

Comparison of Stepwise Lung Recruitment with Conventional Technique on Lung Function During One-Lung Ventilation in Infants Undergoing Segmental Lung Resection

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Objective: Thoracoscopic segmental lung resection utilizes one-lung ventilation (OLV) to isolate and safeguard the lung while enhancing surgical field visibility. This study aimed to assess the protective influence of stepwise lung recruitment maneuvers on lung function in infants undergoing OLV during thoracoscopic segmental lung resection.

Methods: A total of 78 pediatric patients who were slated for elective general anesthesia and segmental lung resection via thoracoscopy were randomly allocated to either the stepwise lung recruitment group (SR group) or the controlled lung expansion group (CR group). The study meticulously documented several key variables, including duration of one-lung ventilation, duration of surgical procedure, amount of blood loss, and volume of intraoperative fluid replacement.

Results: The following did not exhibit any statistically significant differences between the two groups: anesthesia time, surgery time, one-lung ventilation time, and fluid replacement volume ($P > 0.05$). At T1, the experimental group showed lower peak airway pressure and higher levels of Pmean, Cdyn, OI, and V_T compared to the control group [(19.79±1.52) vs (16.48±1.47), (4.32±0.63) vs (3.11±0.49), (177.09±17.34) vs (130.64±15.78), (309.83±20.25) vs (286.21±18.63)]; all differences were statistically significant ($P < 0.05$). In contrast to the CR group, the SR group exhibited a reduced occurrence of pneumonia, atelectasis, and pneumothorax ($P < 0.05$).

Conclusion: Stepwise lung recruitment confers protective benefits on lung function in pediatric patients and concurrently diminishes the incidence of pulmonary complications.

Keywords: infants, lung function, one-lung ventilation, stepwise lung recruitment, thoracoscopic lung segmentectomy

Introduction

Thoracoscopic segmental lung resection has become a frequently employed procedure in pediatric thoracic surgery due to its minimally invasive nature and enhanced recovery outcomes. This technique utilizes one-lung ventilation (OLV) to isolate and safeguard the operative lung, concurrently optimizing surgical field visibility and facilitating precise anatomical dissection.¹ However, OLV presents significant physiological challenges, particularly in children. It can inadvertently induce absorption atelectasis in the non-ventilated lung and may exacerbate or precipitate the formation of atelectatic regions within the dependent, ventilated lung due to gravitational effects and altered mechanics. These alterations result in intrapulmonary shunts, impaired gas exchange, and ventilation-perfusion (V/Q) mismatch, which are primary contributors to intraoperative hypoxemia.

The consequences extend beyond gas exchange abnormalities. The collapse-reexpansion cycle and the inflammatory response to regional hypoxia can trigger the activation and release of various inflammatory cytokines, including interleukins (eg, IL-6, IL-8) and tumor necrosis factor-alpha (TNF- α). These cytokines play a pivotal role in mediating the pathophysiological cascade associated with lung ischemia-reperfusion injury, potentially leading to perioperative

pulmonary complications such as pneumonia, persistent atelectasis, and hypoxemia, which can prolong hospital stay and increase morbidity.²

Research conducted in adults indicates that implementing stepwise lung recruitment as a lung-protective ventilation strategy during thoracoscopic segmental lung resection under OLV may lead to a reduction in the severity of acute lung injury and a decrease in postoperative pulmonary complications.³ The conventional recruitment method, often employed in pediatric cases, serves as a useful comparator but has limitations in achieving sustained recruitment in lower lung zones. Indeed, the efficacy of stepwise lung recruitment has been well-documented in adults. However, its impact on pediatric populations remains an area open for further investigation and exploration. In comparison to adults, pediatric populations exhibit reduced lung functional residual capacities and elevated closing volumes. Consequently, this physiological difference heightens the susceptibility to atelectasis subsequent to anesthesia induction.

This single-center study aimed to assess the effects of a stepwise lung recruitment strategy on intraoperative oxygenation and postoperative lung outcomes in pediatric patients undergoing thoracoscopic segmentectomy with OLV.

