Research Square

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Driving pressure-guided positive end-expiratory pressure for the prevention of postoperative atelectasis in children: a prospective, randomised, controlled clinical trial

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Research Article

Keywords: Children, Lung Protective Ventilation, Driving pressure, PEEP, Atelectasis

Posted Date: October 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10412674/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

Both adult and pediatric patients undergoing general anaesthesia are prone to atelectasis and reduced pulmonary ventilation homogeneity due to anaesthesia, muscle relaxation, and mechanical ventilation with high-concentration oxygen. In adults, evidence indicates that individualised positive end-expiratory pressure (PEEP) setting guided by driving pressure (ΔP) can reduce the incidence of postoperative atelectasis. However, in pediatric patients, there is currently a lack of data supporting this approach.

Methods

This prospective, randomised, controlled study was conducted at the University-affiliated academic tertiary hospital of Zhengzhou University from September 2024 to December 2024. Children were randomly assigned to receive mechanical ventilation with ΔP-titrated PEEP (group P) or fixed PEEP (group C). The incidence of immediate postoperative atelectasis were compared after surgery. We also compared the incidence of PPCs within 7 days and the lung ultrasound scores between two groups.

Results

Based on standardized lung ultrasound assessment, the incidence of immediate postoperative atelectasis was higher in group C than in group P (55% vs. 20%; RR = 0.21, 95% CI 0.05 to 0.83; P = 0.022). Compared with group C, the perioperative LUS score was significantly lower in group P (median 4 [IQR 3 to 6] vs. 6.5 [4 to 10.75], P = 0.032). There was no significant difference in the incidence of PPCs within 7 days between the two groups (0% vs. 15%, P = 0.075).

Conclusion

The individualised PEEP guided by ΔP reduces the incidence of postoperative atelectasis and improves postoperative lung ultrasound scores in pediatric patients.

TRIAL REGISTRATION

Clinicaltrials.gov (NCT06471491). Registered on 31 May, 2024.

Introduction

Atelectasis is a common postoperative pulmonary complication (PPC) in surgical patients, and is associated with prolonged hospital stays, increased healthcare costs, unfavorable prognosis, and even

death[1–5]. The occurrence of perioperative atelectasis has been demonstrated to be associated with patient characteristics, surgical type, body position, and anaesthesia management[6–8]. Studies have reported that the incidence of atelectasis after anaesthesia induction in pediatric patients ranges from 68% to 100%[9, 10]. Postoperative atelectasis can persist for more than 24 hours and contribute to various types of PPCs, including hypoxemia and pneumonia[11–14].

Lung protective ventilation (LPV) optimises intraoperative mechanical ventilation to reduce ventilator-induced lung injury and improve oxygenation[15–17]. Driving pressure (ΔP) is defined as plateau pressure minus positive end-expiratory pressure (PEEP). It is recognised as a key indicator of lung overdistension. Several studies have demonstrated that ventilation strategies targeting minimal ΔP improve postoperative respiratory outcomes[18–22]. Fixed positive end-expiratory pressure (PEEP) regimens fail to accommodate interindividual differences in respiratory compliance, especially in paediatric patients. Individualised PEEP titrated by ΔP effectively reduces postoperative atelectasis in adults, yet robust clinical evidence in children remains scarce[23, 24].

Several techniques can determine optimal individualised PEEP, such as electrical impedance tomography (EIT) and transpulmonary pressure monitoring, but these methods are cumbersome for routine intraoperative use. In contrast, ΔP can be directly calculated from ventilator parameters, making it a simple bedside tool for PEEP adjustment[2, 25–29]. Lung ultrasound (LUS) is another convenient, radiation-free bedside modality to diagnose perioperative atelectasis in children[9, 30–32].

Current LPV regimens for healthy children are mostly derived from adult data without high-quality paediatric trials on ΔP-titrated PEEP[15]. Therefore, we hypothesize that ΔP-guided individualised PEEP during paediatric general surgery can reduce postoperative atelectasis and decrease the incidence of PPCs.

Methods

Study design

This single-center, assessor-blinded, randomised, controlled clinical trial obtained ethical approval [(2024) No. 39] from the Ethical Committee of Henan Provincial People's Hospital on 25 January 2024. The informed consent was obtained from the guardians of all patients. The trial was registered prior to patient enrolment at ClinicalTrials.gov (NCT06471491,registration date 31 May 2024) and conducted in accordance with the Declaration of Helsinki and reported following the Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Patients

We enrolled children aged 3–15 years with ASA Ⅰ-Ⅱ undergoing elective non-cardiac, non-thoracic, non-neurosurgical tracheal intubation general surgery with an operation duration ≥ 1 h. Exclusion criteria: PEEP contraindications (bronchopleural fistula, hypovolaemic shock, right heart failure); history of cardiopulmonary disease; preoperative ventilation; inability to complete LUS; upper respiratory tract infection within two weeks preoperatively; planned postoperative ICU admission; intraoperative adjustment of preset ventilation protocol.

Randomisation and blinding

Eligible patients were randomly assigned to either the individualised PEEP group (group P) or the fixed PEEP group (group C) using a computer-generated random number table via SPSS version 27.0. Allocation concealment was realised with sealed opaque envelopes opened by attending anaesthesiologists on the day of surgery. LUS assessments were performed by an experienced physician. Neither the patients and their families, the ultrasound assessor, nor the researchers were aware of the group assignments.

