



OPEN ACCESS

EDITED BY

Luigi Vetrugno,
University of Studies G. d'Annunzio Chieti and
Pescara, Italy

REVIEWED BY

Savino Spadaro,
University of Ferrara, Italy
Anna Camporesi,
Ospedale dei Bambini Vittore Buzzi, Italy

*CORRESPONDENCE

Yin Xia
✉ xiayin2201@outlook.com
Qi Chen
✉ cq_911@126.com

[†]These authors have contributed equally to
this work and share first authorship

RECEIVED 25 August 2024

ACCEPTED 23 September 2024

PUBLISHED 10 October 2024

CITATION

Yue K, Wang J, Wu H, Sun Y, Xia Y and
Chen Q (2024) A comparison of the effects of
lung protective ventilation and conventional
ventilation on the occurrence of atelectasis
during laparoscopic surgery in young infants:
a randomized controlled trial.
Front. Med. 11:1486236.
doi: 10.3389/fmed.2024.1486236

COPYRIGHT

© 2024 Yue, Wang, Wu, Sun, Xia and Chen.
This is an open-access article distributed
under the terms of the [Creative Commons
Attribution License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use,
distribution or reproduction in other forums is
permitted, provided the original author(s) and
the copyright owner(s) are credited and that
the original publication in this journal is cited,
in accordance with accepted academic
practice. No use, distribution or reproduction
is permitted which does not comply with
these terms.

A comparison of the effects of lung protective ventilation and conventional ventilation on the occurrence of atelectasis during laparoscopic surgery in young infants: a randomized controlled trial

Kun Yue^{1,2†}, Jingru Wang^{1,2†}, Huangxing Wu¹, Yingying Sun²,
Yin Xia^{2*} and Qi Chen^{1*}

¹Department of Anesthesiology and Perioperative Medicine, The Second Affiliated Hospital of Anhui Medical University, Hefei, Anhui, China, ²Department of Anesthesiology and Perioperative Medicine, Anhui Provincial Children's Hospital, Hefei, Anhui, China

Objective: This study utilized lung ultrasound to investigate whether lung protective ventilation reduces pulmonary atelectasis and improves intraoperative oxygenation in infants undergoing laparoscopic surgery.

Methods: Eighty young infants (aged 1–6 months) who received general anesthesia for more than 2 h during laparoscopic surgery were randomized into the lung protective ventilation group (LPV group) and the conventional ventilation group (control group). The LPV group received mechanical ventilation starting at 6 mL/kg tidal volume, 5 cmH₂O PEEP, 60% inspired oxygen fraction, and half-hourly alveolar recruitment maneuvers. Control group ventilation began with 8–10 mL/kg tidal volume, 0 cmH₂O PEEP, and 60% inspired oxygen fraction. Lung ultrasound was conducted five times—T1 (5 min post-intubation), T2 (5 min post-pneumoperitoneum), T3 (at the end of surgery), T4 (post-extubation), and T5 (prior to discharge from the PACU)—for each infant. Simultaneous arterial blood gas analysis was performed at T1, T2, T3, and T4.

Results: Statistically significant differences were observed in pulmonary atelectasis incidence, lung ultrasound scores, and the PaO₂, PaCO₂, PaO₂/FiO₂ ratios at T2, T3, and T4. However, at T5, no statistically significant differences were noted in terms of lung ultrasound scores (4.30±1.87 vs. 5.00±2.43, 95% CI: -1.67 to 0.27, *p*=0.153) or the incidence of pulmonary atelectasis (32.5% vs. 47.5%, *p*=0.171).

Conclusion: In infants aged 1–6 months, lung protective ventilation during laparoscopy under general anesthesia significantly reduced the incidence of pulmonary atelectasis and enhanced intraoperative oxygenation and dynamic lung compliance compared to conventional ventilation. However, these benefits did not persist; no differences were observed in lung ultrasound scores or the incidence of pulmonary atelectasis at PACU discharge.

Clinical trial registration: <http://www.chictr.org.cn/>, identifier: ChiCTR2200058653.

KEYWORDS

pulmonary atelectasis, lung protective ventilation, positive end-expiratory pressure, recruitment maneuvers, infant, laparoscopy, ultrasonography

1 Introduction

Laparoscopic surgery in infants and toddlers is becoming more widespread because of its minimal invasiveness. During laparoscopic surgery, an increase in intra-abdominal pressure elevates the diaphragm and reduces both chest wall compliance and functional residual capacity (FRC), leading to further atelectasis formation in the dependent lung bases (1). Pulmonary atelectasis contributes to perioperative lung dysfunction and potential injury (2). Neonates, infants and small children have low functional residual capacity, high pulmonary closing capacity and high oxygen consumption, making them particularly susceptible to atelectasis and hypoxemia during laparoscopic procedures (2, 3). Studies have shown that lung protective ventilation (LPV), such as small tidal volumes (4), positive end-expiratory pressure (PEEP) (5, 6) combined with lung recruitment maneuvers (RMs) (7) can be effective in preventing atelectasis in children. However, the LPV remains a subject of debate and is not well studied (8), particularly in infants and neonates. Lung ultrasound (LUS) is a reliable and accurate noninvasive imaging technique that is effective for detecting anesthesia-induced atelectasis in children (9). Considering the potential benefits of lung protective ventilation in adult and pediatrics patients and the limited research on its use in laparoscopic surgery for infants, a randomized controlled trial was conducted to compare lung protective ventilation with conventional ventilation in these surgeries. The aim of this study was to evaluate the effectiveness of lung protective ventilation (LPV) in reducing the incidence of pulmonary atelectasis and improving oxygenation and dynamic lung compliance during surgery in young infants, as assessed by ultrasound, compared to conventional ventilation. We hypothesized that LPV would lead to lower pulmonary atelectasis and higher intraoperative oxygenation and dynamic lung compliance. Additionally, we anticipated that LPV would reduce the risk of postoperative pulmonary complications in young infants.

2 Methods

2.1 Ethical approval

This study was approved by the Medical Ethics Committee of Anhui Provincial Children's Hospital, China, on March 23, 2022 (approval number: EYLL-2022-026) and was registered at <http://www.chictr.org.cn/> (trialnumber: ChiCTR2200058653; April 13, 2022). For infants in this study, voluntary informed consent was obtained and signed by their parents or legal guardians. This single-center prospective randomized controlled trial was conducted from April 2022 to December 2023 at Anhui Provincial Children's Hospital in China.

2.2 Participants

Infants aged 1–6 months, classified as American Society of Anesthesiologists (ASA) physical status I-II, and scheduled for laparoscopic abdominal surgery under general anesthesia (>2h) between April 2022 and December 2023 at Anhui Provincial Children's Hospital were recruited for this study.