Materials and Methods

Study Participants

A total of 78 pediatric patients undergoing elective general anesthesia for thoracoscopic lung segmentectomy were meticulously chosen from the period spanning April 2021 to September 2022. The cohort consisted of 42 males and 36 females ranging in age from 1 to 5 years with a weight median between 7.5 to 23.5 kg. The participants were allocated through a computer-based randomization method, resulting in two distinct groups: the stepwise lung recruitment group (SR) and the controlled lung inflation recruitment group (CR). Before the procedures, informed consent forms were duly signed by the families of the pediatric participants. This study was conducted in accordance with the declaration of Helsinki and approved by the Ethics Committee of Children's Hospital of Henan.

The sample size was estimated based on a pilot dataset targeting a detectable 15% difference in oxygenation index with 80% power at $\alpha = 0.05$, resulting in a required minimum of 35 patients per group.

Inclusion and Exclusion Criteria

Inclusion Criteria

(1) American Society of Anesthesiologists (ASA) classification of I to II; (2) Preoperative hemoglobin level ≥ 10 gm/dl, no severe cardiac arrhythmias; (3) Selected procedure of unilateral segmental lung resection under thoracoscopy; (4) No significant impairments in liver, kidney, or coagulation/bleeding functions; (5) Informed consent form signed by relatives.

Exclusion Criteria

(1) Children with severe heart or lung diseases; (2) Presence of a bronchial fistula; (3) History of pulmonary resection; (4) Presence of pulmonary bullae, pneumothorax, or other conditions contraindicating lung re-expansion; (5) Recent systemic infection.

Elimination Criteria

(1) Violation of study protocol requirements; (2) Withdrawal from the study at the request of the child; (3) Occurrence of severe complications and/or adverse events.

Anesthesia and Surgical Methods

Both cohorts of pediatric participants were instructed to observe a 6-hour fasting period and refrain from consuming clear liquids for two hours prior to the surgical procedure. To identify the specific lung segment harboring the lesion, preoperative enhanced chest computed tomography (CT) scans were conducted, incorporating 3D reconstruction techniques. The surgical procedures were consistently performed by a single physician throughout the study. Following anesthesia induction and airway management by the anesthesiologist, the surgical team proceeded with positioning and thoracoscopic access. To maintain stable anesthetic depth and minimize variability in neuroinflammatory

response, anesthesia was guided by bispectral index monitoring, maintaining the index values between 40 and 60 throughout surgery.

Simultaneously, the child was carefully positioned on the healthy side at a precise 90-degree angle. The surgical procedure employed a three-port technique, wherein the viewing port was precisely positioned along the mid-axillary line between the 7th or 8th ribs. Simultaneously, the working ports were strategically placed at the anterior axillary line between the 4th or 5th ribs, and the infra-scapular line between the 8th or 9th ribs. Utilizing preoperative 3D-CT brachial angiography images, the surgical team dissected and severed the vessels and bronchi of the target lung segment, progressing from superficial to deep layers.

During the surgical procedure, electrocoagulation or an ultrasonic scalpel was employed to meticulously sever the smaller branches of pulmonary arteries and veins. In contrast, the larger branches were securely clamped using medium Hem lock clips before being incised. Furthermore, the segmental bronchus was clamped with large Hem lock clips prior to its precision cut using an ultrasonic scalpel. The intersegmental planes underwent evaluation, relying on the demarcation between expanded and collapsed lung tissue or, alternatively, following arterial ischemia. Following that, these planes were meticulously separated through the precise application of electrocoagulation.

All patients observed standard preoperative fasting protocols (solid foods for 6 hours, clear liquids for 2 hours). General anesthesia was administered and managed exclusively by attending pediatric anesthesiologists, not the surgical team. Induction was performed using intravenous propofol (2–3 mg/kg), fentanyl (2 µg/kg), and rocuronium (0.6–1.0 mg/kg) to facilitate endotracheal intubation. A cuffed endotracheal tube was used in all patients, and the size was selected based on the standard formula: endotracheal tube size (mm internal diameter) = (age/4) + 3.5. Intubation was performed under direct laryngoscopy, and placement was confirmed by end-tidal CO₂ and bilateral chest auscultation. A pediatric fiberoptic bronchoscope (2.8 mm outer diameter) was used to guide the accurate placement of the bronchial blocker. A 5 Fr bronchial blocker (Arndt or equivalent) was used for lung isolation. The anesthesia was maintained using sevoflurane (MAC 1.0–1.2) in an oxygen-air mixture (FiO₂ 0.5), with additional fentanyl boluses as needed. Muscle relaxation was maintained with intermittent doses of rocuronium. Depth of anesthesia was continuously monitored using bispectral index (BIS), with target values maintained between 40 and 60.