Anaesthesia protocol

Unified anaesthetic, monitoring and fluid regimens were applied to all participants. Standard intraoperative monitoring included SpO_2, ECG, non-invasive blood pressure, body temperature and $PETCO_2$. Baseline LUS was completed before induction.

Induction consisted of intravenous sufentanil 0.5-1 μg·kg⁻¹, propofol 1.0–2.0 mg·kg⁻¹ and cisatracurium besilate 0.15–0.2 mg·kg⁻¹. Anaesthesia was maintained with continuous propofol and remifentanil infusions plus sevoflurane inhalation, with supplementary cisatracurium besilate administered to maintain neuromuscular blockade. Mechanical ventilation was initiated using the volume-controlled ventilation mode with a fraction of inspired oxygen (FiO_2) of 0.6, VT of 6–8 $ml \bullet kg^{-1}$ for ideal body weight, without PEEP, and an inspiratory-to-expiratory (I:E) ratio of 1:1.5 or 1:2. The respiratory rate was adjusted to maintain an end-tidal carbon dioxide pressure of 35–45 mmHg. The intraoperative fluid infusion rate was set at 6–10 $ml \bullet kg^{-1} \bullet h^{-1}$. Key physiological and respiratory mechanics data were recorded at six predefined time points (T_1-T_6: post-intubation, 15/30/60 min after ventilation initiation, end of surgery, 30 min post-extubation). A second LUS scan was performed immediately after operation. Patients were transferred to post-anaesthesia care unit (PACU) for extubation and routine postoperative care after surgery. **Ventilation intervention protocol**

After tracheal intubation, all patients received a standard recruitment maneuver (RM)[2, 33]: pressure-controlled ventilation, baseline PEEP 0 cmH_2O, initial inspiratory pressure 15 cmH_2O, increased by 5 cmH_2O every 30 s until PEEP 15 cmH_2O and inspiratory pressure 30 cmH_2O, with ΔP maintained at 15 cmH_2O throughout RM.

Group P: PEEP was titrated in a decremental method, starting at 15 cmH_2O and then decreasing to 5 cmH_2O in 2 cmH_2O intervals. ΔP was calculated as Pplat-PEEP. The individualised PEEP was defined as a PEEP that produced the lowest ΔP.

Group C: Fixed PEEP of 5 cmH_2O was applied after RM. The intervention procedures of the two groups are shown in Fig. 1.

Lung ultrasound

LUS examinations were performed before induction and at the end of surgery. All scans were performed by the same investigator using a Mindray ME7 ultrasound machine (Mindray, Shenzhen, China). LUS followed the protocol described by Acosta and colleagues[34]. Each hemithorax was divided into six regions (Fig. 2). The anterior and posterior axillary lines were used to divide the anterior, lateral, and posterior regions of the chest to evaluate the effect of gravity (Fig. 2). The degree of consolidation and B-line were classified into four grades (0–3) according to the grading method described by Song and colleagues[30]. The LUS aeration score was calculated as the sum of points obtained in all the 12 lung regions, ranging from normal aeration (0 point) to the worst possible aeration (36 points). Significant atelectasis was defined as a consolidation score ≥ 2.

Outcomes and follow-up

The primary outcome was the incidence of significant atelectasis detected on LUS performed immediately at the end of surgery. The secondary outcomes were: (□) the occurrence of pulmonary complications within the first 7 postoperative days; (□) LUS scores for each lung region at the end of surgery; and (□) the duration of PACU stay and postoperative hospital length of stay. The intraoperative ventilatory parameters, including peak inspiratory pressure, plateau pressure, VT, PEEP, lung compliance, mean blood pressure, and heart rate (HR), were recorded. We also assessed whether potential adverse effects, including transient hypotension (< 80% of baseline blood pressure) and oxygen desaturation (SpO_2 <95%), were more likely to occur following regular alveolar recruitment.

Sample size calculation

The sample size was calculated based on the assumption of 3% between-group difference in postoperative atelectasis, with a standard deviation (SD) of 3% in both groups. The SD estimate was derived from a previous study[2]. Additional assumptions included α = 0.05, power = 0.85, and a 10% dropout rate. Based on these inputs, a two-tailed Student's *t*-test indicated that 40 patients (20 per group) were required.

Statistical analysis

Statistical analyses were performed using SPSS version 27.0 and GraphPad Prism version 10. Data were summarised as mean (SD), median (interquartile range), or number of patients (percentage), as appropriate. The Shapiro-Wilk test was used to evaluate data normality. Pearson χ^2 or Fisher's exact test was used to compare categorical data. Continuous data were analysed using the Student's *t*-test or the Mann-Whitney U test, as appropriate. Due to cell sparsity, the PPC count was deemed a categorical variable and compared using Fisher's exact test. Respiratory parameter results were analysed using repeated-measures analysis of variance (ANOVA). A *P*-value < 0.05 was considered statistically significant, except for repeated-measure parameters.

Results

From September 2024 to December 2024, a total of 43 children were randomised and 3 children were excluded prior to final analysis (Fig. 3). The baseline characteristics of the enrolled children are summarised in Table 1.

