Review Article

Optimizing perioperative lung protection strategies for reducing postoperative respiratory complications in pediatric patients: a narrative review

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Background and Objective: Despite significant advancements in the safe delivery of anesthesia and improvements in surgical techniques, postoperative respiratory complications (PRCs) remain a serious concern. PRCs can lead to increased length of hospital stay, worsened patient outcomes, and higher hospital and postoperative costs. Perioperative lung injury and PRCs are more common in children than in adults owing to children's unique physiology and anatomical characteristics. Studies have shown that lung-protective ventilation (LPV) strategies can improve lung function and minimize the risk of PRCs in adults. However, individualized LPV in children remains underexplored. This narrative review provides an overview of the various perioperative pulmonary protection strategies and their effect on pediatric PRCs.

Methods: We searched PubMed for articles published from 2000 to 2024, setting our inclusion criteria to include studies that involved pediatric patients, addressed LPV strategies, and reported data on PRCs. Non-English language studies, case reports, editorials, conference abstracts, and non-full text published literatures were excluded. We utilized the following keyword strategy: (((lung protective ventilation) OR (PEEP)) OR (recruitment maneuver)) OR (low tidal volume) AND (2000:2024[pdat])) AND (pediatric) filters. In total, 1,106 articles were retrieved, with only 23 being deemed relevant to the review. Data extraction and analysis were conducted by two independent researchers to ensure accuracy and consistency. We conducted descriptive statistical analysis for quantitative data and thematic analysis for qualitative data.

Key Content and Findings: The key content are an overview of risk factors for PRCs in children including the patients themselves, anesthesia, and surgery, as well as the effectiveness of LPV strategies in pediatric surgery, including low tidal volume (TV), positive end-expiratory pressure (PEEP), ultrasound-guided pulmonary recruitment maneuver (RM), low fraction of inspired oxygen (FiO_2), pressure-controlled ventilation (PCV), as well as fluids, pain, and high-flow nasal cannula (HFNC). We found that age, mechanical ventilation with general anesthesia, and thoracic surgery increased the risk of PRCs in children. The application of LPV strategies in pediatric surgery had positive effect, including low TV combined with titrated PEEP, age- and physiologically appropriate FiO_2, ultrasound-guided RM, target directed fluid infusion, adequate analgesia, and the use of HFNC in special circumstances. However, we also found that the application of LPV has certain potential risks and therefore needs to be implemented according to the patient's actual age and physical condition.

Conclusions: Perioperative LPV strategies show potential benefits in reducing lung injury and PRCs in pediatric patients. These strategies, including low TV, appropriate individualized PEEP, lung RM, and avoidance of high FiO_2, appear to be effective methods for protecting lung function in pediatric patients. Additionally, perioperative fluid management and effective pain control are crucial for lung protection. The emerging use of HFNC therapy shows promise, but further research is needed to fully understand its

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benefits.

Keywords: Lung-protective ventilation (LPV); pediatric patients; anesthesia; postoperative; respiratory complications

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Introduction

Postoperative respiratory complications (PRCs) are common critical events in patients undergoing surgery, with an incidence rate of approximately 11–59%, and are associated with worse outcomes (1-6). PRCs include atelectasis, respiratory failure, respiratory infections, pleural effusion, pneumothorax, bronchospasm, and aspiration pneumonitis (7,8). Some studies have shown that children are prone to PRCs due to their physiological characteristics (9-11). Computed tomography (CT), chest radiography (CR), and magnetic resonance imaging (MRI) can detect and diagnose PRCs. Although anesthesia-induced atelectasis is common in children, the devices required to diagnose atelectasis involve ionizing radiation, are not easily portable, and have high examination costs (9,12). One study, using MRI as a reference, reported that lung ultrasound (LUS) for the diagnosis of atelectasis had an accuracy, specificity, and sensitivity of 88%, 89%, and 88%, respectively (12). Therefore, LUS is a precise, safe, and uncomplicated bedside technique that can be used to detect anesthesia-induced atelectasis in pediatric patients (12-14).

According to the findings from adult cohorts, intraoperative lung-protective ventilation (LPV) has been found to potentially decrease the occurrence of PRCs (12-14). LPV strategy includes ventilating with low tidal volume (TV) of 6–8 $\mathrm{mL \cdot kg^{-1}}$ of predicted body weight (PBW), pulmonary recruitment maneuver (RM), and applying sufficient positive end-expiratory pressure (PEEP). The key tenets of LPV are the avoidance of trauma and atelectrauma (15). However, some studies have shown that LPV has potential risks. An animal study found that the LPV strategy resulted in increased degradation of diaphragmatic muscle proteins, decreased muscle fiber cross-sectional area, and decreased diaphragmatic strength compared with conventional ventilation, which may be related to increased oxidative stress in the diaphragm and downregulation of peroxisome proliferator-activated receptor gamma coactivator-1alpha (PGC-1α) (16). A prospective observational study found that adherence to the LPV strategy in surgical intensive care unit (ICU) patients was only 36.9%. Cox regression analysis showed that the use of the LPV strategy was associated with an increased 90-day mortality rate [hazard ratio =1.73; 95% confidence interval (CI): 1.02–2.94] (17). The process of lung recruitment and higher levels of PEEP may cause hemodynamic changes due to increased intrathoracic pressure (18,19). Higher PEEP may increase the intracranial pressure of patients (20). In surgical patients using LPV strategies, transient hypotension has been reported in a number of studies, with the majority of patients not requiring intervention with vasoactive medications, and a small number of patients who were rapidly corrected with short-acting vasoactive medications, but no patients have been seen to develop persistent hypotension, pneumothorax, cardiac arrhythmias, or other adverse events (21-23). *Table 1* presents studies on the adverse effects of LPV.

