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Original Article

Effect of high positive end-expiratory pressure on perioperative atelectasis in neonates and small infants (0–6 months) with healthy lungs: A randomized controlled trial

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ABSTRACT

Introduction: High positive end-expiratory pressure (PEEP) is commonly used to improve pulmonary ventilation in infants with injured lungs. However, its intraoperative application in infants with healthy lungs remains controversial. This study aimed to evaluate the effect of high PEEP on perioperative pulmonary outcomes (PPCs) in this population.

Methods: Neonates and small infants aged 0–6 months undergoing surgery were randomly assigned to receive mechanical ventilation with a conventional PEEP of 5 cmH_2O or a high PEEP of 8 cmH_2O. Lung ultrasound (LUS) score was measured at four time points: T1, after intubation; T2, at the end of surgery; T3, 30 min after extubation; and T4, 24 h postoperatively. The primary outcome was the LUS score at four time points. The secondary outcome was the incidence of PPCs within the first 7 postoperative days.

Results: A total of 1056 ultrasonographic images were obtained from 44 subjects. During surgery, the driving pressure at PEEP 5 cmH_2O was significantly higher than PEEP 8 cmH_2O (12.4 [1.7] *vs.* 10.8 [1.9] cmH_2O; $p = 0.010$). At the end of surgery, the total LUS score was significantly higher in the PEEP 5 cm H_2O group compared to the PEEP 8 cmH_2O group (14.5 [5.1] *vs.* 11.4 [4.4]; $p = 0.039$). However, no significant difference between groups was observed at T3 or T4. The incidence of PPCs during the first 7 postoperative days remained low in both groups.

Conclusions: Although high PEEP is more effective than conventional PEEP in reducing intraoperative atelectasis, it does not appear to provide any postoperative benefits. The advantages of intraoperative high PEEP may not extend beyond the duration of surgery in neonates and infants with healthy lungs.

Registration: Chinese Clinical Trial Register (ChiCTR2300069230), date of registration: March 10, 2023.

Introduction

The characteristics of infants' respiratory physiology are different from those of adults, with a higher ratio of dead space to tidal volume (V_T), worse ventilation/perfusion matching, higher resistance, lower compliance, and lower functional residual capacity [1]. As a result, infants are more likely to develop atelectasis than adults. The incidence of intraoperative atelectasis under general anaesthesia is between 68% and 100% in children [2], especially in those aged < 3 years [3]. Atelectasis can induce local tissue biological responses, such as inflammation, local immune dysfunction, and damage to the alveolar-capillary barrier. However, the direct impact of intraoperative atelectasis on postoperative pulmonary complications (PPCs) remains unclear [4].

PEEP can prevent alveolar collapse by maintaining alveolar pressure above the critical closing pressure at the end of exhalation. An appropriate PEEP could prevent the reduction of functional residual capacity and the development of atelectasis [5,6]. Consequently, recent studies are using a higher PEEP ranging from 5 to 12 cm H_2O in children with healthy lungs to see its effect on lung aeration; however, the results are inconsistent [7,8]. A study in infants aged 6–12 months concluded that PEEP at 6 cmH_2O was effective [7], while other studies found that PEEP at 7 cmH_2O could be insufficient [3], and that a PEEP of 8–10 cmH_2O was optimal [8,9].

Abbreviations: ANOVA, Analysis of variance; CI, Cardiac index; LUS, Lung ultrasound; PEEP, Positive end-expiratory pressure; PPCs, Postoperative pulmonary complications; RCT, Randomized controlled trial; RM, Recruitment manoeuvres; SD, Standard deviation; SpO_2, Pulse oxygen saturation; TTE, Transthoracic echocardiography; V_T, Tidal volume.

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However, most relevant studies have primarily focused on the intraoperative period, with limited evaluation of the short- and long-term postoperative benefits of high PEEP. Moreover, potential side effects—such as hemodynamic changes—further limit its application in clinical practice [8]. In this study, we compared the effects of a conventional PEEP of 5 cmH_2O with a high PEEP of 8 cmH_2O on perioperative atelectasis and the incidence of PPCs within the first 7 days after surgery in neonates and small infants aged 0–6 months. We hypothesized that high PEEP would be more effective than conventional PEEP in improving perioperative pulmonary outcomes.

Methods

Study design

This single-center RCT was conducted at Shengjing Hospital of China Medical University, Shenyang, China, from March 2023 to June 2024. This study was approved by the Ethics Committee of Shengjing Hospital of China Medical University (number: 2022PS1136K, date of approval: December 2, 2022) and registered at the Chinese Clinical Trial Register (number: ChiCTR2300069230, date of registration: March 10, 2023). Written informed consent was obtained from the parents or guardians of the children one day before surgery.