Table 1
Baseline and intraoperative characteristics.

Variables	Group C	Group P	*P*-value
Age (years)	8.5 (5 to 11.75)	11 (6 to 12)	0.532
Gender			0.168
Male	12 (60%)	16 (80%)	
Female	8 (40%)	4 (20%)	
Height (m)	1.4 (1.1 to 1.6)	1.5 (1.2 to 1.7)	0.692
Weight (kg)	30 (20.1 to 52)	40 (22.3 to 68.3)	0.552
BMI ($kg \bullet m^{-2}$)	16.9 (15.2 to 22.1)	17.7 (15.8 to 25.4)	0.365
ARISCAT Score	16 (0 to 21.5)	16.5 (0 to 23)	0.857
ASA Physical Status			0.525
□	10 (50%)	10 (50%)	
□	12 (60%)	8 (40%)	
Hb ($g \bullet L^{-1}$)	126 (116 to 133.8)	130.5 (126.3 to 134.5)	0.053
SpO_2 on Admission (%)	99.6 ± 0.184	99.25 ± 0.216	0.18
Pre-operative Lung Ultrasound Score	1 (0 to 2)	0 (0 to 1)	0.079
Intraoperative Characteristics			
Anaesthesia Duration (min)	123.5 (79.8 to 180.8)	148.5 (107.3 to 188.8)	0.402
Surgery Duration (min)	107.5 (63.5 to 145)	111.5 (71.5 to 148.8)	0.448
Mechanical Ventilation Duration (min)	147.5 (98.5 to 204.5)	173 (111.8 to 218.5)	0.425
Tidal Volume (ml)	278.75 ± 12.394	309.95 ± 12.942	0.073
Respiratory Rate (bpm)	16.31 ± 0.278	16.06 ± 0.242	0.465
Crystalloid Infusion Volume (ml)	325 (212.5 to 587.5)	475 (300 to 787.5)	0.095
Blood Transfusion	1 (5%)	0	1.000
Estimated Blood Loss	10 (5 to 20)	10 (5 to 27.5)	0.955
Urine Output (ml)	65 (0 to 262.5)	87.5 (0 to 250)	1.000
Surgical Characteristics			
Surgical Type			0.749

Variables	Group C	Group P	*P*-value
Laparoscopic	12 (60%)	8 (40%)	
Non-laparoscopic	11 (55%)	9 (45%)	
Surgical Site			0.756
Abdomen	10 (25%)	11 (27.5%)	
Limbs	6 (15%)	4 (10%)	
Head, Neck and Maxillofacial	4 (10%)	5 (12.5%)	

Data represent median (Q1,Q3), mean ± SD or percent (%).

Primary outcome

All children had a normal LUS without atelectasis (Table 1). At the end of surgery, the incidence of atelectasis was significantly lower in the group P than in the group C (Table 2).

Table 2
Comparisons of intraoperative and postoperative characteristics between the two groups.

Variables	Group C	Group P	*P*-value
Intraoperative Characteristics			
Hypotension	4 (20%)	5 (25%)	0.705
ΔMAP (mmHg)	-13.8 ± 15.6	-6.4 ± 15.1	0.135
ΔHR (bpm)	4.6 ± 20.6	8.1 ± 13.4	0.089
PEEP (cmH_2O)	5 ± 0	8.6 ± 0.4	<0.01
Postoperative Characteristics			
Atelectasis	11 (55%)	4 (20%)	0.022
PPCs	3 (15%)	0	0.075
PACU Length of Stay (min)	86 (76.3 to 106.8)	82.5 (64 to 90)	0.316
Postoperative Hospital Stay (days)	7.5 (5.3 to 9)	7.5 (4 to 8.75)	0.558
SpO_2 During Recovery (%)	99.4 ± 0.13	99.3 ± 0.21	0.928
Postoperative LUS Scores	6.5 (4 to 10.75)	4 (3 to 6)	0.032

Data represent median (Q1,Q3), mean ± SD or percent (%).

Secondary outcomes

There was no significant difference in the incidence of PPCs within 7 days between the two groups (Table 2). Pediatric patients who developed PPCs presented with only one type of complication (i.e. respiratory tract infection, *n* = 3), with no cases of multiple concurrent complications.

Compared with group C, the perioperative LUS score was significantly lower in group P (Table 2). Significant atelectasis occurred more frequently in the dependent posterior chest regions when the patients were in the supine position after surgery (Fig. 4). The effects of gravity on LUS scores are shown in Fig. 4.

The mean (SD) PEEP was 8.6 (0.4) cmH_2O in the group P (Table 2, Fig. 5). Analysis of respiratory mechanics revealed that except for the plateau pressure at T_3, which was higher in the group P than in the group C, there were no significant differences in other parameters, including peak pressure, ΔP, and lung compliance (Fig. 6). Likewise, no significant differences were observed between the two groups in changes in mean arterial pressure (ΔMAP; -13.8 [15.6] vs. -6.4 [15.1], *P* = 0.135) and ΔHR (4.6 [20.6] vs. 8.1 [13.4], *P* = 0.089) before and after titration (Table 2).

Discussion

This study demonstrated that individualised PEEP titrated based on ΔP significantly reduced the incidence of immediate postoperative atelectasis and improved postoperative LUS scores in children, without increasing the risk of intraoperative hemodynamic instability or adverse events. These findings provide important references for the clinical application of individualised lung-protective ventilation strategies in pediatric anaesthesia.