Despite the potential risks, LPV strategies have also been adopted in surgical settings to reduce pulmonary complications during surgery in children under anesthesia (24,25). A prospective, single-center, randomized controlled trial investigated the effect of LPV versus a control group during lobectomy in children aged 5 years and younger. The results showed that the incidence of PRCs was significantly lower in the LPV group (9.1%) than in the control group (25.5%) (26). This study directly evaluated the benefit of LPV in children 5 years and younger undergoing surgery, supporting that LPV reduces the risk of PRCs in this age group. Furthermore, a randomized controlled study evaluated the effect of LPV versus conventional ventilation during laparoscopic surgery in infants aged 1–6 months. The results showed that the LPV group had a better incidence of pulmonary atelectasis, LUS scores and oxygenation indices than the control group in the mid-operative and early postoperative periods (27). This study provided supporting evidence for the benefit of LPV in infant surgery. Conversely, a retrospective cohort analysis revealed that in children above

Table 1 Evidence on the adverse effects of LPV

First author, year	Population	Intervention	Control	Adverse effects
Zhu, 2021 (9)	Aged 1 to 6 years (n=60). Nonabdominal surgery	TV 6 mL·kg^{-1}; FiO$_2$ 0.4; PEEP 5 cmH$_2$O; RM	TV 6 mL·kg^{-1}; FiO$_2$ 0.4; no PEEP; no RM	23 patients in the lung-protective group developed transient arterial hypotension during recruitment, requiring vasopressors
Ingaramo, 2014 (18)	Aged 1 month to 20 years (n=50). Who were admitted to the PICU and mechanically ventilated	PEEP was altered to levels of 0, 4, 8, and 12 cmH$_2$O in random order. Cardiac output was measured at different levels of PEEP by continuous wave Doppler ultrasound		PEEP increase from 0 to 12 cmH$_2$O significantly reduces cardiac output
Girrbach, 2020 (19)	Males 18 years of age (n=40). Robot-assisted laparoscopic radical prostatectomy	TV 8 mL·kg^{-1}; FiO$_2$ 0.4 or higher; individualized optimal PEEP; RM	TV 8 mL·kg^{-1}; FiO$_2$ 0.4 or higher; PEEP 5 cmH$_2$O; no RM	13 patients had bradycardia during RM or PEEP titration, needing drug treatment
Khandelwal, 2018 (20)	Aged 1 to 18 years (n=10). Admitted in neurointensive care unit and need measured intracranial pressure	Synchronized intermittent mandatory ventilation; TV 8 mL·kg^{-1}; FiO$_2$ 0.4; the sequence of PEEP (0 or 3 or 5 cmH$_2$O) was randomized		PEEP above 3 cmH$_2$O may raise intracranial pressure
Sun, 2020 (21)	Aged 1 month to 12 months (n=77). CPB surgery for CHD	TV 6–8 mL·kg^{-1}; FiO$_2$ 0.4–0.6; individualized optimal PEEP; RM	TV 10–12 mL·kg^{-1}; FiO$_2$ 0.4–0.6; without PEEP; RM	Transient hypotension occurred in three patients in LPV group, but was corrected quickly after the use of vasoactive agents without causing other adverse events
Pereira, 2018 (22)	Age above 18 years old (n=40). Abdominal surgery	TV 6–8 mL·kg^{-1}; FiO$_2$ 0.5; individualized optimal PEEP; RM	TV 6–7 mL·kg^{-1}; FiO$_2$ 0.5; PEEP 4 cmH$_2$O; no RM	Most patients needed vasoactive agents during recruitment, but none continuously
Li, 2023 (23)	Adult inpatients (n=40). Laparoscopic bariatric surgery	TV 8 mL·kg^{-1}; FiO$_2$ 0.5; individualized optimal PEEP; RM	TV 8 mL·kg^{-1}; FiO$_2$ 0.5; PEEP 8 cmH$_2$O; RM	Persistent hypotension was not observed in either group

LPV, lung-protective ventilation; TV, tidal volume; FiO$_2$, fraction of inspired oxygen; PEEP, positive end-expiratory pressure; RM, recruitment maneuver; PICU, pediatric intensive care unit; CPB, cardiopulmonary bypass; CHD, congenital heart disease.

the age of 3, elevated TVs during surgical procedures were significantly correlated with an increased risk of PRCs, whereas no such correlation was identified in children 3 years or younger (28). These findings suggest that age may be an important factor influencing the effectiveness of LPV and that there may be potential variations in the response to LPV across different pediatric age groups. Further studies are needed to directly compare and evaluate these different age groups.

In pediatric anesthesia, the clinical practice of mechanical ventilation strategies is mainly based on data extrapolated from practice in adults and anecdotal experience (24). However, in contrast to the situation in adults, the impact of intraoperative LPV on clinical outcomes after pediatric surgery remains unclear (26). We present this article in accordance with the Narrative Review reporting checklist (available at https://tp.amegroups.com/article/view/10.21037/tp-24-453/rc).