The exclusion criteria were those who were preterm infants, had recent pulmonary inflammation (within one month), had preoperative conditions increasing the risks of severe infections, sepsis, or regurgitation and aspiration, or contraindications to radial artery cannulation, classified as ASA III or higher, lacked family consent, or were needed to taken to the postoperative intensive care unit (ICU) after surgery.

2.3 Randomization

Patients were randomized via computer-generated sequence, and their group assignment was sealed in envelopes. Patients were divided into two groups: the lung protective ventilation group (LPV group: small tidal volume, positive end-expiratory pressure, and recruitment maneuvers) and the conventional ventilation group (control group: zero PEEP and no recruitment maneuvers) at a 1:1 ratio. A single investigator opened the envelopes and implemented the respective mechanical ventilation protocols. The assessor responsible for conducting the lung ultrasound evaluations was blinded to the group assignments.

2.4 Anesthesia protocols and ventilator settings

An intravenous cannula was placed prior to transferring the infant to the operating room. Upon the patient's arrival in the operating room, routine monitoring of blood pressure (BP), electrocardiogram (ECG), oxygen saturation (SpO₂), and body temperature was initiated. Following anesthesia induction, invasive arterial pressure monitoring was commenced. Anesthesia induction involved a sequential intravenous slow injection protocol comprising midazolam (0.05 mg/kg), sufentanil (0.3 µg/kg), propofol (3 mg/kg), and cisatracurium (0.1 mg/kg). Following this, a 3.5–4.5 uncuffed endotracheal tube (10) was inserted, and pressure-controlled ventilation was initiated after successful intubation. Prior to intubation, all patients underwent preoxygenation with 60% (11) oxygen. Anesthesia maintenance involved administering a single caudal block of 0.25% ropivacaine (0.6 mL/kg) combined with an intravenous infusion of remifentanyl (0.1 to 0.3 µg/kg/min) and inhalation of sevoflurane (2 to 3%) during surgery. The pneumoperitoneum pressure was consistently maintained at 5–7 mmHg.

Throughout the surgery, haemodynamic stability was maintained, and vasopressors were used as needed. Lactated Ringer's solution was administered at a rate of 10–15 mL/kg/h during surgery. Additionally, suspended red blood cells, plasma, and albumin were administered as needed. At the end of surgery, the administration of sevoflurane via inhalation and the infusion of remifentanyl were ceased. In the LPV group, during surgery, the following ventilation settings were used: tidal volume (TV) of 6 mL/kg, respiratory rate (RR) of 24–28 breaths/min, inspiratory/expiratory (I: E) ratio of 1:1.5, PEEP of 5 cmH₂O, fractional inspired oxygen tension (FiO₂) of 60% (12) and a flow rate of 2 L/min, with a maximum pressure limit of 30 cmH₂O. Lung recruitment maneuvers were performed every 30 min (13). Blood pressure and respiratory parameters were assessed prior to lung recruitment maneuvers to ensure the child was ready for the procedure

(14). Recruitment maneuvers were performed, in pressure-controlled mode, with a constant driving pressure of 15 cmH₂O. PEEP was increased in steps of 5 cmH₂O, from 5 to 15 cmH₂O, every three breaths. The target recruitment pressure of 30 cmH₂O was maintained for 10 breaths (15). For the control group, a tidal volume (TV) of 8–10 mL/kg, a respiratory rate (RR) of 24–28 breaths/min, an I:E ratio of 1:1.5, a PEEP of 0 cmH₂O (16), a FiO₂ of 60%, and a flow rate of 2 L/min were used, with a maximum pressure limit of 30 cmH₂O, and lung recruitment maneuvers were not performed. When mechanical ventilation was performed after induction in both groups, the presence or absence of autoPEEP (17) was observed and recorded. Postoperatively, upon awakening from anesthesia, 0.02 mg/kg atropine and 0.05 mg/kg neostigmine were administered after the infant recovered spontaneous respiration (18). The tracheal tube was removed upon observing indications like a conjugate gaze, purposeful movements, the eye opening, a tidal volume > 5 mL/kg, and facial ghosting (19). All infants were transferred to the postanesthesia care unit (PACU) and received supplemental oxygen at a rate of 2 L/min through a simple mask equipped with an oxygen reservoir. Gradually reduced to room air when the SpO₂ level exceeded 95% and remained stable. After meeting the criteria for discharge from the PACU (20), the infants were returned to their wards.

2.5 Lung ultrasound

Patients were placed in the supine position and scanned using ultrasound (SONIMAGE HS2-KONICA MINOLTA, Shanghai, China) according to the lung ultrasound score examination method described by Acosta et al. (9, 21). Each half of the chest was divided into three regions (anterior, posterior, and lateral) by the anterior and posterior axillary lines and further divided into six regions by an axial line 1 cm above the nipples. The 12 regions in the lung were scanned sequentially from right to left, from cranial to caudal and anterior to posterior ends. Lung ultrasound scores were assessed using ultrasound at T1 (5 min post-intubation), T2 (5 min post-pneumoperitoneum), T3 (at the end of surgery), T4 (post-extubation), and T5 (prior to discharge from the PACU). The 12 quadrants were assigned a score of 0 to 3 based on the following scoring system: 0, 0 to 2 B lines; 1, at least three B lines or one or multiple small subpleural consolidations separated by a normal pleural line; 2, multiple coalescent B lines or multiple small subpleural consolidations separated by a thickened or irregular pleural line; and 3, consolidation or small subpleural consolidation of more than 1 cm × 2 cm (Figure 1). The consolidation scores were recorded at each time point. Significant atelectasis was determined if any region had a consolidation score of 2 (22). The lung ultrasound score (0–36) was then calculated by adding up the 12 individual quadrant scores, with higher scores indicating more severe aeration loss.

2.6 Primary outcome

Lung ultrasound scores and significant atelectasis incidence rates were assessed at T1 (5 min post-intubation), T2 (5 min post-pneumoperitoneum), T3 (at the end of surgery), T4 (post-extubation), and T5 (prior to discharge from the PACU).

2.7 Secondary outcomes

Measurements of PaO₂ (partial pressure of arterial oxygen), PaCO₂ (partial pressure of arterial carbon dioxide), the PaO₂/FiO₂ ratio, HR (heart rate), MAP (mean arterial pressure), and SpO₂ (oxygen saturation) were recorded at T1, T2, T3 and T4. Peak airway pressure (P_{peak}) and dynamic lung compliance (C_{dyn}) were directly measured on the anesthesia machine at T1, T2 and T3. The presence or absence of automatic PEEP and its value were recorded at T1. The time from the recovery of spontaneous breathing to extubation, and the total duration of their stay in the PACU, were both recorded. An independent investigator, blinded to the study details, evaluated the incidence of pulmonary complications within 7 days after surgery. These complications were scored based on the operational definitions of postoperative pulmonary complications provided by Hulzebos et al. (23) (Figure 2).