In evaluating the incidence of postoperative atelectasis, we found that the ΔP-guided individualised PEEP group exhibited a significantly lower incidence of postoperative atelectasis than the fixed PEEP group, consistent with previous reports indicating that individualised PEEP can reduce the extent of lung collapse[35]. The ΔP-guided PEEP titration may exert its effects through several mechanisms. First, a fixed PEEP may be insufficient to counteract anaesthesia-induced reductions in lung compliance and alveolar collapse in dependent regions. In contrast, individualised PEEP based on the principle of ΔP minimization may better preserve alveolar patency by stepwise adjustment of PEEP levels, thereby reducing shear injury associated with cyclic alveolar opening and closure[36]. Second, children have higher chest wall compliance, and the diaphragmatic position is susceptible to the effects of abdominal surgery and body posture, leading to ventilation heterogeneity. Individualised PEEP may improve ventilation homogeneity across different lung regions by balancing ΔP, thereby reducing the risk of atelectasis[20]. Therefore, the ΔP-guided titration strategy dynamically identifies these differences and achieves precise intervention.

The overall incidence of PPCs in our study was 7.5%. The reduction in atelectasis incidence did not translate into a difference in the incidence of PPCs, length of PACU stay or postoperative hospital stay, which is consistent with previous studies[25, 37]. This may be attributed to several mechanisms. First, the high sensitivity of LUS for detecting subclinical atelectasis may lead to a relatively high false-positive rate. Atelectasis detected by ultrasound may reflect subclinical changes that are inconsistent with the development of PPCs in terms of timing or severity[34, 38]. For example, small-scale atelectasis in independent lung regions may resolve rapidly with spontaneous breathing, without progressing to clinically significant complications[38]. Second, the sample size in our study may have been insufficient to detect a true difference. Notably, the overall incidence of PPCs in this study was significantly lower than that reported in previous pediatric studies[9, 39], likely due to the inclusion of patients with ASA physical status of Ⅰ–Ⅱ and low-risk surgical procedures. Third, confounding factors in perioperative management, such as standardized postoperative analgesia, fluid management, and early mobilization, may have mitigated the potential differences between ventilation strategies. Additionally, the exclusion of children with preexisting cardiopulmonary diseases may have resulted in a low baseline risk of PPCs, thereby masking the protective effect of the intervention. However, some studies have shown that ΔP-guided PEEP titration during surgery can reduce the incidence of PPCs[40, 41].

In recent years, LUS has been widely used for the diagnosis of atelectasis. It can easily be applied to patients in the operating room without radiation exposure[34]. The baseline LUS scores in our study were comparable to those reported in other studies[35, 42]. Consistent with previous research[35, 42], the results of this study demonstrated that ΔP-guided individualised PEEP titration during surgery improved postoperative LUS scores.

Several studies have investigated the optimal PEEP level in children. In our study, the individualised PEEP we titrated ranged from 5 to 12 cmH_2O. As the entire respiratory system, including the lungs, airways, and chest wall, continues to develop with a child's growth, a single fixed pressure is unsuitable for children of all age groups[43]. According to Thorsteinsson's study[44], the PEEP that maximises respiratory system compliance is 6 cmH_2O in healthy infants aged 1–6 months, and 12 cmH_2O in children older than 1.5 years. This finding indicates that optimal PEEP levels vary across pediatric age groups[43]. Future research should further explore the impact of age on PEEP.

It is worth noting that although the ΔP in the group P showed an overall decrease compared with the group C, the difference did not reach statistical significance, possibly due to the small difference in PEEP between groups (Δ = 3.6 cmH_2O). Previous trials have shown that when PEEP increases from 5 to 10 cmH_2O, alveolar recruitment accounts for only 6%–9% of total lung volume, which may not reach the threshold for altering overall lung mechanics[45, 46].

Hemodynamic safety is a critical consideration in individualised PEEP. A study conducted among pediatric ICU patients showed that cardiac output significantly decreased when PEEP increased from 0 to 12 cmH_2O[47]. In the present study, patients with individualised PEEP did not develop intraoperative

hypotension, and recruitment maneuvers only caused transient decreases in MAP. These results challenge the traditional notion that "higher PEEP inevitably leads to hypotension"[10, 48], possibly due to the greater compensatory capacity of the pediatric circulatory system. Compared with adults, children have more elastic blood vessels and may compensate for PEEP-related preload reduction through increased HR. Although the HR increase in the group P was slightly higher than that in the group C without statistical significance, it suggests the presence of this compensatory mechanism. Restricted fluid infusion in the study may have reduced the risk of volume overload, and real-time monitoring of ΔP during titration may have helped avoid extreme PEEP values. However, caution is warranted, as the safety of this strategy in children with congenital heart disease or hypovolemia still requires further verification.