Methods

For this literature review, we conducted a comprehensive search of the PubMed database for articles published between 2000 and 2024 to identify evaluations of perioperative lung protection strategies in pediatric patients. We defined our inclusion criteria to encompass studies that involved pediatric patients, addressed LPV strategies, and reported data on PRCs. We excluded non-English language studies, case reports, editorials, conference abstracts, and non-full text published literatures. The search strategy

Table 2 The search strategy summary

Items	Specification
Date of search	The initial search was conducted from January 1, 2022 to December 31, 2023, and a follow-up search was carried out on July 26, 2024
Database searched	PubMed
Search terms used	(((lung protective ventilation) OR (PEEP)) OR (recruitment maneuver)) OR (low tidal volume) AND (2000:2024[pdat]) AND (pediatric)
Timeframe	2000–2024
Inclusion criteria and exclusion criteria	Inclusion criteria: English-language articles were included Exclusion criteria: non-English language studies, case reports, editorials, conference abstracts, and non-full text published literatures were excluded
Selection process	Selection of relevant articles was conducted independently by authors. Disagreements between authors were resolved via discussion

PEEP, positive end-expiratory pressure.

consisted of a combination of keywords related to LPV, PEEP, RM, and low TV in the pediatric population. Due to the limited data on perioperative lung protection in children, we included studies involving some adult patients. The search strategy is summarized in *Table 2*. In total, 1,106 articles were retrieved, with only 23 being deemed relevant to the pediatric context. Data extraction was performed by two independent researchers (Q.W. and K.Z.) using a pre-designed form to record study design, sample size, patient characteristics, specific measures of LPV strategies, and outcomes related to PRC. For each study, two researchers extracted data independently and resolved any discrepancies through discussion. For quantitative data, we performed descriptive statistical analysis to summarize the impact of LPV strategies on PRCs. Qualitative data were used to gain a deeper understanding of the challenges in implementing LPV strategies and patient experiences.

PRC-related factors in children

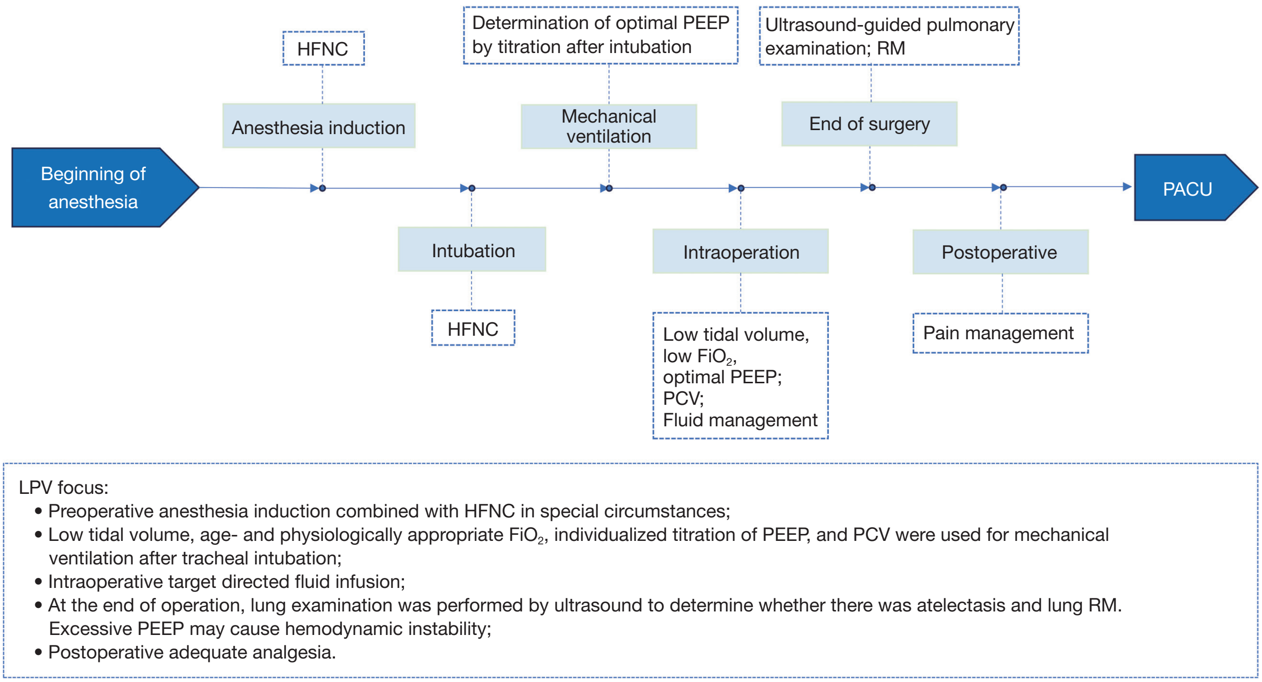
PRCs may generally originate from patient-, anesthesia-, or surgery-related factors (29).

Patient-related factors associated with PRCs

Perioperative lung injury is more likely to occur in children than in adults owing to the unique physiological and anatomical characteristics of younger children (30). Pediatric patients have a markedly high airway closure volume and low absolute functional residual capacity, and the incidence of perioperative lung injury and PRCs is significantly higher in children than that in adults (26). A study has shown that the incidence of atelectasis is negatively correlated with children's age, with a younger age being correlated with a higher the incidence of hypoxemia and atelectasis (31). In addition, in both adults and children, American Society of Anesthesiologists (ASA) physical class ≥ III, obesity, respiratory infection before surgery, and other systemic diseases (such as congenital heart disease, kidney failure, and anemia) also increase the risk of PRCs (32-34).

Anesthesia-related factors in PRCs

Anesthesia causes respiratory impairment and thus determines whether the patient is ventilated mechanically or maintains spontaneous breathing (24). Mechanical ventilation, an essential component of general anesthesia, can induce lung injury via the repetitive and rapid opening and closing of the alveoli during mechanical ventilation. This may potentially induce damage to the alveolar-capillary barrier and disrupt the extracellular matrix—particularly in lungs with unevenly distributed regions of ventilation—contribute to the development of pneumonia and atelectasis, induced respiratory failure, and negatively impact lung function (3,29,35-37). There are various forms of ventilator-induced lung injury (VILI), including volutrauma (injury caused by overdistension of the lung), atelectrauma (injury due to repeated opening and closing of lung units), and biotrauma (release of mediators that can induce lung injury or aggravate preexisting injury,



LPV focus:

- Preoperative anesthesia induction combined with HFNC in special circumstances;
- Low tidal volume, age- and physiologically appropriate FiO_2, individualized titration of PEEP, and PCV were used for mechanical ventilation after tracheal intubation;
- Intraoperative target directed fluid infusion;
- At the end of operation, lung examination was performed by ultrasound to determine whether there was atelectasis and lung RM. Excessive PEEP may cause hemodynamic instability;
- Postoperative adequate analgesia.