Lung Recruitment Technique

During bilateral lung mechanical ventilation, both groups employed a pressure-limited ventilation (PCV) approach. For OLV, the following calibrations were used: the tidal volume was set at 8–10 mL/kg, positive end expiratory pressure (PEEP) at 5 cm H₂O, the inspiratory to expiratory ratio at 1:2, respiratory rate at 25 breaths per minute, the end-tidal carbon dioxide (P_{et}CO₂) maintained between 35 and 45 mmHg and the maximum airway pressure (P_{max}) was set at 28 cm H₂O.

In the SR group, stepwise lung recruitment was executed twice: just before the initiation of OLV and immediately upon the restoration of bilateral lung ventilation. The stepwise lung recruitment technique involved setting the inspiratory peak pressure at 28 cm H₂O, then increasing PEEP by 3–5 cm H₂O every 15 seconds over three breathing cycles until PEEP reached 15 cm H₂O. This level was then maintained for three cycles. Following this, PEEP was gradually reduced by 2–3 cm H₂O per breathing cycle until the oxygen saturation dropped by more than 1% compared to the previous cycle. The PEEP was then meticulously adjusted back to the value from the previous step. This PEEP value was considered the optimal PEEP, which maintained consistently throughout the remainder of the surgical procedure.

For the CR group, administration of controlled lung re-expansion occurred immediately prior to the initiation of the OLV and was repeated upon the restoration of bilateral lung ventilation. The CR group was selected as a comparator because it represents a conventional and widely used lung recruitment method in pediatric surgical practice. The procedure was as follows: under the manual control mode of the anesthesia machine, the inspiratory peak pressure was set at 28 cm H₂O and was maintained for 15–20 seconds, followed by switching to the PCV mode until the end of the surgery.

Both the CR and SR groups underwent lung ultrasound assessments guided by a 7–13 Hz linear array probe performed by anesthesiologists. It was conducted five minutes after the intubation and the commencement of the mechanical ventilation. It was repeated again at the end of the surgery. For this diagnostic procedure, the child was

placed in a supine position, with the arm on the examined side elevated. Following that, a probe was positioned vertically within the intercostal space to acquire a standardized “bat sign” image, referring to an image resembling a bat, formed by the pleural line and the upper and lower ribs. Following the initial positioning, the probe was meticulously slid horizontally along the intercostal spaces, systematically scanning each area. In regions where atelectasis was identified, precise lung re-expansion maneuvers were conducted.

Observation Indicators

(1) The following general information and surgical details were observed: The changes in anesthesia time, surgery time, one-lung ventilation time, and fluid replacement volume were monitored. (2) The observation points were set at post-anesthesia induction pre-OLV (T0), 20 minutes after OLV lung re-expansion (T1), and 20 minutes after full lung re-expansion post-OLV (T2), recording changes in each parameter. Hemodynamic parameters included HR, MAP; respiratory parameters included oxygenation index (OI) = (PaO₂/FiO₂), CO, V_T, peak airway pressure (Ppeak), Pmean, C_{dyn}, and PaCO₂. (4) Recording of pulmonary complications (pneumonia, hypoxemia, atelectasis, pneumothorax) occurring within 7 days post-surgery.

Statistical Methods

SPSS software version 25.0 was used for data analysis. Quantitative data were represented in means and standard deviations ($\bar{x} \pm s$). Normally distributed quantitative data were analyzed using the *t*-test, intra-group differences over time were analyzed using repeated measures analysis of variance, and count data were analyzed using the χ^2 test. A *P*-value < 0.05 was considered statistically significant.