Limitations

Our study has several limitations. First, our study adopted a single-center design, with a small sample size. Although rigorous randomization and baseline matching enhanced internal validity, the small sample size may have limited statistical power. Additionally, the single-center design may introduce selection bias (e.g., surgical types, anaesthesia team practices), potentially affecting the generalizability of the findings. Future multi-center, large-sample studies are warranted to validate these findings, with subgroup analyses to elucidate effects across surgical types or age groups. Second, our study did not include long-term postoperative LUS assessment. Lung atelectasis was evaluated only at the T_5 timepoint, and single-timepoint assessments may fail to capture dynamic changes in atelectasis. For example, some intraoperative alveolar collapse may resolve with spontaneous breathing or cough reflex postoperatively, while delayed atelectasis may go undetected. Future studies should include repeated LUS at 6 and 24 hours postoperatively, complemented by CT imaging to quantify atelectasis volume and provide a comprehensive evaluation of the long-term effects. Third, our study lacked regional ventilation monitoring. Advanced techniques such as EIT were not employed to assess regional lung ventilation, precluding analysis of differential alveolar recruitment between dependent and independent regions. Incorporation of transpulmonary pressure monitoring (via esophageal pressure measurement) could also distinguish chest wall and lung parenchymal mechanics, minimizing PEEP-setting errors attributable to the high chest wall compliance in children. Fourth, we excluded patients with ASA physical status of ≥ III, those with cardiopulmonary diseases, or those undergoing cardiothoracic or neurosurgical procedures, which limited the cohort to low-risk children. These children's low baseline risk of PPCs may have attenuated intervention benefits. However, high-risk children (e.g., those undergoing congenital heart disease surgery, with obese, or with severe infections) have greater needs for lung-protective ventilation strategies. Current findings cannot be directly extrapolated to these groups. Therefore, future stratified randomised trials in high-risk populations should explore the combined use of individualised PEEP and lung recruitment maneuvers. Fifth, for ethical considerations, routine arterial blood gas analysis was not performed, which precluded assessment of the oxygenation index—a key physiological parameter reflecting ventilation-perfusion matching and the efficacy of PEEP titration. Although LUS scores correlate with oxygenation, they are not equivalent. Future studies could estimate

oxygenation index using SpO_2 combined with arterial oxygen concentration (with parental consent) or transcutaneous carbon dioxide monitoring to address this limitation.

Conclusions

This study demonstrates that ΔP-guided individualised PEEP strategy reduces the incidence of immediate postoperative atelectasis and improves postoperative LUS scores in children, without increasing hemodynamic risk. However, the reduction in atelectasis did not translate into a difference in the incidence of PPCs within 7 days. Our results support the application of ΔP-titrated personalised PEEP and intraoperative LUS monitoring in paediatric anaesthesia to optimise lung aeration status.

Declarations

Acknowledgements

The authors thank all the patients who participated in this study and the clinical staff of the endoscopy center for their support.

Authors' contributions

Qian Wang: Conceptualization, Methodology, Investigation, Data Curation, Writing-Original Draft, Formal Analysis, Visualization. Jun Zhou: Methodology, Supervision, Writing-Review & Editing. Kuangyu Zhao, Yanhong Li, Jiaqiang Zhang: Investigation, Data Curation. All authors read and approved the final manuscript.

Funding

No funding was received for this study.

Data availability

The datasets generated and analyzed during the current study are not publicly available due to patient privacy and confidentiality agreements but are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This study was approved by the Ethical Committee of Henan Provincial People's Hospital [(2024) No. 39].

All procedures performed were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments. Written informed consent was obtained from all individual participants included in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