Figure 1 Flowchart of the LPV strategy implementation process. HFNC, high-flow nasal cannula; PEEP, positive end-expiratory pressure; FiO_2, fraction of inspired oxygen; PCV, pressure-controlled ventilation; RM, recruitment maneuver; PACU, postanesthesia care unit; LPV, lung-protective ventilation.

potentially leading to multiple organ failure) (38).

Surgery-related factors associated with PRCs

The occurrence of perioperative lung injury and PRCs is related to the surgery duration and type. Prolonged surgery over 3 hours is associated with an increased risk of PRCs (32). Adult patients undergoing pneumonectomy have a significantly higher risk of pulmonary complications due to preexisting lung disease, massive surgical invasion, loss of lung parenchyma, and injury factors related to unilateral lung ventilation (39). Research on PRCs in pediatric thoracic surgery is limited, but the surgical processes are similar for both children and adults, such as opening the chest cavity, one-lung ventilation, and resection of the lung tissue. These factors can lead to loss of negative chest pressure, ventilation/blood flow ratio imbalance, pulmonary atelectasis due to unilateral lung ventilation, pulmonary edema and injury due to surgical manipulation, as well as inflammation and pain-related physiological responses due to pleural incisions and intercostal dissections, delayed recovery of lung function postoperative due to pain or other causes, and preexisting lung diseases or respiratory dysfunction in thoracic surgery patients , all of which increase the severity of pulmonary complications (40-42). A study of pediatric patients mentioned that children undergoing chest surgery may have a higher risk of developing PRCs due to the above factors (26).

Overview of LPV in pediatric patients

As previously mentioned, mechanical ventilation is life-saving; however, numerous experimental and clinical studies have shown that it can induce lung injury, leading to potentially irreversible structural and functional damage, a phenomenon known as VILI (43,44). Mechanical ventilation in children results in complications, such as atelectasis, pneumonia, and pleural effusion, which can be diagnosed using CR, CT, MRI, and LUS. LPV strategies, which are largely associated with adult age groups, aim to reduce the morbidity and mortality associated with PRCs (45). The term protective ventilation is defined as a combination of PEEP, low TV, RM, and avoidance of a high fraction of inspired oxygen (FiO_2) (46). For a flowchart detailing the steps on how to implement LPV strategies, as well as the focus points of the strategy, please refer to *Figure 1* for more detailed information.

Table 3 Evidence on the effects of perioperative LPV on pediatric clinical outcomes

First author, year	Population	Intervention	Control	Results
Lee, 2019 (26)	Aged ≤5 years (n=114). Video-assisted thoracoscopic lung lobectomy or segmentectomy	TV 6 mL·kg^{-1}, FiO$_2$ 0.5 for two-lung ventilation; TV 4 mL·kg^{-1}, FiO$_2$ 1.0 for OLV; PEEP 6 cmH$_2$O; RM	TV 10 mL·kg^{-1}, FiO$_2$ 0.5 during two-lung ventilation; TV 8 mL·kg^{-1}, FiO$_2$ 1.0 during OLV; without PEEP; RM	Lower incidence of pulmonary complications in the low-TV group
Park, 2021 (30)	Aged 6 to 12 months (n=90). Urological or general surgery	TV 6 mL·kg^{-1}; PEEP 6 or 9 cmH$_2$O; RM; FiO$_2$ 0.4	TV 6 mL·kg^{-1}; PEEP 3 cmH$_2$O; RM; FiO$_2$ 0.4	Higher PEEP associated with lower lung ultrasound score
Song, 2017 (31)	Aged ≤1 years (n=40). Elective minor surgery	TV 8 mL·kg^{-1}; PEEP 5 cmH$_2$O; FiO$_2$ 0.4; RM	TV 8 mL·kg^{-1}; PEEP 5 cmH$_2$O; FiO$_2$ 0.3; without RM	Lower incidence of atelectasis in the RM group
Song, 2018 (48)	Aged ≤5 years (n=120). Cardiac surgery	TV 8 mL·kg^{-1}; PEEP 5 cmH$_2$O; FiO$_2$ 0.4; RM	TV 8 mL·kg^{-1}; PEEP 5 cmH$_2$O; FiO$_2$ 0.4; without RM	Lower incidence of postoperative desaturation in the RM group
Jang, 2020 (49)	Age <3 years (n=73). Noncardiac surgery in the prone position	TV 6 mL·kg^{-1}; PEEP 7 cmH$_2$O; FiO$_2$ 0.4; RM	TV 6 mL·kg^{-1}; PEEP 7 cmH$_2$O; FiO$_2$ 0.4; no RM	Lower incidence of atelectasis before extubation in the RM group
Acosta, 2018 (50)	Aged 6 months to 7 years (n=42). Abdominal laparoscopic surgery	TV 6 mL·kg^{-1}; FiO$_2$ 0.5; PEEP 5 cmH$_2$O; RM	TV 6 mL·kg^{-1}; FiO$_2$ 0.5; PEEP 5 cmH$_2$O; without RM	Lower incidence of atelectasis in the RM group
Tusman, 2003 (51)	Aged ≤5 years (n=24). Cranial magnetic resonance imaging	TV was not monitored; FiO$_2$ 1.0; PEEP 5 cmH$_2$O; RM	TV was not monitored; FiO$_2$ 1.0; PEEP 5 cmH$_2$O; without RM	Significantly lower frequency of atelectasis in the RM group

LPV, lung-protective ventilation; TV, tidal volume; FiO$_2$, fraction of inspired oxygen; OLV, one-lung ventilation; PEEP, positive end-expiratory pressure; RM, recruitment maneuver.