Inclusion criteria

Neonates and small infants aged 0–6 months (chronological age) with an American Society of Anaesthesiologists physical status I–III scheduled for elective surgery in the supine position under general anaesthesia were eligible.

Exclusion criteria

We excluded patients who met any of the following criteria: (i) body weight < 3.3 kg; (ii) untreated congenital heart disease; (iii) respiratory complications found on preoperative chest radiography, such as atelectasis, pneumothorax, pleural effusion, or pneumonia; (iv) history of thoracic surgery; and (v) undergoing thoracic, epigastric, or laparoscopic surgery.

Randomization and blinding

Randomization was performed using computer-generated randomization software (https://www.randomizer.org) to allocate patients to the PEEP 5 cmH_2O or 8 cmH_2O groups at a ratio of 1:1. The attending anaesthesiologist, who was aware of the group allocation, was not involved in the data analysis. The researchers who performed, scored the lung ultrasound (LUS), and recorded the incidence of PPCs, were blinded to the group allocation.

Study protocol

Anaesthesia was induced with intravenous cis-atracurium 0.1–0.2 mg/kg, sufentanil 0.1–0.2 μg/kg, and propofol 2–3 mg/kg. All patients were intubated with a cuffed tracheal tube and were anaesthetized using the same anaesthesia machine (Primus Infinity Empowered Dräger, Lübeck, Germany). The same ventilation settings, except PEEP, were used in both groups, including the pressure-controlled ventilation-volume guarantee ventilation mode, a V_T of 6 mL/kg, a fraction of inspired oxygen of 0.4, and recruitment manoeuvres (RM) before and after surgery. The RM was performed with a continuous airway pressure of 30–35 cmH_2O through a closed system for 3–5 s and was repeated three times. The ventilatory frequency was adjusted to 25–40 breaths/min to maintain an end-tidal CO_2 of 35–45 mmHg. Anaesthesia was maintained using sevoflurane 1.0–1.2 MAC. Neuromuscular monitoring was performed, and an additional bolus of cis-atracurium 0.1–0.2 mg/kg was administered to maintain a train-of-four count of 0–1.

LUS was performed at four time points: T1 (after intubation), T2 (at the end of surgery), T3 (30 min after extubation), and T4 (24 h postoperatively) (Fig. 1). At T1, the initial PEEP was set at 0 cmH_2O in both groups. The baseline lung aeration was assessed by LUS. Then, patients were assigned to receive PEEP at either 5 or 8 cmH_2O according to the group allocation, and the predetermined PEEP was maintained until the end of anaesthesia. At T2, LUS was performed, then the patient was extubated after gaining complete consciousness and breathing spontaneously well, and was transferred to the post-anaesthesia care unit (PACU). Note that RM was performed twice: the first at T1, between intubation and performance of LUS; the second at T2, after performance of LUS but before extubation. At T3, LUS was performed at the PACU. A face mask was used to inhale 100% oxygen at 6 L/min when SpO_2 was < 95%. The incidence of bronchospasm, laryngospasm, and desaturation was recorded in the OR room or PACU within 30 min postoperatively. Desaturation was recorded when SpO_2 was < 95%. At T4, the incidence of PPCs, including significant atelectasis, pleural effusion, and pneumothorax, was diagnosed with LUS. The incidence of upper respiratory symptoms, including cough and sneezing, was asked from the parents or guardians of the children. Within the first 7 postoperative days, the incidence of pneumonia was recorded.

Determination of PEEP and V_T

An educational review recommended mechanical ventilation with a V_T of 6–10 mL/kg and avoiding a V_T of > 10 mL/kg in children with healthy lungs [10]. We used a low V_T of 6 mL/kg in both groups. Recently, studies have been using a higher PEEP ranging from 5 to 12 cmH_2O to see its effect on preventing intraoperative atelectasis and intratidal recruitment/derecruitment, but the results are inconsistent [7,8]. A high level of PEEP may result in hemodynamic changes, such as an increased incidence of hypotension and the need for more vasoactive drugs [8]. In this study, we chose a PEEP of 8 cmH_2O, which is higher than that commonly used in clinical practice, while not being too high to cause significant cardiovascular compromise.