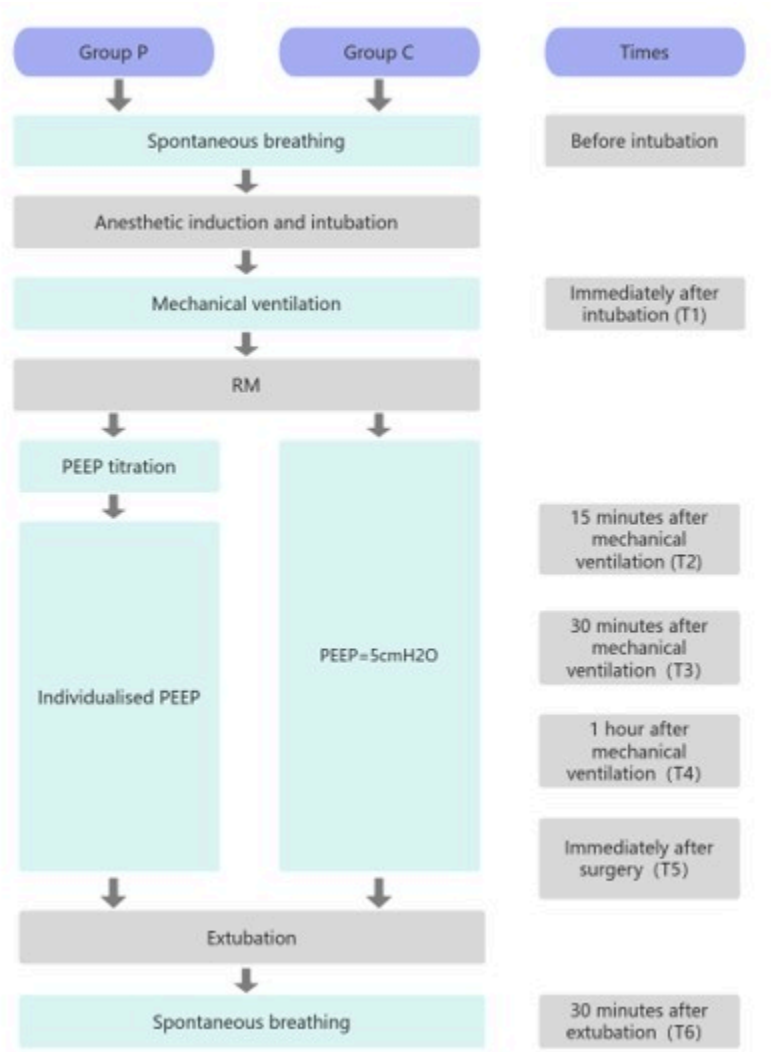

Figure 1

The experimental flow chart. RM: Recruitment maneuver; PEEP: Positive end-expiratory pressure; T_1: After intubation; T_2: 15 minutes after mechanical ventilation; T_3: 30 minutes after mechanical ventilation; T_4: 1 hour after mechanical ventilation; T_5: Immediately after surgery; T_6: 30 minutes after extubation.

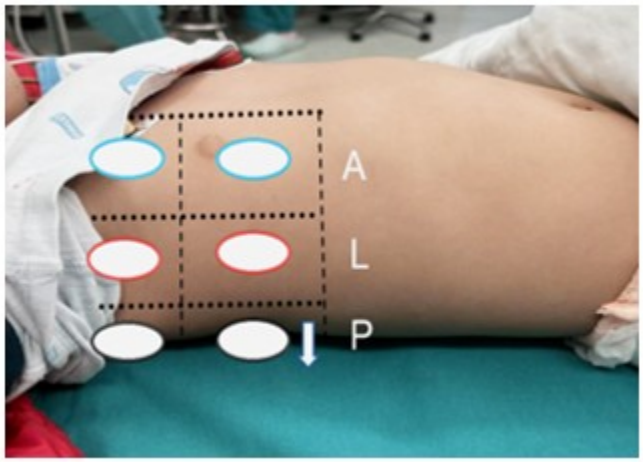

Figure 2

Chest regions. A: Anterior; L, lateral; P, Posterior.

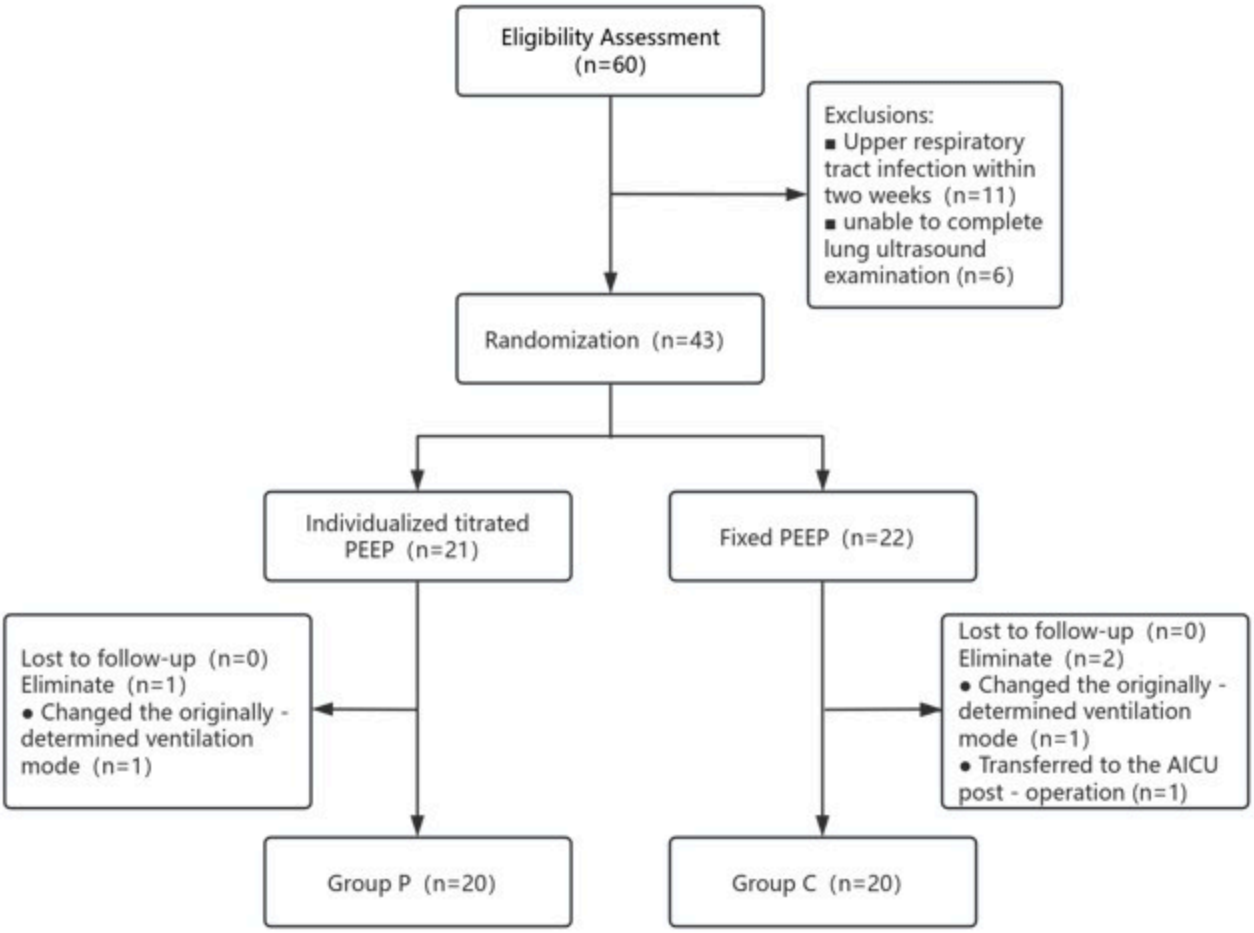

Figure 3

The Flow Chart. AICU: Anaesthesia Intensive Care Unit.