Results

General Information

Baseline characteristics including age, gender, and weight were similar between the two groups, with no statistically significant differences (*P* > 0.05), as shown in [Table 1](#). A CONSORT flow diagram was shown in [Supplementary Figure 1](#).

Surgical Details

There were no statistically significant differences in surgical details (anesthesia time, surgery time, one-lung ventilation time, fluid replacement volume) between the two groups (*P* > 0.05, [Table 2](#)).

Table 1 Comparative Analysis of General Characteristics Across Cohorts

Group	Age (years, $\bar{x} \pm s$)	Weight (kg, $\bar{x} \pm s$)	Height (cm, $\bar{x} \pm s$)	Gender (M/F)
CR Control Group	2.69±0.88	14.29±2.85	93.38±10.98	16/23
SR Experimental Group	2.71±0.90	14.15±2.73	92.14±10.89	18/21
χ^2/t value	-0.099	0.222	0.501	0.209
<i>P</i> -value	0.461	0.413	0.309	0.648

Table 2 Comparative Analysis of Surgical Parameters Across Cohorts ($\bar{x} \pm s$)

Group	OLV Time (min)	Surgery Time (min)	Anesthesia Time (min)	Fluid Replacement Volume (mL)
CR Control Group	55.43±9.18	64.61±8.37	93.56±9.96	64.92±9.33
SR Experimental Group	56.59±8.87	66.21±7.95	95.15±9.39	63.89±9.01
<i>t</i> value	-0.567	-0.866	-0.725	0.496
<i>P</i> -value	0.286	0.195	0.235	0.312

Table 3 Comparative Analysis of Hemodynamic and Respiratory Parameters Across Cohorts ($\bar{x} \pm s$)

Parameter	Group	T0	T1	T2	P-value
MAP (mmHg)	CR Control Group	65.84±4.24	58.51±3.91	61.66±3.33	0.018
	SR Experimental Group	66.15±3.93	60.28±3.75	64.21±4.74	
HR (beats/min)	CR Control Group	134.15±6.22	145.11±5.61	137.07±8.64	0.037
	SR Experimental Group	132.66±6.27	143.74±5.77	133.62±6.96	
CO (mL/min)	CR Control Group	2.14±0.21	1.73±0.16	1.88±0.18	0.010
	SR Experimental Group	2.08±0.21	1.82±0.18	2.02±0.18	
Ppeak (cmH ₂ O)	CR Control Group	13.56±1.15	24.03±1.33	13.69±1.32	0.000
	SR Experimental Group	13.47±1.32	20.12±1.41	12.84±1.37	
Pmean (mmol/L)	CR Control Group	9.41±0.65	16.48±1.47	9.73±1.01	0.000
	SR Experimental Group	9.35±0.71	19.79±1.52	9.66±1.03	
Cdyn (mL/cmH ₂ O)	CR Control Group	8.44±0.98	3.11±0.49	7.78±1.64	0.000
	SR Experimental Group	8.52±0.94	4.32±0.63	7.69±1.53	
PaCO ₂ (mmHg)	CR Control Group	40.56±4.13	47.39±5.13	39.03±5.38	0.107
	SR Experimental Group	39.99±3.98	48.66±5.08	40.01±4.96	
OI (mmHg)	CR Control Group	422.05±40.86	130.64±15.78	278.19±30.61	0.000
	SR Experimental Group	418.97±38.72	177.09±17.34	277.58±31.35	
V _T (mL)	CR Control Group	255.83±20.79	286.21±18.63	259.35±22.17	0.000
	SR Experimental Group	257.04±22.13	309.83±20.25	258.84±23.06	

Table 4 Comparative Analysis of Pulmonary Complications Between Cohorts [n (%)]

Group	Pneumonia	Hypoxemia	Atelectasis	Pneumothorax
CR Control Group	10(25.64)	8(20.51)	10(25.64)	9(23.08)
SR Experimental Group	0(0.00)	3(7.69)	2(5.13)	1(2.56)
χ^2 value	11.471	2.646	6.303	7.341
P-value	0.001	0.104	0.012	0.007