2.8 Safety of the intervention

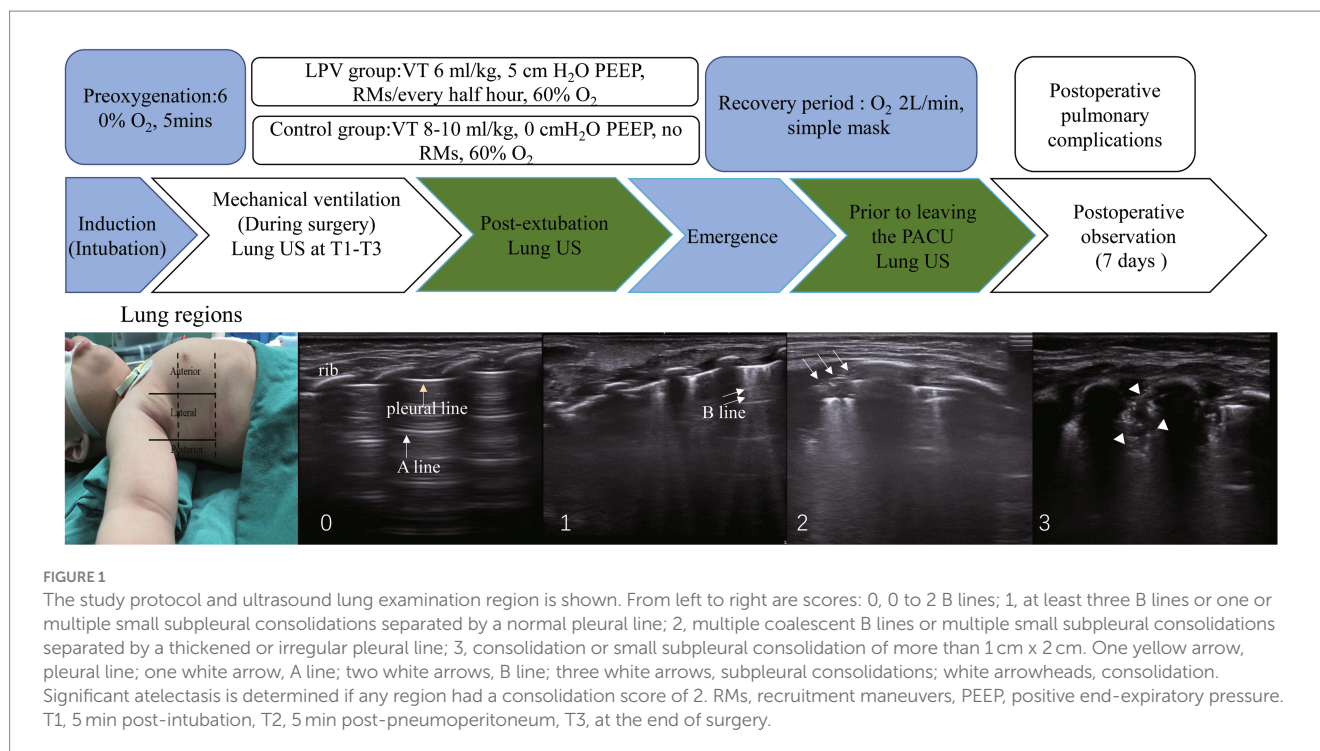
The study evaluated the likelihood of potential side effects, such as transient hypotension (defined as less than 80% of baseline blood pressure) and oxygen desaturation (SpO₂ below 95%), following regular alveolar recruitment maneuvers.

2.9 Statistical analysis

Unless otherwise specified, all the data are presented as the mean ± standard deviation or median (interquartile range). The Shapiro–Wilk test was used to assess the normality of the distribution. Outcomes were assessed using independent t tests, Mann–Whitney U tests and chi-square tests. A two-tailed *p* value < 0.05 was considered to indicate statistical significance. Repeated-measures ANOVA was used to detect differences in the measured parameters between treatment groups and over time via a mixed-model procedure, with Bonferroni's test for multiple comparisons. *p* values < 0.05 were considered to indicate statistical significance. Data analysis was performed using SPSS software (version 25.0; SPSS, Inc., Chicago, Illinois, USA) and data visualization were carried out with GraphPad Prims 9 (GraphPad Software, San Diego, CA, USA).

2.10 Sample size calculation

We used PASS 15.0 to calculate the sample size, basing our calculations on data from prior research. One study reported that lung ultrasound had an accuracy of 88% for detecting pulmonary atelectasis (9). According to our pilot study, the incidence of ultrasound-detected pulmonary atelectasis was 70%. We assumed this incidence would be halved by lung recruitment maneuvers and PEEP (15). With an alpha error of 0.05 and a power of 80%, the required sample size was calculated to be 29 patients per group. Accounting for a 20% dropout rate, we determined that a total of 73 patients would be needed, and thus we planned to enroll 80 patients in the study.



3 Results

Patient enrolment started on April 2022. A total of 80 patients were randomly assigned to the LPV ($n=40$) or control ($n=40$) group (Figure 3). There were no statistically significant differences in age, gender, height, weight, duration of surgery, or duration of anesthesia between the two groups of children (Table 1).

3.1 Primary outcome

There were statistically significant differences between the LPV group and the control group at T2 in terms of ultrasound scores (6.35 ± 2.66 vs. 10.95 ± 4.07 , 95% CI $(-6.13$ to $-3.07)$, $p < 0.001$) and the incidence of atelectasis (62.5% vs. 87.5%, $p = 0.010$); at T3 in terms of ultrasound scores (6.65 ± 3.15 vs. 12.53 ± 4.29 , 95% CI $(-7.55$ to $-4.20)$, $p < 0.001$) and the incidence of atelectasis (55% vs. 90%, $p = 0.0005$); and at T4 in terms of ultrasound scores (5.50 ± 2.75 vs. 8.00 ± 2.92 , 95% CI $(-3.76$ to $-1.24)$, $p < 0.001$) and the incidence of atelectasis (35% vs. 72.5%, $p = 0.001$). At T1, there was no statistically significant difference in lung ultrasound score (7.35 ± 5.06 vs. 5.85 ± 4.14 , 95% CI $(-0.56$ to $3.56)$, $p = 0.151$), the incidence of atelectasis (80% vs. 77.5%, $p = 0.785$). Moreover, there were no statistically significant differences between the LPV group and the control group at T5 in terms of ultrasound score (4.30 ± 1.87 vs. 5.00 ± 2.43 , 95% CI $(-1.67$ to $0.27)$, $p = 0.153$) or incidence of atelectasis (32.5% vs. 47.5%, $p = 0.171$) (Table 2). Ultrasound scores of both groups at various time points are presented in Figure 4.