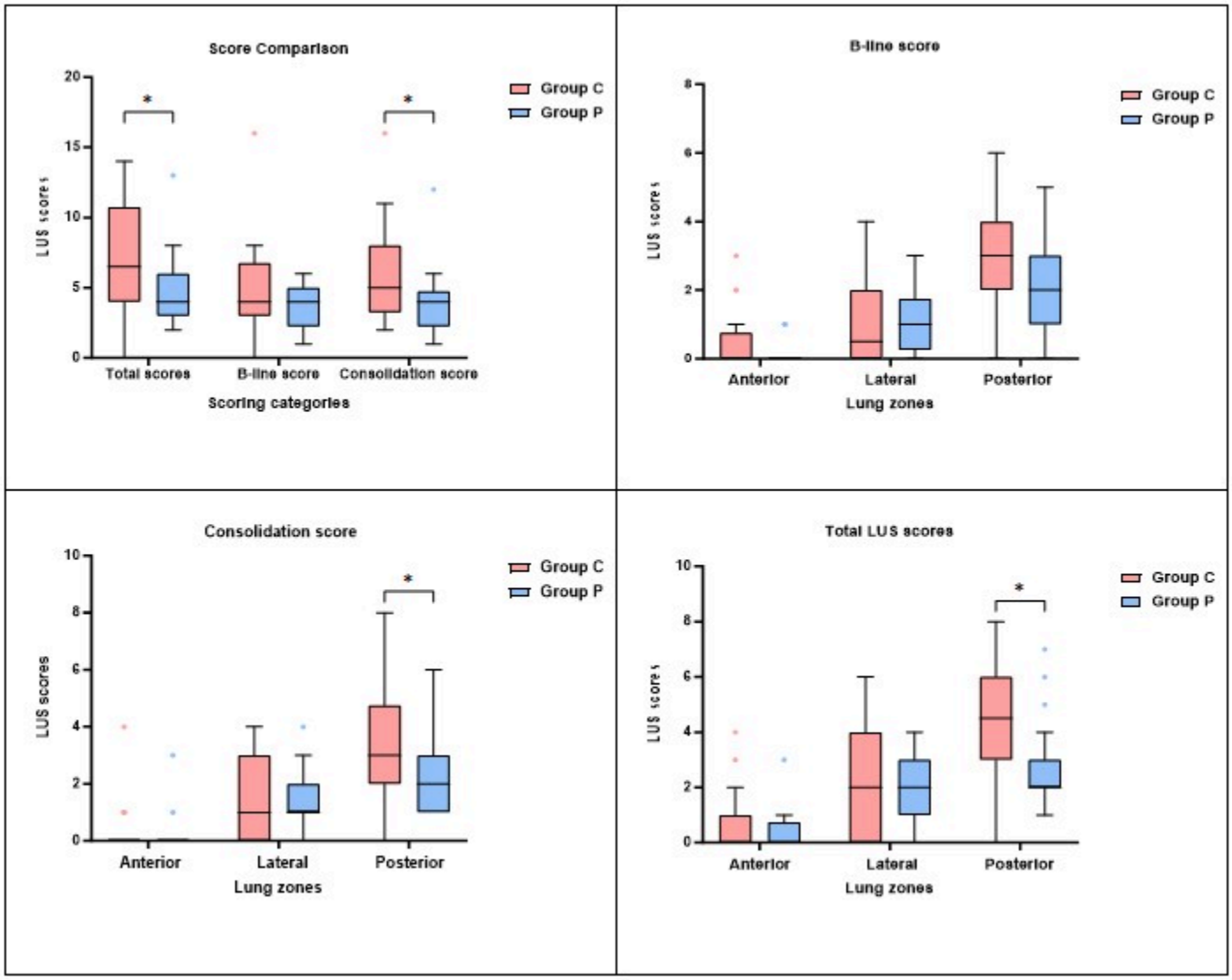

Figure 4

The LUS scores.