Measurements

LUS can be used to assess lung aeration at the bedside [11], with diagnostic accuracies of 97.2% for atelectasis, 96.7% for pneumothorax, and 95.1% for pleural effusion [12]. In this study, LUS was performed by an experienced researcher using an ultrasound machine (M9 Mindray, Shenzhen, China) with a 5–20 MHz linear transducer (L20-5 s). The LUS was performed in six regions per hemithorax: anterior, lateral, and posterior regions were identified by the sternum, anterior, and posterior axillary lines; superior and inferior regions were identified by an axial line 1 cm above the nipple [13]. The scoring method of LUS was described by Park *et al.* [7]. Significant atelectasis was defined as the consolidation score ≥ 2, and the total LUS score was the sum of the B-line score and the consolidation score in each region. Moreover, the LUS score of the anterior, lateral, and posterior regions was recorded, respectively.

In the intraoperative period, hemodynamic and respiratory parameters were recorded using a patient monitor (BeneVision N17 OR; Mindray, Shenzhen, China). The hemodynamic parameters included heart rate, electrocardiography, pulse oxygen saturation (SpO_2), and noninvasive blood pressure. Additionally, transthoracic echocardiography (TTE) was used to measure cardiac index (CI) in both groups, using an ultrasound machine (M9, Mindray, Shenzhen, China) with a 4–10 MHz phase array probe (P10-4). It was performed twice for each patient: the first at T1, after patients received PEEP according to the group allocation, and the second at T2, before the

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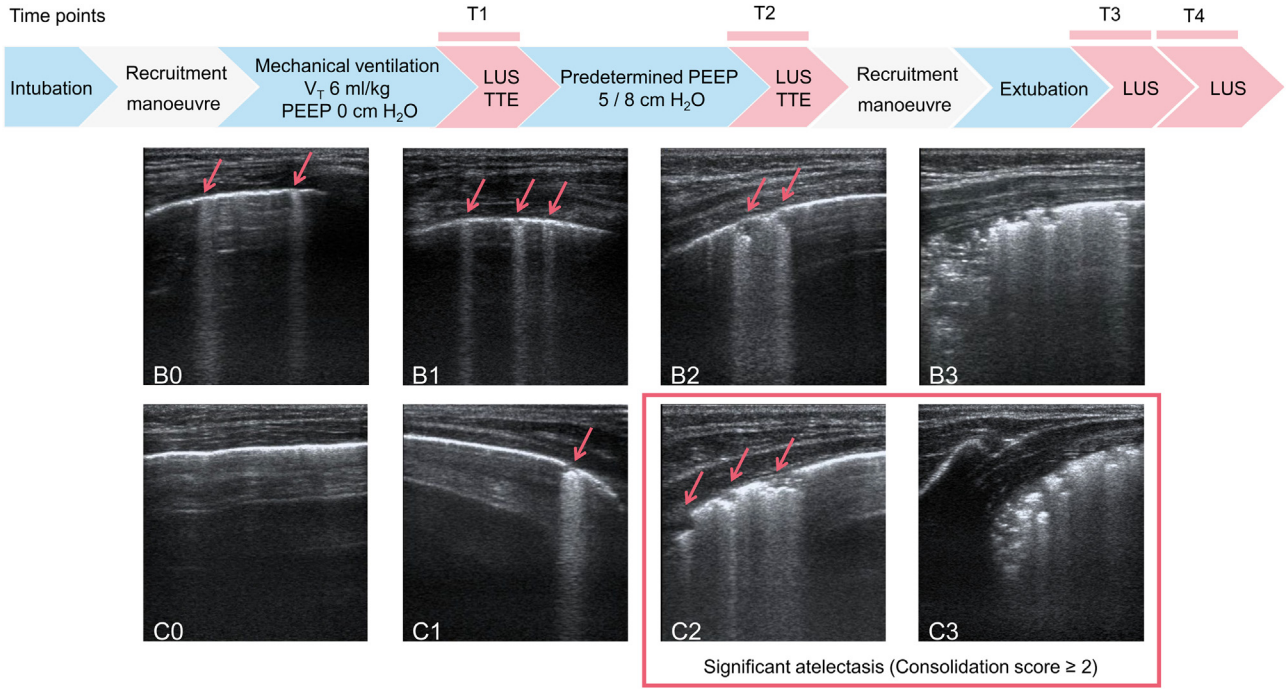

Fig. 1. Study protocol. The scoring method of LUS was described by Park *et al.* The degree of B-lines was categorised into 0–3 grades: (B0) isolated B-lines < 3; (B1) multiple well-defined B-lines ≥ 3; (B2) multiple coalescent B-lines; (B3) white lung. The degree of consolidation was also categorised into 0–3 grades: (C0) no consolidation; (C1) minimal consolidation; (C2) small-sized consolidation; (C3) large-sized consolidation. Significant atelectasis was defined as the consolidation score ≥ 2. VT, tidal volume; PEEP, positive end-expiratory pressure; LUS, lung ultrasound; TTE, transthoracic echocardiography; T1, after intubation; T2, at the end of surgery; T3, 30 min after extubation; T4, 24 h postoperatively.

performance of LUS. The CI was estimated following the method described by Singh (Supplementary Fig. 1) [14]. The respiratory parameters included respiratory rate, end-tidal CO_2, tidal volume, PEEP, peak inspiratory pressure, plateau pressure, mean airway pressure, dynamic compliance, and airway resistance. The drive pressure was calculated as the plateau pressure minus PEEP. The calculated data were extracted at 5-minute intervals throughout anaesthesia.