Although considerable uncertainty remains regarding the implementation of LPV strategies, studies have demonstrated the benefits of such strategies in pediatric patients (26,30,46-48). The perioperative application of LPV strategies can prevent the lung injury caused by the excessive expansion and collapse of the alveoli in children and reduce perioperative lung injury and PRCs (45). The use of LPV during surgery can reduce the incidence of immediate postoperative atelectasis; however, its long-term positive effects have not yet been clarified (15).

Several studies have reported that LPV can reduce lung injury and improve lung outcomes in pediatric patients (26,30,31,49-51), while others suggest that LPV does not reduce PRCs in these patients (52,53). In a study by Song *et al.* (48), although RM reduced the occurrence of postoperative desaturation, it did not contribute to the reduction of PRCs. The use of high FiO$_2$ has been speculated to cause direct pulmonary toxicity and complications, such as absorption atelectasis (53). To test this, Song *et al.* divided the children into a high-FiO$_2$ group (FiO$_2$ 0.6) and a low-FiO$_2$ group (FiO$_2$ 0.3) but did not observe a difference in the incidence of atelectasis between the two groups (53). However, a different study reported that FiO$_2$ 0.6 during anesthetic induction was associated with less atelectasis formation immediately after anesthetic induction in children (54). *Table 3* presents the studies that support the use of LPV strategies in pediatric patients undergoing surgery.

Low TV combined with PEEP

In studies of animals, high TV has been found to cause alveolar damage with pulmonary edema and to induce the release of inflammatory mediators into systemic circulation (55-57). LPV relies on limiting the TV, and successful implementation of these strategies requires accurate TV delivery. Mechanical ventilation practices have changed over the past few decades, and the use of low TV ventilation has become more prevalent both in adults and children (48-51,53,58). Several studies in adults have demonstrated the effect of low TV. In a study on adults with acute respiratory distress syndrome, patients with a lower TV of 6 $mL{\cdot}kg^{-1}$ had better 28-day mortality and required fewer days mechanical ventilation than did those with a conventional TV of 12 $mL{\cdot}kg^{-1}$ (59). A meta-analysis of adults showed that patients who received LPV compared with control patients have a reduced likelihood of experiencing lung injury and pulmonary infection (60). Therefore, anesthesiologists have accepted the concept of mechanical ventilation with a small TV. However, evidence has been published that does not support lung-protection strategies. Karalapillai *et al.* (52) randomly divided pediatric patients into a low TV-group, who received a TV of 6 $mL{\cdot}kg^{-1}$, and a conventional-TV group, who received a TV of 10 $mL{\cdot}kg^{-1}$. All patients underwent PEEP with 5 cmH_2O. The results showed that the incidence of pulmonary complications in the low-TV group was not significantly reduced within the first 5 postoperative days (52). Despite these limitations, the biological plausibility for a benefit with low TV ventilation has strongly suggested. Given the sparsity of pediatric randomized clinical trials (RCTs), no absolute recommendation can be made regarding the optimal TV in the mechanical ventilation of pediatric patients undergoing surgery (24). Currently, the accepted standard for TV is 6–8 $mL{\cdot}kg^{-1}$, as this may limit lung overdistension.

In addition to limiting TV, PEEP is an important component of the LPV method. The use of low TV increases the risk of atelectasis formation and hypoxemia. Hence, low TV is usually associated with the application of PEEP and RM. The perioperative use of PEEP can maintain alveolar distention and improve lung compliance. Multiple small RCTs in adults have found that patients undergoing laparoscopic surgery who receive 5 cmH_2O PEEP experience significantly better oxygenation, less postoperative atelectasis, and better pulmonary compliance than do those receiving zero PEEP (61-63). A study on adults indicated that during nonabdominal surgery, PEEP alone was sufficient for minimizing the atelectasis of patients with healthy lungs and could thus maintain oxygenation (46).

PEEP application in children has shown similar benefits. In one pediatric study, 30 patients younger than 15 years with no a history of lung injury were randomly divided into 0- and 5-cmH_2O PEEP groups. An analysis of respiratory mechanics revealed that PEEP at 5 cmH_2O was preferable in anesthetized healthy children. This indicates that the use of PEEP can improve lung mechanics and limit the lung injury associated with mechanical ventilation (64). Lung lobectomy or segmentectomy is a special type of surgery because it requires one-lung ventilation during the procedure. In a recent study, children aged ≤5 years scheduled for pneumonectomy either received LPV (low TV with PEEP) or control ventilation (conventional ventilation) (26). It was found that compared with conventional ventilation, LPV more drastically decreased PRCs in children requiring one-lung ventilation. Therefore, LPV can also benefits pediatric patients in this particular type of surgery.

Excessive PEEP during the perioperative period can increase pulmonary vascular resistance and right ventricular afterload, thus reducing stroke output and causing hemodynamic fluctuations. A study of pediatric patients (mean age 16.5 months) in the ICU showed a significant decrease in cardiac output as PEEP increased from 0 to 12 cmH_2O (18). Another study reported patients who developed bradycardia during pulmonary resuscitation or titration of PEEP, requiring pharmacological intervention (19). A review found a significantly increased risk of sinus bradycardia in the LPV strategy group compared with conventional mechanical ventilation (risk ratio =2.51; 95% CI: 1.31–4.81; P=0.005) (65). In addition, higher levels of PEEP may increase intracranial pressure in patients. A recent study has shown that intracranial pressure measured through the optic nerve sheath in children with traumatic brain injury increases proportionally with increasing PEEP. Therefore, if both 6 and 9 cmH_2O pressures are effective, it is preferable to choose the lower pressure for safety reasons (20). Moreover, if the PEEP level is too low, there is no protective effect on the lungs. Regarding the level of PEEP, it is currently believed that in generally anesthetized pediatric patients with healthy lungs, PEEP at 5 cmH_2O effectively prevents the return of atelectasis after an alveolar RM (66). However, the level of PEEP and the criteria under which the maximum benefit can be obtained have not yet been specified in adults or children.