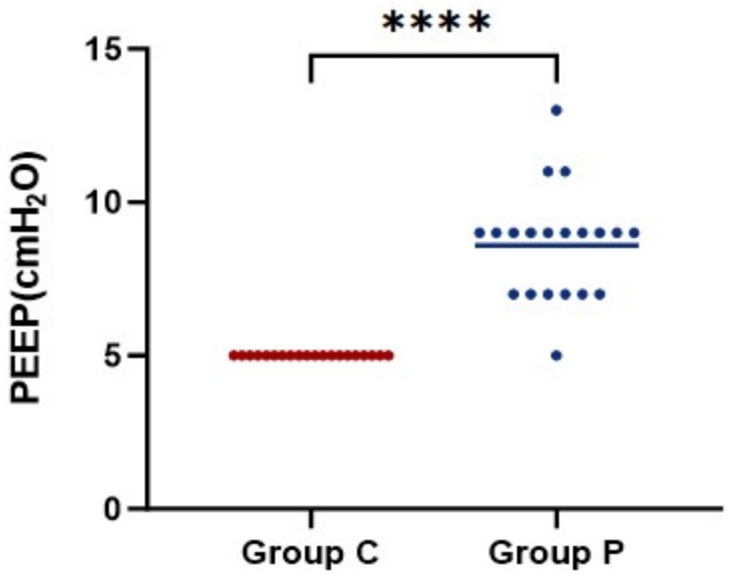

Figure 5

The distribution of PEEP during surgery in the two groups. "•" represents the PEEP value of each patient, the solid line indicates the mean. ****P<0.01.

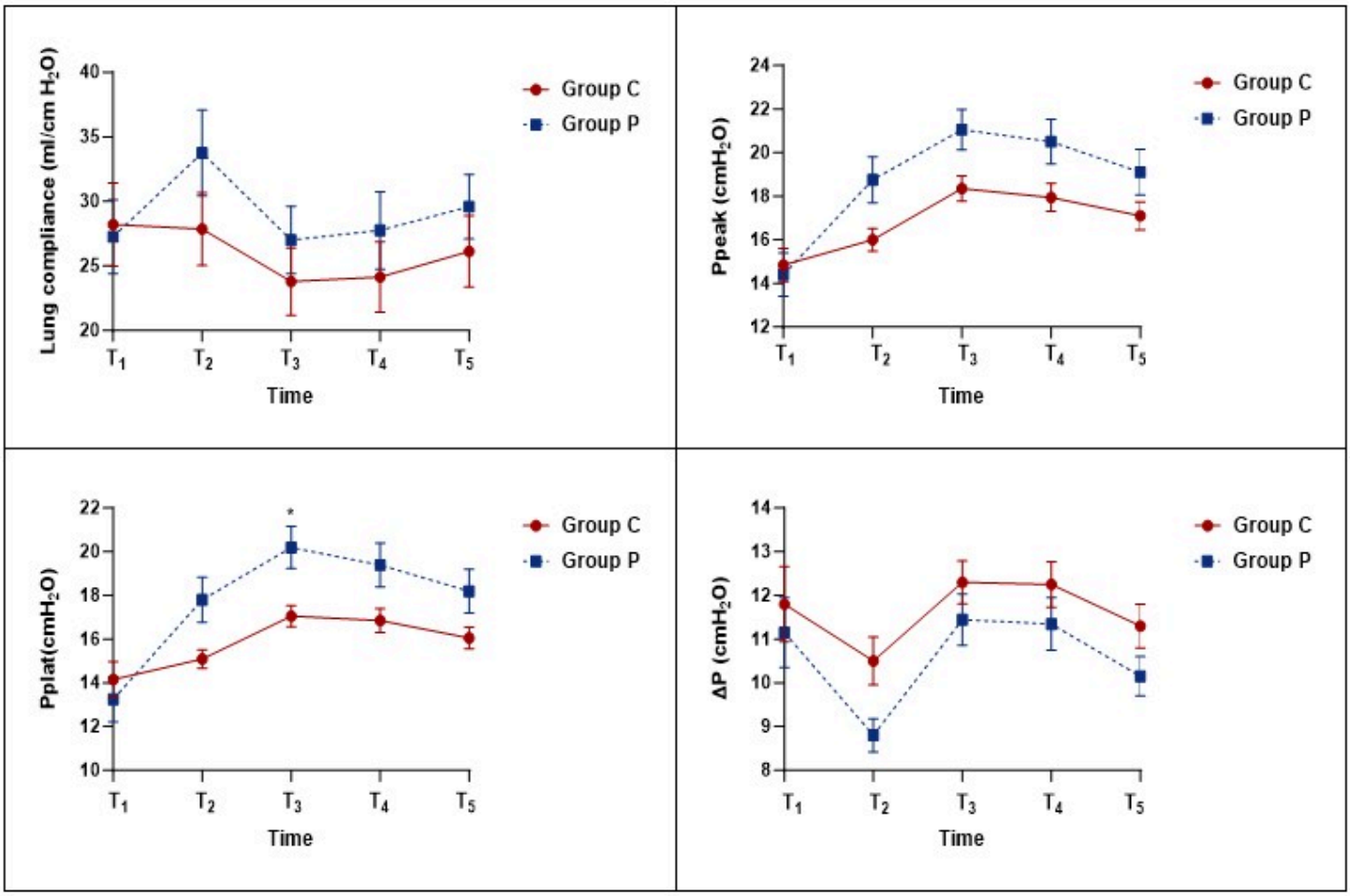

Figure 6

The respiratory mechanics between two groups. T_1: After intubation; T_2: 15 minutes after mechanical ventilation; T_3: 30 minutes after mechanical ventilation; T_4: 1 hour after mechanical ventilation; T_5: Immediately after surgery; T_6: 30 minutes after extubation.

Supplementary Files

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