.06	0.11	T0	344 ± 19.31	345 ± 12.17	-0.11
T1	276 ± 21.82	280 ± 42.89	-0.34	T1	345 ± 27.27	350 ± 53.61	-0.33
T2	279 ± 21.93	285 ± 44.05	-0.49	T2	349 ± 27.41	356 ± 53.80	-0.50
T3	296 ± 24.68	318 ± 40.63	-2.04*	T3	370 ± 30.85	377 ± 50.79	-0.53
T4	293 ± 30.30	291 ± 37.50	0.15	T4	366 ± 37.88	364 ± 46.87	0.15
T5	80 ± 4.36	79 ± 4.08	0.67	T5	381 ± 20.75	377 ± 19.44	0.67
P_{time}	< 0.001	< 0.001		P_{time}	< 0.001	0.07	
A-aDO$_2$				**Q$_s$/Q$_t$**			
T0	30 ± 3.85	32 ± 5.03	-1.19	T0	1.83 ± 0.23	1.93 ± 0.30	-1.18
T1	249 ± 21.40	245 ± 42.57	0.38	T1	13.38 ± 0.99	13.16 ± 1.99	0.44
T2	244 ± 23.16	240 ± 43.43	0.38	T2	13.14 ± 1.07	12.91 ± 2.05	0.44
T3	229 ± 24.85	206 ± 40.00	2.21*	T3	12.43 ± 1.17	11.29 ± 1.76	2.41*
T4	232 ± 30.35	233 ± 38.77	-0.09	T4	12.57 ± 1.42	12.61 ± 1.83	-0.08
T5	23 ± 6.26	25 ± 8.31	-0.79	T5	1.40 ± 0.38	1.51 ± 0.50	-0.78
P_{time}	< 0.001	< 0.001		P_{time}	< 0.001	< 0.001	
RI				**V$_T$/D$_T$**			
T0	0.42 ± 0.09	0.42 ± 0.06	0.00	T0	–	–	–
T1	0.92 ± 0.16	0.92 ± 0.31	0.00	T1	0.20 ± 0.10	0.21 ± 0.06	-0.38
T2	0.89 ± 0.16	0.88 ± 0.30	0.13	T2	0.20 ± 0.06	0.22 ± 0.07	-0.97
T3	0.79 ± 0.16	0.67 ± 0.21	2.03*	T3	0.24 ± 0.09	0.21 ± 0.05	1.30
T4	0.81 ± 0.20	0.83 ± 0.25	-0.28	T4	0.22 ± 0.09	0.22 ± 0.06	0.00
T5	0.29 ± 0.09	0.32 ± 0.12	-0.89	T5	–	–	–
P_{time}	< 0.001	< 0.001		P_{time}	0.74	0.90	

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 5 Follow Up Results

Variable	V Group	P Group	t/χ^2 value	P-value
Length of Stay (d)	12 ± 1.72	12.10 ± 1.52	-0.2	0.36
Incidence of PPCs	2/18	1/19	0.85	0.55

prone positioning during general anesthesia causes significant hemodynamic changes through elevated intrathoracic pressure, leading to reduced cardiac index and altered hemodynamics through multiple physiological mechanisms (Park, 2000; Hatada et al, 1991; Balick-Weber et al, 2007). However, this observation is consistent with the conclusion of a recent study that compares hemodynamic effects between VCV and PCV-VG modes in spinal surgery. It demonstrated no significant hemodynamic differences between VCV and PCV-VG modes in spinal surgery, with cardiac index reduction linked to heart rate changes rather than peak airway pressure (Lee et al, 2020).

Secondly, for the results of respiratory mechanics outcomes over two groups, the P_{peak} in PCV-VG mode was significantly lower than VCV ($P < 0.05$) during all mechanical ventilation stages. Although both groups added fixed 5 cmH_2O positive end-expiratory pressure (PEEP), under PCV-VG mode's intelligent regulation, P_{peak} levels were notably lower compared to the VCV group at 10 minutes post-intubation, 10 and 60 minutes after prone positioning, and 10 minutes after returning to supine position for mechanical ventilation. These results are similar to evidence from previous studies (Dion et al, 2014; Boules and Ghobrial, 2011) on respiratory mechanics in obese patients undergoing laparoscopic bariatric surgery and one-lung ventilation (OLV). Additionally, we observed that when patients changed to a prone position, P_{peak} increased significantly in both groups, but the magnitude of increase was notably lower in the PCV-VG group, consistent with Lee's (Lee et al, 2020) findings. For C_{dyn}, compared to the VCV group, it showed significant improvement throughout the mechanical ventilation process in the PCV-VG group: at 10 minutes post-intubation, 10 and 60 minutes after prone positioning, and 10 minutes after returning to supine position for mechanical ventilation, the PCV-VG group consistently demonstrated superior C_{dyn} compared to the VCV group. Furthermore, after changing to prone position, the percentage decrease in compliance was smaller in the PCV-VG group (18% versus 22% in VCV mode), with similar results observed in laparoscopic surgery (Turan Civraz et al, 2023).