Comparison of Hemodynamic Parameters Between Groups

At T1, the SR experimental group showed lower Ppeak and higher levels of Pmean, Cdyn, OI, and V_T compared to the control group [(20.12±1.41) vs (24.03±1.33), $P = 0.000$; (19.79±1.52) vs (16.48±1.47), $P = 0.000$; (4.32±0.63) vs (3.11±0.49), $P = 0.000$; (177.09±17.34) vs (130.64±15.78), $P = 0.000$; (309.83±20.25) vs (286.21±18.63), $P = 0.000$]. These suggest better compliance, gas exchange, and alveolar recruitment. At T2, the SR group maintained a more stable hemodynamic profile with return of HR and CO toward baseline faster than CR. Refer to [Table 3](#).

Comparison of Pulmonary Complications Between Groups

Postoperative complications were significantly lower in the SR experimental group. The incidence of pneumonia dropped from 25.6% (CR) to 0% (SR), and atelectasis from 25.6% to 5.1%. Pneumothorax also declined markedly (23.1% vs 2.6%, $P = 0.007$). Although hypoxemia trended lower in SR, it did not reach statistical significance ($P = 0.104$). Refer to [Table 4](#).

Discussion

Lung re-expansion procedures are important in general anesthesia surgery. These interventions serve the purpose of opening collapsed alveoli, enhancing oxygenation, optimizing lung compliance, and mitigating any adverse effects on patient cardiopulmonary function.⁴ While both groups aimed to restore lung volume after OLV, the SR group employed a gradual increase in PEEP, minimizing hemodynamic fluctuations and improving postoperative outcomes. To our knowledge, this is one of the first studies comparing SR to CR in pediatric thoroscopic segmentectomy.

In the context of this study, during OLV at T1, observed reductions in MAP and CO, coupled with an elevated HR, indicate alterations in lung compliance. These changes are directly associated with the diminished oxygen supply during OLV in infants. However, by T2, the MAP, CO, and HR values in the SR experimental group had largely returned to pre-intervention levels, indicating that the stepwise lung recruitment technique has a minimal impact on hemodynamic parameters and allows for faster postoperative recovery. Importantly, all anesthesia procedures were conducted by qualified pediatric anesthesiologists using a standardized protocol. This controlled for any confounding impact of anesthetic depth or agent variability on hemodynamic stability and inflammatory responses. These findings offer robust evidence supporting the importance of sustaining perioperative oxygen delivery in pediatric patients.

The rationale behind this phenomenon may stem from the fact that the stepwise lung recruitment technique avoids imposing excessive and prolonged pressure, affording the body adequate time to self-regulate cardiovascular parameters and chemoreceptor responses. Consequently, this mitigates the reflexive effects on HR and prevents dilation under elevated vascular pressure, thereby promoting stability in pediatric blood circulation.^{5,6}

In the context of this study, at time point T1, the SR experimental group demonstrated a decrease in P_{peak} compared to the CR control group and increases in P_{mean}, C_{dyn}, OI, and V_T ($P < 0.05$). This observation implies that stepwise lung recruitment has the potential to reduce peak airway pressure during surgical procedures, elevate mean airway pressure, and improve dynamic lung compliance. Our analysis suggests that stepwise lung recruitment, achieved by incrementally increasing the level of PEEP, stabilizes intrathoracic and pulmonary pressures. This gradual approach prevents abrupt spikes and ensures a consistent transition. This steady increase in P_{mean} subsequently reduces intrapulmonary shunt, facilitates the re-expansion of collapsed alveoli, improves ventilation, and decreases dead space ventilation.^{7,8}

Simultaneously, stepwise lung recruitment can swiftly restore the child's hemodynamics, dampen the excitability of the pulmonary vagal reflex, and prevent changes in CO caused by increase in intrathoracic pressure, thereby mitigating cardiovascular suppression's impact on improving lung oxygenation and compliance.^{9,10} Furthermore, compared to the CR control group, the SR experimental group showed increased levels of V_T and C_{dyn}, and a reduced incidence of postoperative pulmonary complications. This phenomenon can be attributed to the gradual elevation of lung re-expansion pressure, which facilitates a systematic increase in lung pressure. Consequently, this approach effectively mitigates lung shear injuries, prevents direct harm to the alveolar endothelium and epithelium, and mitigates the release of inflammatory factors. Additionally, it contributes to a reduction in the number of ischemia-reperfusion alveoli on the non-ventilated side, thereby diminishing pulmonary oxidative stress and preventing excessive secretion of inflammatory mediators.¹¹ A uniform size of 5 Fr bronchial blocker and 2.8 mm pediatric fiberoptic bronchoscope was used in all cases to maintain consistency and ensure safe and accurate lung isolation.