3.2 Secondary outcomes

At T1, there was no statistically significant difference in PaO₂ (260.64 ± 23.43 vs. 262.39 ± 25.89 , 95% CI $(-12.74$ to $9.25)$, $p = 0.752$),

PaCO₂ (38.32 ± 3.15 vs. 37.94 ± 4.16 , 95% CI $(-1.27$ to $2.02)$, $p = 0.653$), or the PaO₂/FiO₂ ratio (434.40 ± 39.05 vs. 437.31 ± 43.16 , 95% CI $(-21.23$ to $15.41)$, $p = 0.752$). There were statistically significant differences between the LPV group and the control group at T2 and T3 in terms of the PaO₂, PaCO₂, PaO₂/FiO₂ or Cdyn; at T4, in terms of the PaO₂ or PaO₂/FiO₂. The LPV group demonstrated shorter extubation times and reduced lengths of stay in the PACU compared to the control group (Table 2). There was no significant difference in autoPEEP between the two groups at T1. The two groups showed no significant difference in HR, MAP or SpO₂ at T1, T2, T3, or T4 (Table 3). No significant difference was observed in the incidence of pulmonary complications within 7 days after surgery ($p = 0.516$) (Table 4). Alveolar recruitment maneuvers did not show transient hypotension and oxygen desaturation.

4 Discussion

In this prospective RCT, the primary outcome indicated that lung protective ventilation reduced the incidence of pulmonary atelectasis in infants during laparoscopy under general anesthesia compared to conventional ventilation, enhanced intraoperative oxygenation and Cdyn, the duration of extubation and the length of stay in the PACU were both reduced. However, this improvement was transient, with no observed differences in lung ultrasound scores or incidence of pulmonary atelectasis at discharge from the PACU. Moreover, no significant differences were observed in the incidence of postoperative pulmonary complications within 7 days after surgery.

Our results align with previous studies (7, 15) demonstrating that laparoscopic surgery under general anesthesia can lead to pulmonary atelectasis in children, we provide data on infants. Acosta et al. (15) discovered that lung collapse resulting from capnoperitoneum can be mitigated through the use of LPV in all children aged 6 months to 7 years undergoing laparoscopic surgery. The incidence of pulmonary

Grade 1
Cough, dry
Microatelectasis: abnormal lung findings and temperature > 37.5 °C without other documented cause; results of chest radiograph either normal or unavailable
Dyspnoea, not due to other documented cause
Grade 2
Cough, productive, not due to other documented cause
Bronchospasm: new wheezing or preexistent wheezing resulting in change therapy
Hypoxemia: alveolar-arterial gradient >29 and symptoms of dyspnoea or wheezing
Atelectasis: radiological confirmation plus either temperature >37.5 °C or abnormal lung findings
Hypercarbia, transient, requiring treatment, such as naloxone or increased manual or mechanical ventilation
Adverse reaction to pulmonary medication
Grade 3
Pleural effusion, resulting in thoracentesis
Pneumonia, suspected: radiological evidence without bacteriological confirmation
Pneumonia, proved: radiological evidence and documentation of pathological organism by Gram stain or culture
Pneumothorax
Reintubation postoperative or intubation, period of ventilator dependence does not exceed 48 hours
Grade 4
Ventilatory failure: postoperative ventilator dependence exceeding 48 hours, or reintubation with subsequent period of ventilator dependence exceeding 48 hours

FIGURE 2
Operational definitions of postoperative pulmonary complications (23).

atelectasis resulting from pneumoperitoneum can potentially be reduced through the use of LPV. The primary mechanisms involve the application of lung recruitment maneuvers and PEEP, which effectively mitigate diaphragmatic elevation and subsequent intra-abdominal pressure increase caused by intraperitoneal gas accumulation (24). Recruitment maneuvers can re-expand atelectatic lung tissue and improve lung compliance; however, they may also carry risks such as barotrauma, hemodynamic instability, and worsening oxygenation (14), the pressure-volume curve or loop method, the end-expiratory lung volume–static compliance method, and ultrasound can all be used to assess the effectiveness of lung recruitment (7, 25). Other studies have shown that the optimal PEEP under RM can be determined based on the static compliance of the respiratory system (crs) (26). This study revealed that combining lung recruitment maneuvers with PEEP effectively reopened collapsed alveoli and enhanced intraoperative oxygenation and dynamic lung compliance during laparoscopic surgery in small infants. However,

one limitation is that the extent of alveolar recruitment remains somewhat unclear.

Our findings indicate that recruitment maneuvers, followed by a PEEP of 5 cmH₂O, are both effective and safe for reducing the number of atelectatic areas following laparoscopic surgery in young infants, but the specific numerical setting for PEEP remains controversial. J-H Lee's (4) study posits that a PEEP of 10 cm H₂O is an appropriate level for children in mechanically ventilation. However, other studies (6, 27) have indicated improvements in lung ultrasound scores and reductions in the incidence of atelectasis in children administered a PEEP of 5 cmH₂O. Although the application of PEEP facilitates the reopening of collapsed alveoli and improves oxygenation, the use of high levels of PEEP must be carefully considered due to potential risks such as alveolar overdistension and hemodynamic instability (28). These effects are particularly undesirable in infants undergoing laparoscopic surgery. Due to potential side effects, clinicians must exercise caution when using 10 cmH₂O PEEP during laparoscopic