In one study examining the individualized PEEP values in adults, the optimal median PEEP level was found to be 12 cmH_2O (range, 6–16 cmH_2O) (22). In another study, compared to PEEP with 3 cmH_2O, PEEP with 6 or 9 cmH_2O could more effectively reduce the severity of atelectasis in healthy children. However, the effect was similar between the 6 and 9 cmH_2O groups; therefore, using the lower PEEP was recommended to reduce the risk of hemodynamic changes (30). Additionally, the optimal PEEP within an appropriate range should be individualized based on the condition of the child.

The optimal PEEP for different patients can be titrated through several methods, including assessment of respiratory compliance, evaluation of driving pressure, electrical impedance tomography, analysis of the pressure-volume curve, and use of LUS (19,39,48,67-72). However, some of these are not suitable for clinical use due to their technical complexity. The following are the specific practices of driving pressure-titrated PEEP and respiratory compliance-titrated PEEP in adults, which are similar for children, but the optimal PEEP obtained may be quite different from that of adults.

Airway driving pressure, which is a surrogate for alveolar stress, can be easily measured as the plateau pressure minus the PEEP (38). Minimizing the driving pressure can benefit patients. The decremental titration of PEEP commences at 10 cmH_2O and gradually decreases to 0 cmH_2O in increments of 1 cmH_2O. PEEP titration is conducted using the volume-controlled mode, a ventilatory frequency of 12 min^{-1}, and an inspiratory-to-expiratory (I:E) ratio of 1:2 for five respiratory cycles at each PEEP level. During surgery, the lowest driving pressure can be applied based on the results obtained from this process. Research suggests that ventilation guided by driving pressure significantly enhances intraoperative pulmonary mechanics (39).

Based on respiratory compliance to titration, the optimal PEEP is easy to obtain since respiratory compliance can be assessed using only a ventilator without additional equipment (23). Li *et al.* (23) described a method for titrating PEEP with respiratory compliance in obese adults. All patients underwent a titration trial immediately after intubation. The titration trial commenced with an RM under the following ventilator settings: pressure-controlled ventilation (PCV) mode, 25 cmH_2O inspiratory pressure, 10 cmH_2O PEEP, a respiratory rate of 6 breaths per minute, and an I:E ratio of 1:2. Inspiratory pressure and PEEP were then increased every 30 seconds in increments of 5 cmH_2O until 25 cmH_2O PEEP and 40 cmH_2O inspiratory pressure were reached. The driving pressure was maintained at 15 cmH_2O throughout the experiment. Subsequently, dynamic compliance-guided PEEP involved a gradual reduction of PEEP by 2 cmH_2O at intervals of 30 seconds until a final level of 5 cmH_2O in volume-controlled ventilation mode. Other ventilatory parameters were the same as those used at the beginning. Dynamic compliance was calculated as follows: TV/(peak pressure − PEEP) (23).

The evidence collected thus far suggests a PEEP range of 5–8 cmH_2O in healthy children, but the optimal perioperative PEEP level for children remains controversial (73), and there is no defined method for setting the most suitable PEEP. Larger clinical studies are required to establish the optimal PEEP in pediatric patients.

Lung RM

The application of low TV ventilation limits the injuries caused by alveolar overdistention but does not address those injuries resulting from repetitive alveolar opening and closing (74). In several clinical studies, lung RM, a strategy used to open atelectatic lungs with sufficient inspiratory pressure, effectively prevented postoperative complications. In studies involving adults, RM has demonstrated the ability to improve oxygenation and reduce the occurrence of PRCs in patients (75,76). However, the long-term benefits of lung resuscitation are not clear. In one study, the benefit of lung resuscitation 15 minutes after extubation was not significant compared with the non-resuscitated group, and the process of lung resuscitation may cause hemodynamic instability (9).

For pediatric patients (51), one study reported that children aged 6 months to 6 years who underwent cranial MRI were divided into three groups: the alveolar recruitment strategy (ARS), continuous positive airway pressure (CPAP), and zero end-expiratory pressure (ZEEP) groups. In the ARS group, the RM was conducted by manually providing ventilation to the lungs using a peak airway pressure of 40 cmH_2O and maintaining a PEEP of 15 cmH_2O for a duration of 10 breaths. The PEEP was subsequently decreased to 5 cmH_2O and consistently maintained at this level. The CPAP group received CPAP of 5 cmH_2O without any recruitment. The ZEEP group did not receive any PEEP or RM. The findings revealed a significant reduction in the incidence of atelectasis among the pediatric patients who underwent a recruitment intervention compared to those who did not undergo any recruitment intervention. However, no significant difference in the therapeutic effect was observed between the control group without PEEP and the group treated with a CPAP of 5 cmH_2O without a prior RM. This suggests that ARS is required before the application of PEEP.