Outcomes

The primary outcome was the LUS score at four time points. The secondary outcome was the incidence PPCs within the first 7 postoperative days. The components of PPCs included desaturation, bronchospasm, laryngospasm, significant atelectasis, pleural effusion, pneumothorax, and pneumonia.

Sample size calculation

The sample size was calculated using G*Power 3.1 (University of Kiel, Kiel, Germany). In the study by Park *et al.* [7], the total LUS score at the end of anaesthesia was 12.8 ± 5.1 (mean ± standard deviation (SD)) at PEEP 6 cmH_2O. Based on this reference value, we assumed that the total LUS score at the end of anaesthesia would be 15 ± 5 at PEEP 5 cmH_2O and 10 ± 5 at PEEP 8 cmH_2O. With a type I (α) error of 0.05 and type II (β) error of 0.1, and allowing for a dropout rate of 10%, 24 patients were required in each group.

Statistical analysis

Statistical analyses were performed using SPSS (version 26.0; SPSS Inc. Chicago, IL, USA). Continuous variables were presented as mean [standard deviation] or median [interquartile range (IQR)], and categorical variables were presented as numbers or percentages (%). Distribution normality was assessed using the Shapiro–Wilk test. Repeated-measures analysis of variance (ANOVA) was used to assess the CI and LUS score. Post hoc pairwise comparisons were performed with Bonferroni adjustment for multiple testing. Other continuous variables were assessed using two independent samples *t*-test. In the subgroup analysis, patients were divided into preterm (gestational age < 37 weeks) and term (gestational age ≥ 37 weeks) groups to assess the effect of PEEP on the primary outcome. A post hoc analysis was conducted to assess the total LUS score at 4 time points between neonates and infants. Statistical significance was defined as a p-value < 0.05. Bonferroni-adjusted p-values are reported for pairwise comparisons.

Results

Participant characteristics

Of the 54 patients who were assessed for eligibility, 6 were excluded due to undergoing laparoscopy or for lack of consent (Fig. 2). 48 patients were randomized into the PEEP 5 or 8 cmH_2O group. Among them, 4 were transferred to the neonatal intensive care unit without extubation after the operation. Finally, 44 patients (10 neonates and 34 small infants) were analyzed (Table 1). The major surgery type was abdominal surgery, which consisted of ileostomy closure (16 patients), intestinal resection (6 patients), bile duct reconstruction (6 patients), and ileostomy (4 patients).

Hemodynamic and respiratory parameters

During surgery, the driving pressure at PEEP 5 cmH_2O was significantly higher than PEEP 8 cmH_2O (12.4 [1.7] *vs.* 10.8 [1.9] cmH_2O; Cohens'd: 0.860; $p = 0.010$) (Table 2). The dynamic compliance at PEEP 5 cmH_2O was not different from PEEP 8 cmH_2O (2.5 [0.8] *vs* 3.0 [1.0] mL/cmH_2O; Cohens'd: -0.568; $p =$ 0.080). In addition, the peak inspiratory pressure, plateau pressure, and mean

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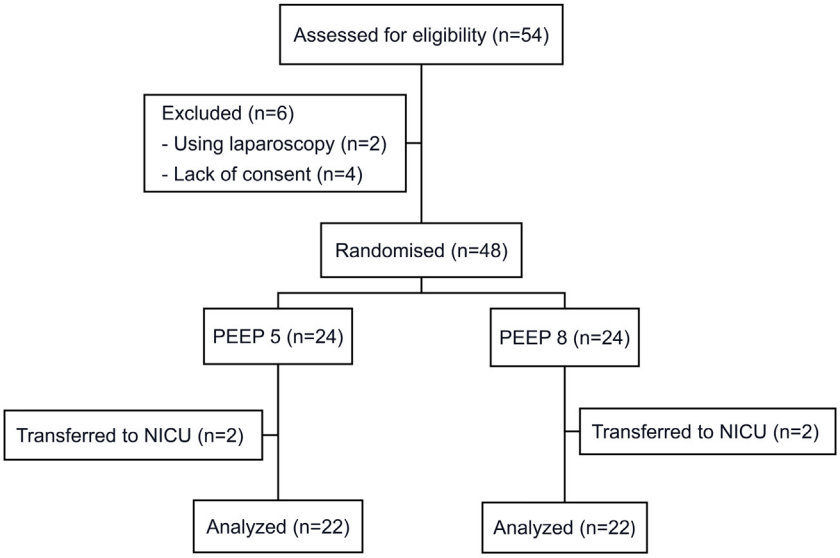

Fig. 2. Study flow chart. NICU, neonatal intensive care unit.