For the results of respiratory functions measures, firstly, both groups maintained normal $PaCO_2$ levels with no significant differences, indicating stable acid-base balance during mechanical ventilation. Secondly, when patients changed to prone position (time points V2 and V3), both groups showed increased PaO_2 values, with decreased A-aDO_2, Q_s/Q_t, and RI values, but overall, the PCV-VG group performed better than the VCV group. The results also demonstrate that oxygenation gradually improved significantly during prone ventilation (T2 timepoint: V group 279.35 ± 21.93; P group 284.77 ± 44.05 vs T3 timepoint: V group 296.08 ± 24.68; P group 317.76 ± 40.63). These findings align with Jin et al (2013), who found that oxygenation parameters improved during prone ventilation, peaking at 4 hours. This improvement likely stems from prone positioning's effects on airway pressure and ventilation/perfusion distribution, combined with PCV-VG's ability to support unstable alveoli through decelerated gas flow and reduced airway pressures, ultimately improving lung compliance and reducing inflammation. Thirdly, while mechanical ventilation can typically cause lung injury, decreased oxygenation, and increased pulmonary shunt fraction (Q_s/Q_t) (Papazian et al, 2005), our study found stable oxygenation and shunt values, likely due to prone positioning benefits and the use of 80% FiO_2, which research shows is optimal for minimizing atelectasis and shunt fraction during ventilation (Munshi et al, 2017). Finally, we also observed that when patients awakened in the recovery room 30 minutes after deoxygenation compared to pre-surgery (T0), PaO_2 and OI values increased while A-aDO_2, Q_s/Q_t, and RI values decreased. Research suggests this may be a beneficial "residual" effect of prone ventilation: maintaining improved oxygenation for a short time after returning to the supine position (Jo et al, 2020).

Finally, postoperative follow-up data comparison showed no statistically significant differences between groups as show in Table 5. Related reasons may include: (1) Prone ventilation can reduce differences between dorsal and ventral pleural pressures, promoting lung recruitment and improving ventilation uniformity, reducing alveolar overdistension and collapse while improving patient oxygenation. (2) The elderly patients selected in this study were all ASA grade II-III, with good preoperative pulmonary function and general condition, resulting in low perioperative pulmonary complication rates. (3) This study is a single-center clinical randomized controlled trial with a relatively small sample size. Currently, there is a lack of multi-center, large-sample clinical trial evidence regarding PCV-VG ventilation mode's long-term effects on elderly patient prognosis.

This study strictly followed randomized control requirements and trial protocols for patient secondary screening but still has several limitations: First, this is a single-center small-sample study requiring expanded sample size for multi-center research; Second, postoperative respiratory function assessment was limited to hospitalization period, without detailed comprehensive understanding of patients' long-term postoperative respiratory function status. Additionally, due to varying surgery durations, we couldn't collect more data, resulting in partial data missing issues that may cause certain research result bias. Finally, this study didn't observe changes in related inflammatory mediators, unable to explain inflammatory mediators' effects on respiratory function in elderly patients undergoing prone position spine surgery.

Conclusion

The present cohort study shows that for elderly patients undergoing prone spinal surgery, applying PCV-VG mode demonstrated significant advantages over VCV mode, particularly in optimizing respiratory mechanics and improving respiratory function. PCV-VG provided lower peak airway pressures, higher dynamic lung compliance, improved oxygenation parameters, and reduced pulmonary shunt fraction during the critical prone position phase. Although these benefits did not translate to significantly different postoperative pulmonary complication rates, our findings suggest that PCV-VG represents a valuable ventilation strategy for this vulnerable patient population. Future multi-center studies with larger sample sizes are needed to evaluate the impact on long-term outcomes and clarify the underlying physiological mechanisms.

Data Availability

Original contributions presented in this study are included in the article and its supplementary materials. Additional data requests can be addressed to the corresponding author.

Ethics Statement

This study was approved by the Institutional Review Board of General Hospital, Ningxia Medical University (approval number: KYLL-2021-0386, date of approval: April 22, 2021). The study protocol complied with all relevant institutional and national guidelines. Written informed consent was obtained from all participants prior to their enrollment in the study.

Author Contribution

XH, SM, and HM conceived and coordinated the study. XH and HM performed the experiment and collected the data. SM designed and applied all statistical analysis for the study. SM and XH wrote and revised the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of Interest

The authors declare no competing interests or potential conflicts of interest that could influence the work reported in this paper.

Additional information

Supplementary Information: we provide supplementary material that contains more information about respiratory mechanics and function measures, information on Anesthetic drugs and devices, and abbreviations of terminologies.

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