LUS is an emerging tool in perioperative care and can be used for the individualized guidance of perioperative LPV strategies, the optimization of mechanical ventilation therapy under anesthesia, and the monitoring of therapeutic effects (48,49). It is playing an increasingly prominent

Table 4 Lung recruitment maneuver strategies in pediatric patients

First author, year	Lung recruitment maneuver strategies	Specific steps
Song, 2017 (31)	Manual maneuver	A stepwise increase in airway pressure is manually applied. The target pressure of 40 cmH_2O is maintained
Jang, 2020 (49)	CPAP maneuver	The application of CPAP at a pressure of 30–40 cmH_2O should be maintained for approximately 5–10 seconds until no areas of lung collapse are visually detectable
Acosta, 2018 (50)	PCV maneuver	The RM is performed in a pressure-controlled mode, with a constant driving pressure of 15 cmH_2O being maintained. PEEP is gradually increased in increments of 5 cmH_2O, ranging from 5 to 15 cmH_2O. The target pressure is maintained for 10 breaths

CPAP, continuous positive airway pressure; PCV, pressure-controlled ventilation mode; RM, recruitment maneuver; PEEP, positive end-expiratory pressure.

role in anesthesia departments and is suitable for use in children during general anesthesia (50). Song *et al.* (48) screened children scheduled for elective cardiac surgery to evaluate the utility of intraoperative LUS and to investigate the impact of ultrasound-guided RM in pediatric cardiac surgery. Children in the control group underwent LUS examinations twice. Patients in the intervention group underwent LUS examination and RM based on the ultrasound results. The results showed that the incidence of postoperative desaturation was lower in the intervention group than in the control group. This indicates that the RM can effectively reverse atelectasis and improve gas exchange, particularly under LUS guidance.

The common lung recruitment strategies in clinical settings currently include manual and ventilator-driven lung recruitment strategies. There are three ventilator-driven lung RM strategies. First, the CPAP maneuver involves the application of CPAP from 30 to 40 cmH_2O for approximately 5 to 10 seconds until no evidence of lung collapse is discernible on LUS. Mansfield *et al.* (77) and Jang *et al.* (49) used this approach for children in their research. Second, the PCV maneuver involves RM performed with a constant driving pressure in a pressure-controlled mode. PEEP is incrementally raised on every third breath, while the desired recruitment pressure is sustained for 10 consecutive breaths. Acosta *et al.* (50) and Pereira *et al.* (22) used this method in children and adults, respectively. Third, the cycling maneuver involves a constant driving pressure which is applied to achieve a TV of ≤8 $mL \cdot kg^{-1}$ (≈10–15 cmH_2O in normal lungs). PEEP is increased from 5 to 20 cmH_2O in increments of 5 cmH_2O. Each PEEP is maintained for at least five breaths. This pressure is approximately 40 cmH_2O of the plateau pressure and is maintained for 10 breaths. Subsequently, the PEEP is decreased progressively in decrements to the baseline. This method is commonly used in adult patients (39,78). There are few studies in the field of pediatrics, and the impact of this method on pediatric patients should be further investigated in the future. The different lung RM strategies for children are listed in *Table 4*.

High intrathoracic pressure can interfere with hemodynamic function (51). In mitigating the risk of high thoracic pressure, the cycling maneuver has certain advantages over the CPAP maneuver (79). First, the initial gradual increase in PEEP allows patients to gradually adjust to higher pressures within their chest and aids the anesthesiologist in identifying and treating any undetected hypovolemic condition. Second, the cycling maneuver potentially results in lower stress on the pulmonary tissue compared with that observed with CPAP maneuvers due to the progressive distribution of pressure increments and gas volume throughout the increasingly recruited tissue as the maneuver proceeds. Third, through monitoring of the appropriate ventilatory variables during cycling maneuvers, real-time breath-by-breath information regarding lung function can be obtained. Therefore, it is more advisable to use cycling maneuvers to reopen alveolar collapse. Whether these advantages apply to children warrants further exploration.

FiO_2

Perioperative oxygenation is crucial because tissue hypoxia can cause organ dysfunction (80). Despite the benefits of perioperative use of pure oxygen, evidence suggests that high oxygen concentrations can promote the development of atelectasis (79,81). Resorption atelectasis is caused by the ongoing absorption of oxygen into the pulmonary capillaries beyond the closed airways and can be worsened by pure oxygen (3). An RCT found an association between postinduction atelectasis and an increase in FiO_2, with the magnitude of this correlation varying according to the dosage. Depending on the age and physiological status of the patient, controlling or reducing FiO_2 to maintain a clinically appropriate level of oxygenation and saturation should be considered to be a component of LPV (24).

A study in adults showed that breathing 100% oxygen during preoxygenation and induction of anesthesia was more likely to cause atelectasis than was breathing 80% or 60% oxygen (82). In other study, ventilation of the lungs with pure oxygen after a vital capacity maneuver had reopened previously collapsed lung tissue resulted in the rapid reappearance of atelectasis. Conversely, when 40% oxygen in nitrogen was used to ventilate the lungs, atelectasis slowly reappeared (81).

High FiO_2 levels can cause direct pulmonary toxicity and other complications. In one pediatric study, a higher FiO_2 resulted in a lower functional residual capacity and higher ventilation heterogeneity than did an FiO_2 of 0.3 (80). In another study (53), the incidence of atelectasis was not significantly different between the low-FiO_2 (FiO_2 =0.3) and high-FiO_2 (FiO_2 =0.6) groups, which contradicts findings indicating that high FiO_2 promotes absorption atelectasis. However, the application of moderate PEEP and RM could potentially be effective in preventing atelectasis following induction with a high FiO_2 (51,83). Nevertheless, high perioperative FiO_2 can result in worse consolidation and B-line scores on lung ultrasonography.

Therefore, for current LPV strategies, an FiO_2 of 1.0 should be avoided to delay or to prevent the occurrence of atelectasis.