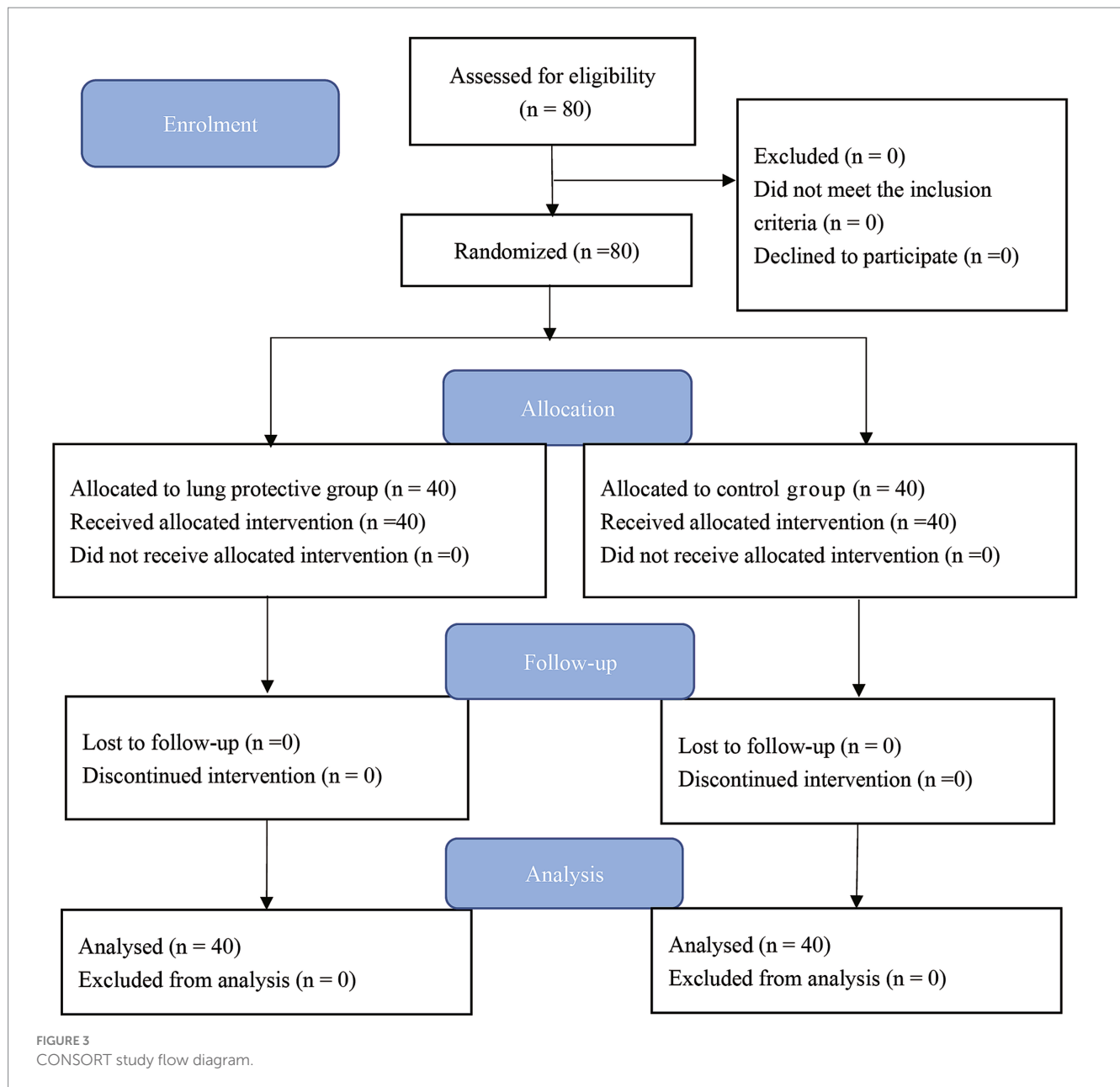


TABLE 1 Comparisons of baseline characteristics between the two groups.

Variables	LPV group (n = 40)	Control group (n = 40)	P value
Age/month	2.5 (1.8,4.5)	2.9 (1.7,4.4)	0.788
Sex (male/female), n	28/12	34/6	0.181
Height, cm	59.0 (56.5,65.0)	58.0 (55.0,64.0)	0.451
Weight, kg	6.0 (5.3,7.0)	6.1 (5.0,7.8)	0.496
Duration of surgery, min	141.5 (120.5,189.3)	153.5 (123.0,195.5)	0.630
Duration of anesthesia, min	189.5 (172.2,237.0)	189.5 (157.3,227.8)	0.507

Values are median (inter-quartile range), n (%).

surgery for small infants. For safety considerations, this study employed 5 cmH₂O PEEP in the LPV group.

Studies have shown that the detrimental effects of capnoperitoneum could be reversed by a protective ventilation

strategy combining lung recruitment and an individualized PEEP titration during laparoscopic surgery in children (5), the individualized lung protective ventilation during laparoscopic surgery in young infants should be the matter of future studies.

TABLE 2 Lung ultrasound score and comparison of intra- and postoperative variables between the LPV group and control group.

	Parameters	LPV group (n = 40)	Control group (n = 40)	Mean differences (95% CI)	P value
T1	Incidence of significant atelectasis	32 (80)	31 (77.5)		0.785
	Lung ultrasound score	7.35 ± 5.06	5.85 ± 4.14	1.50 (−0.56 to 3.56)	0.151
	PaO ₂ (mmHg)	260.64 ± 23.43	262.39 ± 25.89	−1.75 (−12.74 to 9.25)	0.752
	PaCO ₂ (mmHg)	38.32 ± 3.15	37.94 ± 4.16	0.37 (−1.27 to 2.02)	0.653
	PaO ₂ /FiO ₂ (mmHg)	434.40 ± 39.05	437.31 ± 43.16	−2.91 (−21.23 to 15.41)	0.752
	P _{peak} (cmH ₂ O)	11.0 (10.3,12.0)	14 (13.0,15.0)		<0.001*
	Cydn (mL/cmH ₂ O)	6.34 ± 2.44	4.17 ± 1.10	2.17 (1.33 to 3.00)	<0.001*
	autoPEEP (cmH ₂ O)	0 (0,1)	0 (0,1)		0.772
T2	Incidence of significant atelectasis	25 (62.5)	35 (87.5)		0.010*
	Lung ultrasound score	6.35 ± 2.66	10.95 ± 4.07	−4.60 (−6.13 to −3.07)	<0.001*
	PaO ₂ (mmHg)	248.26 ± 24.30	209.62 ± 29.68	38.64 (26.57 to 50.72)	<0.001*
	PaCO ₂ (mmHg)	47.68 ± 3.36	38.34 ± 2.86	9.35 (7.96 to 10.73)	<0.001*
	PaO ₂ /FiO ₂ (mmHg)	413.77 ± 40.50	349.37 ± 49.47	64.40 (44.28 to 84.53)	<0.001*
	P _{peak} (cmH ₂ O)	14.0 (14.0,15.0)	17 (17.0,18.0)		<0.001*
	Cydn (mL/cmH ₂ O)	4.07 ± 1.26	3.39 ± 0.89	0.68 (0.19 to 1.17)	<0.001*
T3	Incidence of significant atelectasis	22 (55)	36 (90)		0.0005*
	Lung ultrasound score	6.65 ± 3.15	12.53 ± 4.29	−5.88 (−7.55 to −4.20)	<0.001*
	PaO ₂ (mmHg)	246.94 ± 25.49	172.53 ± 14.86	74.41 (65.12 to 83.70)	<0.001*
	PaCO ₂ (mmHg)	48.24 ± 3.39	40.99 ± 2.35	7.26 (5.96 to 8.56)	<0.001*
	PaO ₂ /FiO ₂ (mmHg)	411.56 ± 42.49	287.54 ± 24.76	124.02 (108.54 to 139.50)	<0.001*
	P _{peak} (cmH ₂ O)	11.0 (11.0,12.0)	14.5 (13.0,15.0)		<0.001*
	Cydn (mL/cmH ₂ O)	5.93 ± 1.93	4.10 ± 1.07	1.83 (1.14 to 2.53)	<0.001*
T4	Incidence of significant atelectasis	14 (35)	29 (72.5)		0.001*
	Lung ultrasound score	5.50 ± 2.75	8.00 ± 2.92	−2.50 (−3.76 to −1.24)	<0.001*
	PaO ₂ (mmHg)	85.42 ± 3.73	72.04 ± 6.72	13.38 (10.96 to 15.80)	<0.001*
	PaCO ₂ (mmHg)	40.65 ± 3.58	40.55 ± 3.21	0.10 (−1.41 to 1.62)	0.893
	PaO ₂ /FiO ₂ (mmHg)	427.09 ± 18.63	360.20 ± 33.59	66.89 (54.80 to 78.98)	<0.001*
T5	Incidence of significant atelectasis	13 (32.5)	19 (47.5)		0.171
	Lung ultrasound score	4.30 ± 1.87	5.00 ± 2.43	−0.70 (−1.67 to 0.27)	0.153
	Time to extubation, min	15.0 (13.0,18.5)	18.0 (16.0,20.0)		0.003*
	PACU duration, min	29.5 (29,33)	34.0 (30.5,35.8)		<0.001*