Table 1
Subject characteristics and surgical information.

	PEEP 5	PEEP 8
Chronological age (months)	2.0 [0.8–3.0]	2.0 [0.8–3.0]
Adjusted age (months)	1.0 [0.0–2.0]	1.3 [0.0–2.1]
Gestational age (weeks)	37.0 [35.5–39.0]	38.0 [36.5–40.0]
Neonate	5 (22.7%)	5 (22.7%)
Preterm	9 (40.9%)	5 (22.7%)
Male	11 (50.0%)	12 (54.5%)
Height (cm)	55.0 [50.5–59.3]	57.0 [52.8–61.0]
Weight (kg)	4.7 [3.5–5.1]	4.7 [3.3–5.9]
ASA physical status		
?	1 (4.5%)	1 (4.5%)
?	17 (77.3%)	18 (81.8%)
?	4 (18.2%)	3 (13.6%)
Type of surgery		
Abdominal surgery	17 (77.3%)	15 (68.2%)
Plastic surgery	3 (13.6%)	1 (4.5%)
Neurosurgery	0 (0.0%)	2 (9.1%)
Anal Surgery	1 (4.5%)	4 (18.2%)
Urologic surgery	1 (4.5%)	0 (0.0%)
Ventilation time (min)	112.5 [98.8–151.3]	107.5 [73.8–131.3]
Operative time (min)	92.5 [72.5–130]	82.5 [53.8–105.0]

Data are presented as median [interquartile range (IQR)] or number (proportion).

airway pressure were higher at PEEP 8 cmH_2O. There was no difference in CI at the end of surgery (2.3 [0.9] *vs.* 2.1 [0.7] $L/min/m^2$; Cohens'd:0.326; $p = 0.349$) between the two groups. The other hemodynamic parameters did not differ either.

Primary outcome

The total LUS score at PEEP 5 cmH_2O was significantly higher than PEEP 8 cmH_2O at the end of surgery (14.5 [5.1] *vs.* 11.4 [4.4]; Cohens'd: 0.644; $p = 0.039$) (Table 3). The consolidation score was significantly higher at PEEP 5 cm H_2O than 8 cmH_2O (3.5 [1.9] *vs.* 2.5 [1.2]; Cohens'd: 0.632; $p = 0.042$). However, the B-line score was not different between groups (11.0 [3.9] *vs.* 8.9 [4.0]; Cohens'd: 0.158; $p = 0.093$). The incidence of significant atelectasis (consolidation score ≥ 2) was significantly higher at PEEP 5 cmH_2O than 8 cmH_2O (50% *vs.* 13.6%; Phi: -0.390; $p = 0.010$). The total LUS score in the posterior region was different between PEEP 5 cm H_2O and PEEP 8 cmH_2O groups (7.5 [2.1] *vs.* 5.6 [2.3]; Cohens'd: 0.824; $p = 0.009$) , but not in the anterior and lateral regions (Supplementary Table 1). The LUS score was significantly higher in the posterior region than in the anterior and lateral regions in both groups (Supplementary Fig. 2). No difference was found in the LUS score between groups at T3 and T4. The total LUS score at T1 was significantly higher than at T4 in both groups (Fig. 3).

Secondary outcome

Considering the low incidence, it was underpowered to compare the incidence of PPCs between groups. The exact number of each component of PPCs was listed (Supplementary Table 2). In total, 9 patients in the PEEP 5 group and 4 patients in the PEEP 8 group reported PPCs within the first 7 postoperative days.

Additional analyses

In the subgroup analysis, the total LUS score did not differ between the preterm and term groups at T1-T4 (Supplementary Table 3). In the post hoc analysis, the total LUS score was significantly higher in neonates than in infants at T1 (21.0 [4.6] *vs.* 12.1 [4.6]; Cohens'd: 1.945; $p < 0.001$), T3 (16.3 [4.4] *vs.* 11.2 [4.7]; Cohens'd: 1.102; $p = 0.004$), and T4 (16.6 [5.1] *vs.* 10.0 [4.6]; Cohens'd: 1.406; $p < 0.001$).(Supplementary Table 4).