Cardiac Troponin T (cTnT) serves as a biomarker for myocardial ischemia; however, it does not directly correlate with the severity of myocardial injury. Subsequently, High-sensitivity cardiac troponin T (hs-cTnT) provides greater sensitivity, which is detectable in the early stages, and positively correlates with the severity of the pathological condition.¹²

TNF- α and IL-6 are pivotal inflammatory cytokines present in serum.¹³ They play crucial roles in systemic inflammatory responses and contribute to the pathogenesis of various diseases.¹⁴ They can exacerbate inflammation and tissue damage.¹⁵ Furthermore, heightened expression of inflammatory factors may facilitate the aggregation of lung tissue mast cells, intensify histamine activity, and result in the liberation of a substantial number of eosinophils. These processes contribute to the development of hyperreactive airways, which, in turn, have the potential to precipitate airway spasms or obstruction. Ultimately, this intricate interplay further compromises cardiopulmonary function during OLV.¹⁶

Inflammatory factors have the potential to disrupt the integrity of cardiomyocyte membranes, leading to structural damage within the myocardium and consequent reduction in cardiac function.¹⁷ Following surgery, the incidence rates of pneumonia, pneumothorax, and atelectasis are reduced. This favorable outcome can be attributed to the gradual elevation of pulmonary pressure. This approach activates endogenous protective mechanisms, mitigates reperfusion injury resulting from ischemia during ventilation in segmental lung resection, and consequently diminishes the release of inflammatory factors.¹⁸ The CR group served as the control group in this study, representing the conventional method of lung re-expansion widely practiced in pediatric thoracic anesthesia, thus offering a valid clinical benchmark for comparison.

Furthermore, controlled lung re-expansion may result in a swift elevation of intrapulmonary pressure, potentially compromising the integrity of the pulmonary interstitial capillary membrane. This process, in turn, triggers the expression of inflammatory factors, increasing the risk of myocardial injury.¹⁹ In contrast, the stepwise lung recruitment technique effectively mitigates the abrupt elevation in intrapulmonary pressure that is typically associated with controlled lung re-expansion and as a result, it affords myocardial protection.²⁰

Stepwise lung recruitment maneuver has also been considered a safe and well tolerated technique in hemodynamically stable children with acute respiratory distress syndrome (ARDS) and in adult patients with early ARDS.^{21,22} In lung resection, stepwise lung recruitment is primarily used to assess lung function after surgical resection, while in ARDS, it is used to treat and improve lung function. During lung resection, stepwise lung recruitment aims to evaluate and optimize the function of the remaining lung tissue, maintain hemodynamic stability, and improve the function of the healthy lung, which may experience small airway closure due to the chest wall being soft and functional residual capacity being low. In ARDS, the focus is on alleviating symptoms and improving lung function. The stepwise lung recruitment maneuver is also being investigated for its potential use in pediatric patients following cardiac surgery.²³ The use of this technique in other population warrants further investigation.

To summarize, the stepwise lung recruitment technique proves advantageous in safeguarding lung function and minimizing the occurrence of pulmonary complications in infants. Nevertheless, this study is constrained by certain limitations, including a small sample size, single-center design, and the absence of long-term follow-up. These factors may potentially introduce bias into the obtained results. Moreover, the presence of ETT cuff is a protective factor against pneumonia, therefore it could have generated a bias in analysis. In future investigations, researchers should explore the protective effects of stepwise lung recruitment on lung function in infants undergoing segmental lung resection with OLV. This could be achieved by either expanding the sample size or conducting a multicenter study.

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