Values are median (inter-quartile range), n (%), or mean ± standard deviation. * P value <0.05. T1 was 5 min post-intubation, T2 was 5 min post-pneumoperitoneum, T3 was at the end of surgery, T4 was post-extubation, and T5 was prior to discharge from the PACU.

Avoiding high fractions of oxygen in inspired gas during induction and maintenance of anesthesia may prevent the formation of atelectasis (29). Studies have shown that a lower oxygen concentration during anesthesia induction is associated with a lower risk of atelectasis immediately after anesthesia induction in children, and 60% oxygen should be applied to prevent atelectasis (11). The changes in oxygen concentration were consistent in both groups, with 60% FiO₂ used at induction and intraoperatively, potentially reducing the occurrence of pulmonary atelectasis. At extubation, the air oxygen concentration was used, and in the PACU, the infants' FiO₂ was 0.29. To avoid residual effects of anesthetic drugs, incomplete lung re-expansion, reduced chest wall, and diaphragmatic activity caused by surgical injury and pain, and

gastrointestinal reactions (30), postoperative oxygen respiratory support was maintained during the awakening period until SpO₂ stabilized at 95% or higher. Once the SpO₂ level exceeded 95% and stabilized, the FiO₂ was gradually reduced to room air levels. The infants in both groups did not develop hypoxemia after breathing air. The potential effects of oxygen concentration changes warrant further exploration.

Our study demonstrated that patients in both groups experienced significant improvements in pulmonary ventilation after extubation, despite variations in PaO₂, extubation times, and lengths of stay in the PACU. There were no statistically significant differences in ultrasound scores and incidence of significant pulmonary atelectasis in infants discharged from the PACU, which is consistent with the findings of

TABLE 3 Changes in vital signs at each time point between the LPV group and the control group.

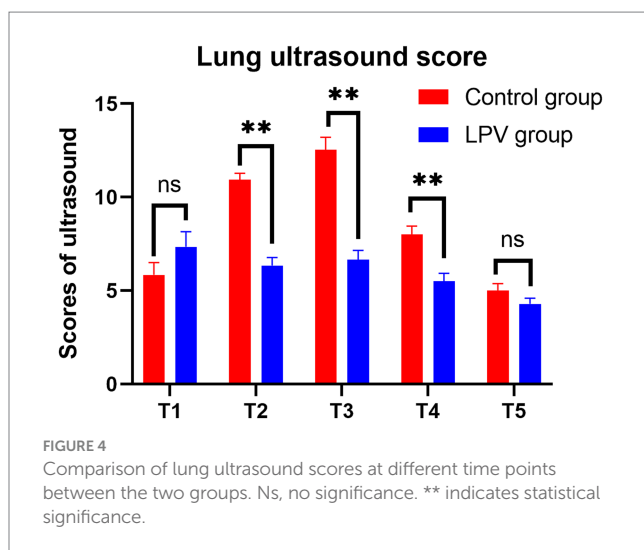
	LPV group (n = 40)	Control group (n = 40)	P value
MAP (mmHg) at T1	55.83 ± 5.78	57.05 ± 6.40	0.300
HR (bpm) at T1	130.43 ± 9.74	128.54 ± 9.67	0.434
SpO ₂ (%) at T1	100 (97–100)	100 (98–100)	0.937
MAP (mmHg) at T2	56.25 ± 4.05	57.49 ± 4.20	0.148
HR (bpm) at T2	123.25 ± 6.34	121.18 ± 6.73	0.179
SpO ₂ (%) at T2	100 (97–100)	100 (98–100)	0.706
MAP (mmHg) at T3	55.60 ± 4.04	56.28 ± 3.83	0.368
HR (bpm) at T3	118.95 ± 5.03	117.56 ± 4.57	0.219
SpO ₂ (%) at T3	100 (98–100)	100 (98–100)	0.513
MAP (mmHg) at T4	60.75 ± 3.41	61.77 ± 4.21	0.240
HR (bpm) at T4	132.93 ± 9.29	132.97 ± 8.79	0.981
SpO ₂ (%) at T4	100 (97–100)	100 (96–100)	0.259

Values are mean ± standard deviation, median (range).

TABLE 4 Incidence of PPCs within 7 days after surgery [n (%)].

Groups	n	Incidence of PPCs (n, %)	Grading of PPCs			
			Grade 1	Grade 2	Grade 3	Grade 4
LPV group*	40	4 (10)	3	1	0	0
Control group	40	7 (17.5)	5	2	0	0

PPCs, Postoperative Pulmonary Complications.* The Incidence of PPCs within 7 days after surgery did not differ between the groups, *p* = 0.516.



findings indicated no variation in respiratory complications within 7 days after surgery, which may relate to the normal respiratory physiology of the infants included in the study. In fact, the potential of different tidal volumes to reduce the risk of postoperative pulmonary complications depends on the patient’s respiratory compliance (34). Moreover, large-sample, multicenter studies are necessary to further investigate the clinical significance of lung protective ventilation in small infant laparoscopic surgery.