Pressure support ventilation

The deterioration of atelectasis during the emergence period has been extensively investigated. Pressure support ventilation is extensively used in the ICU to facilitate the weaning process of patients from ventilators and has recently become available in anesthesia machines. A randomized trial compared the effect of pressure support ventilation on emergence from anesthesia with that of intermittent artificially assisted spontaneous ventilation. The occurrence of postoperative atelectasis detected through LUS in the postanesthesia care unit (PACU) among patients who received pressure support ventilation during emergence from general anesthesia was less than that in patients who received intermittent manual assistance. There are two mechanisms that possibly underlie this finding. First, when inspiratory pressure support is provided, the driving pressure helps expand the lungs during inspiration, resulting in a potential reduction of 30–40% in respiratory effort (84,85). Second, the application of PEEP results in an increase in lung volume at the end of expiration, prevents airway closure, and plays a significant role in the lower lung region. These effects are adequate for preventing or counteracting atelectasis in surgical patients with healthy lungs (86). A study involving adults indicates that pressure support ventilation is a supplementary protective strategy in preventing postoperative atelectasis (87). However, whether pressure-supported ventilation can also prevent atelectasis during emergence in children needs to be determined in further research.

Other perioperative lung protection measures

Perioperative fluid management

Perioperative fluid management plays an important role in lung protection. Attention should be paid to fluid management in children in the perioperative period, and target-directed fluid therapy should be adopted to avoid the occurrence of pulmonary oedema. The purpose of perioperative fluid management is to maintain or re-establish a normal physiological state in children (88). Compared with adults, children have smaller blood volumes and are more sensitive to changes in perioperative fluid management. Therefore, the requirements for perioperative fluid management in children have become increasingly sophisticated. Previous studies have indicated that the implementation of targeted fluid therapy may improve arterial oxygenation, microcirculation perfusion, and tissue oxygen delivery (89,90). The new concept of target-directed fluid therapy in perioperative fluid management is based on the dynamic changes observed in intraoperative hemodynamic parameters. In contrast to conventional liquid therapy, this approach facilitates individualized fluid replacement based on the patient's hemodynamic status, thereby mitigating the risks of excessive fluid administration through large infusions and inadequate volume due to restricted infusion (89). However, fluid management strategies need to be implemented with consideration to surgical risk and patient health evaluations and should be adjusted individually according to the clinical conditions. A study on endoscopic total radical resection in older adults patients with esophageal cancer and undergoing single-lung ventilation showed that target-directed fluid therapy could inhibit inflammatory cytokine levels and provide better lung protection (89). Additional studies on the application of targeted fluid therapy in children are needed.

Postoperative pain management

Postoperative pain can be debilitating and may result in negative consequences, such as respiratory complications including pneumonia and atelectasis, thereby prolonging hospitalization, diminishing quality of life, and promoting chronic persistent postoperative pain syndrome (40). Appropriate analgesia can help patients recover from pain. Several analgesic options are available for patients undergoing surgery. However, the use of analgesics has also been associated with respiratory failure. Nevertheless, a combination of different pain management techniques is still considered the most efficient strategy for addressing the needs of these individuals. For example, neuraxial analgesia combined with general anesthesia reduces the risk of PRCs (45).

High-flow nasal cannula (HFNC)

HFNC therapy is being widely used to treat hypoxic respiratory failure. HFNC therapy consists of pure oxygen and humidified high-flow oxygen (3). HFNC has been demonstrated to produce a positive pressure equivalent to that of nasal CPAP (91). Additionally, HFNC delivers a low level of PEEP (92) and increases end-expiratory lung volume (93). The application of high-flow nasal oxygen therapy in the operating room has attracted the attention of anesthesiologists in recent years. Studies have shown that the use of this therapy benefits obese patients, children, those with difficult airways, etc. (94,95). In one RCT, HFNC therapy in the PACU reduced the occurrence of atelectasis and significantly improved LUS scores compared with conventional nasal cannula oxygen therapy for children aged <2 years undergoing general anesthesia for more than 2 hours (96). However, in another large-scale study, HFNC compared with CPAP did not demonstrate noninferiority in shortening extubation time (97). Therefore, the timing and effectiveness of HFNC application require further clarification (96).

Limitations and findings

There are some limitations to this study. Firstly, adult literature was included because of the scarcity of pediatric research data, which may have affected the consistency of the overall results. Secondly, the literature search did not stratify results by age, leading to an incomplete exploration of the true toxicity at different age stages. Thirdly, our study lacks long-term outcomes, which is an issue that has not yet been addressed. Given the identified limitations, there is a clear imperative for future research to address these gaps and enhance the evidence base for LPV in pediatric patients.

Our findings reveal two key points: (I) the application of LPV in pediatric surgical patients has positive outcomes, but its implementation requires individualized protocols based on age and physiology; (II) the potential harms and adverse effects of LPV are due to stereotypical implementation in accordance with adult data, which does not negate the positive effects of LPV when appropriately tailored to the pediatric population.

Conclusions

To reduce perioperative lung injury and PRCs in pediatric patients, LPV strategies have been widely adopted in clinical practice. These strategies include using low TV (6–8 $\mathrm{mL\cdot kg^{-1}}$) and individualized PEEP settings to prevent excessive alveolar collapse and barotrauma. Additionally, lung RM can be employed to reopen atelectatic regions and maintain normal lung function. Moreover, avoiding high FiO_2 is considered an important measure to minimize lung injury. Using PCV mode during extubation also can reduce postoperative atelectasis. In addition to ventilation settings, other methods of lung protection include perioperative fluid and pain management. HFNC are still-developing approaches for preventing postoperative atelectasis during the emergence period. Using LUS can help with observing the lung status quo of children quickly and directly and with determining whether lung RM and other LPV strategies are required. From a physiological perspective, the LPV strategy is reasonable.

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Footnote

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