Discussion

High PEEP is commonly used in intensive care units to improve pulmonary ventilation in infants with lung injury. However, its effect in infants with healthy lungs remains controversial. In this study, high PEEP was found to be more effective than conventional PEEP in reducing intraoperative atelectasis; however, its benefits did not persist after extubation. Recent studies have applied high PEEP levels ranging from 5 to 12 cmH_2O to prevent intraoperative atelectasis. A study in children aged between 5 weeks and 2 years concluded that a PEEP of 5 cmH_2O can reduce atelectasis [15]. Similarly, a study in infants aged 6–12 months concluded that PEEP 6 cmH_2O was sufficient [7]. Another study found PEEP 8 cmH_2O could prevent intraoperative atelectasis and overdistension in most children $\leq$ 6 years [8]. Furthermore, an observational study found that

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Table 2
Hemodynamic and respiratory parameters.

Parameters	PEEP 5	PEEP 8	MD (95% CI)	*p*-value
Hemodynamic				
T1 CI (L/min/m^2)	2.4 [1.1]	2.3 [0.8]	0.2 (−0.5 to 0.8)	0.558
T2 CI (L/min/m^2)	2.3 [0.9]	2.1 [0.7]	0.3 (−0.3 to 0.8)	0.349
HR (beats min^{-1})	131.5 [10.3]	132.5 [15.0]	−1.0 (−8.8 to 6.8)	0.799
SpO_2 (%)	97.9 [2.0]	97.9 [2.2]	−0.0 (−1.3 to 1.3)	0.997
Systolic BP (mmHg)	74.5 [14.3]	72.3 [19.8]	2.2 (−8.3 to 12.7)	0.676
Diastolic BP (mmHg)	36.0 [10.1]	35.5 [16.0]	0.5 (−7.7 to 8.6)	0.905
Mean BP (mmHg)	47.5 [12.0]	45.3 [17.6]	2.2 (−7.0 to 11.3)	0.636
Respiratory				
RR (min^{-1})	33.7 [1.8]	32.5 [2.6]	1.2 (−0.2 to 2.5)	0.083
$ETCO_2$ (cmH_2O)	40.4 [4.1]	38.8 [4.0]	1.6 (−0.8 to 4.1)	0.186
V_T (ml)	30.3 [9.1]	32.2 [10.8]	−1.9 (−8.3 to 4.5)	0.559
PIP (cmH_2O)	18.0 [1.7]	19.4 [2.4]	−1.4 (−2.7 to 0.0)	0.042*
P_{plat} (cmH_2O)	17.4 [1.7]	18.8 [1.9]	−1.4 (−2.6 to −0.2)	0.02*
P_{mean} (cmH_2O)	9.4 [0.8]	11.3 [0.7]	−1.9 (−2.4 to −1.4)	<0.001*
DP (cmH_2O)	12.4 [1.7]	10.8 [1.9]	1.6 (0.4 to 2.8)	0.010*
Cdyn (ml/cmH_2O)	2.5 [0.8]	3.0 [1.0]	−0.5 (−1.1 to 0.1)	0.080
Raw (cmH_2O/L/S)	52.6 [12.1]	47.9 [9.4]	4.7 (−2.2 to 11.6)	0.177

Data are presented as mean [standard deviation]. MD, mean differences; CI, cardiac index; HR, heart rate; SpO_2, saturation of pulse oxygen; BP, blood pressure; RR, respiratory rate; $ETCO_2$, end-tidal CO_2; V_T, tidal volume; PIP, peek inspiratory pressure; P_{plat}, plateau pressure; P_{mean}, mean airway pressure; DP, driving pressure; C_{dyn}, dynamic compliance; and R_{aw}, airway resistance.
* *p*-value < 0.05 with Bonferroni correction.

Table 3
Lung ultrasound score.