Our study has several limitations. First, we included only infants with normal respiratory physiology, and those with lung disease or who were critically ill were not evaluated. Second, while all sonographers involved in our study were professionally trained, the observed atelectasis may be explained by the fact that small atelectasis can be hidden within the ribs’ acoustic shadows whenever the longitudinally oriented probe placed in the traditional orientation crosses the rib (9), during the second ultrasound examination, factors such as the patient’s positioning, the presence of surgical drapes, the requirement for sterility, and the surgeon’s maneuvers can impede the accessibility and effectiveness of the ultrasound, we conducted a comprehensive examination of pulmonary ultrasound images by adjusting the probe orientation and pausing the surgery to minimize the potential for misinterpretation (35). Third, we were unable to confirm the effect of recruitment maneuvers, although we assessed the potential risks associated with recruitment maneuvers and adhered to the established standards for their implementation, we could not rule out the possibility of overinflation, and we applied a PEEP of 5 cmH₂O in this trial, which might not be the optimal PEEP during laparoscopic surgery in infants. Fourth, we did not take into account the effect of autoPEEP when setting up ventilation, we recorded auto PEEP during mechanical ventilation after endotracheal intubation, however, the data of the two groups showed no difference, equalizing the

Zhu’s (18) study. Some patients might have performed uncontrolled recruitment maneuvers by sighing or coughing (31), the sigh is a normal homeostatic reflex that maintains lung compliance and decreases the risk of atelectasis (32). Both groups of infants have different body movements, coughing or crying, which may improve ventilation of the lungs.

Despite hypercapnia occurring during the intraoperative period, it was restored to acceptable levels by the time of extubation (33). The findings of our research indicate that LPV not only enhances ventilation and mitigates intraoperative atelectasis but also preserves hemodynamic stability without inducing fluctuations. Our secondary

possible influence of auto PEEP on the results. And we looked for the etiology and manage patients with auto PEEP (17), such as the use of increased depth of anesthesia to reduce sputum obstruction and avoid airway spasm, as well as the avoidance of thinner tracheal intubation (36, 37), thus reducing the potential impact that autoPEEP could have on this study. Further exploration of individualized PEEP in small infants via laparoscopy at a later date is warranted.

In conclusion, lung protective ventilation significantly reduced the incidence of pulmonary atelectasis in infants aged 1–6 months during laparoscopy under general anesthesia compared with conventional ventilation and improved intraoperative oxygenation and C_{dyn}, reduced in both the time to extubation and the length of stay in the PACU, however, pulmonary atelectasis did not seem to last very long, there was no difference in its incidence at discharge from the PACU, and nor in postoperative pulmonary complications within 7 days after surgery.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Medical Ethics Committee of Anhui Provincial Children's Hospital. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

KY: Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. JW: Data curation, Formal

analysis, Investigation, Methodology, Validation, Writing – original draft. HW: Data curation, Writing – original draft. YS: Formal analysis, Methodology, Visualization, Writing – review & editing. YX: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. QC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by grants from the Natural Science Foundation of Anhui Children's Hospital (grant No. 21etty005 to YX), the major project of Natural Science Research of Anhui Higher Education Institutes (grant No.2023AH040376 to QC).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Spadaro S, Karbing DS, Mauri T, Marangoni E, Mojoli F, Valpiani G, et al. Effect of positive end-expiratory pressure on pulmonary shunt and dynamic compliance during abdominal surgery. *Br J Anaesth.* (2016) 116:855–61. doi: 10.1093/bja/aew123
- Lagier D, Zeng C, Fernandez-Bustamante A, Vidal Melo MF. Perioperative pulmonary atelectasis: part II. Clinical Implications. *Anesthesiology.* (2022) 136:206–36. doi: 10.1097/aln.0000000000004009
- Baroncini S, Gentili A, Pigna A, Fae M, Tonini C, Tognù A. Anaesthesia for laparoscopic surgery in paediatrics. *Minerva Anestesiol.* (2002) 68:406–13. doi: 10.1016/j.eeus.2006.08.003
- Lee JH, Kang P, Song IS, Ji SH, Lee HC, Jang YE, et al. Determining optimal positive end-expiratory pressure and tidal volume in children by intratidal compliance: a prospective observational study. *Br J Anaesth.* (2022) 128:214–21. doi: 10.1016/j.bja.2021.09.024
- Acosta CM, Poliotto S, Abrego D, Bradley D, de Esteban S, Mir F, et al. Effect of an individualized lung protective ventilation on lung strain and stress in children undergoing laparoscopy: an observational cohort study. *Anesthesiology.* (2023) 140:430–41. doi: 10.1097/ALN.0000000000004856
- Lee HM, Min JY, Lee JR, Lee MH, Byon HJ. Effects of positive end-expiratory pressure on pulmonary atelectasis after paediatric laparoscopic surgery as assessed by ultrasound: a randomised controlled study. *Anaesth Crit Care Pain Med.* (2022) 41:101034. doi: 10.1016/j.accpm.2022.101034
- Gao Q, Ji H, Wu Z, Zhao P. Effect of ultrasound-guided lung recruitment manoeuvre on perioperative atelectasis during laparoscopy in young infants: a randomised controlled trial. *J Clin Anesth.* (2023) 86:111075. doi: 10.1016/j.jclinane.2023.111075
- Musch G, Vidal Melo MF. Intraoperative protective mechanical ventilation: fact or fiction? *Anesthesiology.* (2022) 137:381–3. doi: 10.1097/ALN.0000000000004366
- Acosta CM, Maidana GA, Jacovitti D, Belaunzaran A, Cereceda S, Rae E, et al. Accuracy of transthoracic lung ultrasound for diagnosing anesthesia-induced atelectasis in children. *Anesthesiology.* (2014) 120:1370–9. doi: 10.1097/ALN.0000000000000231
- Isa M, Holzki J, Hagemeyer A, Rothschild MA, Coté CJ. Anatomical in vitro investigations of the pediatric larynx: A call for manufacturer redesign of tracheal tube cuff location and perhaps a call to reconsider the use of Uncuffed tracheal tubes. *Anesth Analg.* (2021) 133:894–902. doi: 10.1213/ANE.0000000000005565
- Kim HI, Min JY, Lee JR, Kwan Woong C, Cho MR, Byon HJ. The effect of oxygen concentration on atelectasis formation during induction of general anesthesia in children: a prospective randomized controlled trial. *Paediatr Anaesth.* (2021) 31:1276–81. doi: 10.1111/pan.14304
- Abdallah NM, Elela AHA, Maghawry HH, Alkoniaes RM. Effect of different mechanical ventilation modes on cerebral blood flow during thoracoscopic surgery in neonates: a randomised controlled trial. *Indian J Anaesth.* (2022) 66:651–6. doi: 10.4103/ija.ija_1065_21
- Jang Y-E, Ji S-H, Kim E-H, Lee J-H, Kim J-T, Kim H-S. Effect of regular alveolar recruitment on intraoperative atelectasis in paediatric patients ventilated in the prone position: a randomised controlled trial. *Br J Anaesth.* (2020) 124:648–55. doi: 10.1016/j.bja.2020.01.022
- Bruins S, Sommerfield D, Powers N, von Ungern-Sternberg BS. Atelectasis and lung recruitment in pediatric anesthesia: an educational review. *Paediatr Anaesth.* (2022) 32:321–9. doi: 10.1111/pan.14335

15. Acosta CM, Sara T, Carpinella M, Volpicelli G, Ricci L, Poliotto S, et al. Lung recruitment prevents collapse during laparoscopy in children: a randomised controlled trial. *Eur J Anaesthesiol.* (2018) 35:573–80. doi: 10.1097/EJA.0000000000000761
16. Sun Y, Shen S, Deng X, Cai Y, Du Y. Lung protective ventilation in infants undergoing cardiopulmonary bypass surgery for congenital heart disease: a prospective randomized controlled trial. *Pediatr Anesth.* (2020) 30:814–22. doi: 10.1111/pan.13894
17. Keller M, Applefeld W, Acho M, Lee BW. How I Teach Auto-PEEP: Applying the Physiology of Expiration. *Sch.* (2022) 3:610–24. doi: 10.34197/ats-scholar.2022-0024HT
18. Zhu C, Zhang S, Dong J, Wei R. Effects of positive end-expiratory pressure/recruitment manoeuvres compared with zero end-expiratory pressure on atelectasis in children: a randomised clinical trial. *Eur J Anaesthesiol.* (2021) 38:1026–33. doi: 10.1097/EJA.0000000000001451
19. Templeton TW, Goenaga-Diaz EJ, Downard MG, McLouth CJ, Smith TE, Templeton LB, et al. Assessment of common criteria for awake Extubation in infants and young children. *Anesthesiology.* (2019) 131:801–8. doi: 10.1097/ALN.0000000000002870
20. Bizuneh YB, Berhe YW, Ashagrie HE, Lema GF, Fentie DY. Current practice of discharging patients from post anesthesia care unit after surgical operations. *Res Square.* (2020) 2018. doi: 10.21203/rs.3.rs-110088/v1
21. Monastesse A, Girard F, Massicotte N, Chartrand-Lefebvre C, Girard M. Lung ultrasonography for the assessment of perioperative atelectasis: a pilot feasibility study. *Anesth Analg.* (2017) 124:494–504. doi: 10.1213/ane.0000000000001603
22. Song IK, Kim EH, Lee JH, Ro S, Kim HS, Kim JT. Effects of an alveolar recruitment manoeuvre guided by lung ultrasound on anaesthesia-induced atelectasis in infants: a randomised, controlled trial. *Anaesthesia.* (2017) 72:214–22. doi: 10.1111/anae.13713
23. Hulzebos EHJ, Helders PJM, Favié NJ, De Bie RA, Brutel de la Riviere A, Van Meeteren NLU. Preoperative intensive inspiratory muscle training to prevent postoperative pulmonary complications in high-risk patients undergoing CABG surgery: a randomized clinical trial. *JAMA.* (2006) 296:1851–7. doi: 10.1001/jama.296.15.1851
24. Zeng C, Lagier D, Lee J-W, Vidal Melo MF. Perioperative pulmonary atelectasis: part I. Biology and Mechanisms. *Anesthesiology.* (2022) 136:181–205. doi: 10.1097/ALN.0000000000003943
25. Zheng M. Respiratory mechanics: revisiting the appraisal of lung recruitment. *Respir Care.* (2023) 68:1262–70. doi: 10.4187/respcare.10601
26. D'Antini D, Rauseo M, Grasso S, Mirabella L, Camporota L, Cotoia A, et al. Physiological effects of the open lung approach during laparoscopic cholecystectomy: focus on driving pressure. *Minerva Anesthesiol.* (2018) 84:159–67. doi: 10.23736/S0375-9393.17.12042-0
27. Zhu C, Zhang R, Jiang Y, et al. (2020). Protective Lung Ventilation in Children at Low Risk: Is it Necessary?. *SSRN Electronic Journal.* doi: 10.2139/ssrn.3605344
28. Serpa Neto A, Schultz MJ. Optimizing the settings on the ventilator: high PEEP for all? *JAMA.* (2017) 317:1413–4. doi: 10.1001/jama.2017.2570
29. Grandville B, Petak F, Albu G, Bayat S, Pichon I, Habre W. High inspired oxygen fraction impairs lung volume and ventilation heterogeneity in healthy children: a double-blind randomised controlled trial. *Br J Anaesth.* (2019) 122:682–91. doi: 10.1016/j.bja.2019.01.036
30. Suzuki S. Oxygen administration for postoperative surgical patients: a narrative review. *J Intensive Care.* (2020) 8:79. doi: 10.1186/s40560-020-00498-5
31. Pereira SM, Tucci MR, Morais CCA, Simoes CM, Tanelotto BFF, Pompeo MS, et al. Individual positive end-expiratory pressure settings optimize intraoperative mechanical ventilation and reduce postoperative atelectasis. *Anesthesiology.* (2018) 129:1070–81. doi: 10.1097/ALN.0000000000002435
32. Hartland BL, Newell TJ, Damico N. Alveolar recruitment maneuvers under general anesthesia: a systematic review of the literature. *Respir Care.* (2015) 60:609–20. doi: 10.4187/respcare.03488
33. Wong SK, Chim M, Allen J, Butler A, Tyrrell J, Hurley T, et al. Carbon dioxide levels in neonates: what are safe parameters? *Pediatr Res.* (2022) 91:1049–56. doi: 10.1038/s41390-021-01473-y
34. Suleiman A, Costa E, Santer P, Tartler TM, Wachtendorf LJ, Teja B, et al. Association between intraoperative tidal volume and postoperative respiratory complications is dependent on respiratory elastance: a retrospective, multicentre cohort study. *Br J Anaesth.* (2022) 129:263–72. doi: 10.1016/j.bja.2022.05.005
35. Cammarota G, Simone R, Longhini F, Spadaro S, Vetrugno L, De Robertis E. Advanced point-of-care bedside monitoring for acute respiratory failure. *Anesthesiology.* (2023) 138:317–34. doi: 10.1097/ALN.0000000000004480
36. Coppola S, Caccioppola A, Froio S, Ferrari E, Gotti M, Formenti P, et al. Dynamic hyperinflation and intrinsic positive end-expiratory pressure in ARDS patients. *Crit Care Lond Engl.* (2019) 23:375. doi: 10.1186/s13054-019-2611-6
37. Blanco-Schweizer P, Ángel de Ayala-Fernández J, Blanco J. Estimating airway opening pressure, trapped gas volume, and hidden intrinsic positive end-expiratory pressure in mechanically ventilated patients. *Ann Am Thorac Soc.* (2021) 18:356–60. doi: 10.1513/AnnalsATS.202008-927CC