Time	Lug ultrasound score	PEEP 5	PEEP 8	MD or OR (95% CI)	*p*-value
T1	Total score	14.7 [5.5]	13.5 [6.4]	1.2 (−2.4 to −4.8)	0.514
	Consolidation score	3.3 [1.5]	2.9 [1.6]	0.4 (−0.6 to 1.3)	0.448
	B-line score	11.4 [5.0]	10.6 [5.9]	0.8 (−2.5 to 4.1)	0.640
	Significant atelectasis	8 (36.4%)	6 (27.3%)	0.7 (0.2 to 2.4)	0.517
T2	Total score	14.5 [5.1]	11.4 [4.4]	3.0 (0.2 to 5.9)	0.039*
	Consolidation score	3.5 [1.9]	2.5 [1.2]	1.0 (0.0 to 2.0)	0.042*
	B-line score	11.0 [3.9]	8.9 [4.0]	2.0 (−0.4 to 4.4)	0.093
	Significant atelectasis	11 (50%)	3 (13.6%)	0.2 (0.0 to 0.7)	0.010*
T3	Total score	12.6 [5.6]	12.1 [4.6]	0.5 (−2.7 to 3.6)	0.772
	Consolidation score	2.7 [1.5]	2.5 [1.2]	0.2 (−0.6 to 1.0)	0.579
	B-line score	9.9 [4.8]	9.6 [4.2]	0.2 (−2.5 to 3.0)	0.868
	Significant atelectasis	4 (18.2%)	3 (13.6%)	0.7 (0.1 to 3.6)	1.000
T4	Total score	12.1 [5.2]	10.9 [5.7]	1.2 (−2.1–4.6)	0.461
	Consolidation score	3.0 [1.9]	2.3 [1.0]	0.7 (−0.2 to 1.6)	0.119
	B-line score	9.1 [4.1]	8.6 [5.2]	0.5 (−2.3 to 3.3)	0.725
	Significant atelectasis	2 (9.1%)	1 (4.5%)	0.5 (0.0 to 5.7)	1.000

Data are presented as mean [standard deviation] or absolute number of patients (%). Lung ultrasound score is presented as the mean difference with 95% confidence intervals and Cohen's d. Incidence of significant atelectasis is presented as odds with 95% confidence intervals and Phi. MD, mean differences; OR, odds ratios; CI, confidence interval; T1, after intubation; T2, at the end of surgery; T3, 30 min after extubation; T4, 24 h postoperatively.
* *p*-value < 0.05 with Bonferroni correction.

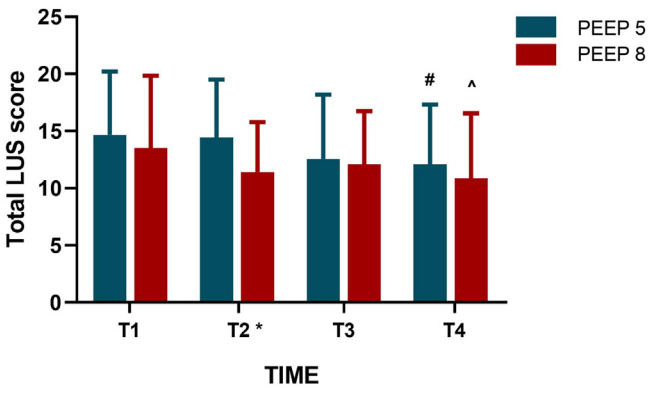

Fig. 3. The total lung ultrasound score from T1 to T4 in the PEEP 5 and PEEP 8 groups. The bars represent the mean value, and the error bars indicate the standard deviation (SD). T1, after intubation; T2, at the end of surgery; T3, 30 min after extubation; T4, 24 h postoperatively. **p*-value < 0.05, PEEP 5 group *vs.* PEEP 8 group at T2 with Bonferroni correction. #*p*-value < 0.05, T1 *vs.* T4 in the PEEP 5 group with Bonferroni correction. ^*p*-value < 0.05, T1 *vs.* T4 in the PEEP 8 group with Bonferroni correction.

ventilation with PEEP 12 cmH_2O and V_T 5 mL/kg could ensure optimal lung aeration in infants [9]. However, PEEP 12 cmH_2O might affect venous return and cardiac output, especially in children who were already hemodynamically compromised [16]. A potential limitation of these studies is the lack of evidence regarding the short- and long-term postoperative benefits of high PEEP following the surgery.

LUS is a convenient method for assessing lung aeration during surgery. In addition to the total LUS score, the LUS scores in different lung regions were also compared. It was found that PEEP 8 cmH_2O could improve lung aeration better than 5 cmH_2O in the posterior region of the lungs, while no difference was found in the anterior and lateral regions. Decreased lung aeration and atelectasis are more likely to occur in the posterior region than in other regions in the supine position, caused by gravitational forces and a potential increase in intrathoracic blood volume [17]. It is suggested that a high PEEP could be more effective in preventing atelectasis in regions that are easier to collapse. Besides lung regions, there were also differences among the total LUS score, the consolidation score, and the B-line score. Unlike the others, the B-line score was not significantly different

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between groups at the end of surgery. In radiographically normal lungs, B-lines can also be found [18,19]. Neonates' and infants' lungs are characterized by high fluid content, leading to more observed normal B-lines than those in adults or older children. Compared with B-line, the consolidation is not affected by the high fluid content, and can be used to diagnose intraoperative atelectasis in children [11]. Lung ultrasound has also proved to be a fast and reliable method to verify single-lung ventilation in children presenting for thoracic surgery [20].

During surgery, a lower driving pressure was found at PEEP 8 cmH_2O. Intraoperative atelectasis can cause higher driving pressure and lower compliance [17,21]. PEEP 8 cmH_2O could improve respiratory mechanics by preventing intraoperative atelectasis. This finding is consistent with previous studies, which find the driving pressure is lower at PEEPs of 6–12 cmH_2O compared with 3–5 cmH_2O [7–9]. In children with healthy lungs, the suggested driving pressure is limited to 10–15 cmH_2O [22,23]. However, the dynamic compliance was not improved by high PEEP. Compliance in infants can be as low as 0.6 mL/cmH_2O/kg in infants [24]. In a study by Lee J-H *et al.*, intratidal compliance differed significantly during ventilation with PEEP levels of 8 – 12 cmH_2O, whereas dynamic compliance did not show a significant change [9]. Intratidal compliance is a method of compliance calculation using the gliding-SLICE method that can show the change in compliance within a single breath [25]. It is indicated that intratidal compliance may reflect the change in respiratory mechanics better than dynamic compliance in infants.

In this study, the benefit of high PEEP was not observed after extubation. However, in our former study, which used LUS-guided RM in infants of a similar age who were scheduled for laparoscopic abdominal surgery. It was found that LUS-guided RM reduced the incidence of significant atelectasis at the end of surgery and in PACU [26]. Compared with our study, the prolonged effective time indicates that LUS-guided RM may prevent atelectasis better than high PEEP.

Intraoperative atelectasis may also trigger local biological responses that contribute to the development of PPCs. However, we failed to demonstrate a significant effect of high PEEP on PPCs. Two factors may have contributed to this result. First, the small sample size made the study underpowered to compare PPCs between groups. Second, the children undergoing pulmonary surgery who were prone to getting PPCs were excluded. According to a study in children undergoing pulmonary resection, PEEP 6 cmH_2O with low V_T could decrease PPCs[27]. In adult studies, the effect of high PEEP on PPCs remains inconclusive. Some studies found that compared with ventilation with a V_T of 9–12 mL/kg and no PEEP, low V_T 6–8 mL/kg and a PEEP of 6–10 cmH_2O could improve postoperative pulmonary outcomes [28,29]. However, when setting a low V_T of 7–8 mL/kg in both groups, studies have not found a positive effect of high PEEP on PPCs [30,31]. It is implied that the benefit of setting low V_T and high PEEP comes from the use of low V_T [32,33]. A meta-analysis showed that low V_T and driving pressure-titrated PEEP strategies could prevent PPCs, instead of high PEEPs $\geq$ 6 cmH_2O [34]. A new study in adults undergoing major abdominal surgery confirmed that the LUS score on 1 day postoperatively could predict the occurrence of PPCs [35]. The effect of high PEEP on PPCs in both children and adults warrants further investigation.

In the subgroup analysis, no significant difference in total LUS scores was observed between the preterm and term groups. The unequal enrolment — with only 14 preterm infants among 44 patients — likely rendered the study underpowered to detect a meaningful difference in this outcome. We also found that the total LUS score was significantly higher in neonates than in infants at T1, T3, and T4. The respiratory physiology in neonates differs from that in infants, with increased extravascular lung water. Further studies focusing on neonates are warranted in the future.

There are two limitations to this study. First, due to concerns about potential hemodynamic alterations associated with higher PEEP levels, we did not use that of higher than 8 cmH_2O [8]. In this study, no cardiovascular compromise was found at PEEP 8 cmH_2O. The result was in line with former findings, suggesting PEEPs < 10 cmH_2O could not cause a significant hemodynamic compromise in healthy infants [7]. However, we did not use transesophageal echocardiography (TEE) or a continuous hemodynamic measurement. Second, we did not assess lung aeration with LUS preoperatively, which made it difficult to compare lung aeration before and after mechanical ventilation. Although the RM was performed after anaesthesia induction at T1, it might not allow aeration to recover to the preoperative state.

In conclusion, though high PEEP is more effective than conventional PEEP in reducing intraoperative atelectasis, it does not appear to provide any short- or long-term postoperative benefits. The advantages of intraoperative high PEEP may not extend beyond the duration of surgery in neonates and infants with healthy lungs.

Ethical statement

This study was approved by the Ethics Committee of Shengjing Hospital of China Medical University (number: 2022PS1136K, date of approval: December 2, 2022). Written informed consent was obtained from the parents or guardians of the children one day before surgery.

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Declaration of competing interest

The authors report no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.accpm.2025.101679.

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