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Effect of one-lung ventilation in children undergoing lateral thoracotomy cardiac surgery with cardiopulmonary bypass on postoperative atelectasis and postoperative pulmonary complications

Hualin Chen[1†], Ting Liu[1†], Wei Dong[2] and Ying Sun[1*]

Abstract

Background Right lateral thoracotomy is increasingly used because of its cosmetic benefits, shorter hospital stays, rapid return to full activity, and ease of reoperation in pediatric patients with uncomplicated congenital heart disease. Currently, one-lung ventilation (OLV) is used in these children to facilitate surgical exposure. We aimed to assess the effect of OLV on postoperative outcomes.

Methods Children aged 6 months to 6 years undergoing right lateral thoracotomy cardiac surgery with cardiopulmonary bypass (CPB) were randomized into an OLV group or a control group. For the OLV group, the tidal volume was 5 ml/kg with 6 cmH_2O positive end-expiratory pressure from the incision until the end of CPB, whereas patients in the control group received two-lung ventilation, except during vena cava occlusion. Lung ultrasonography was performed twice in the supine position for each patient: first, 3 min after intubation before surgery (T_1), and second, 3 min after lung recruitment maneuvers at the end of surgery (T_2). The primary outcome was the incidence of postoperative pulmonary complications within 72 h of surgery and significant atelectasis (defined by a consolidation score of ≥ 2 in any region) at T_2.

Results Overall, 54/96 (56.3%) children developed postoperative pulmonary complications after lateral thoracotomy cardiac surgery with CPB. The incidence of postoperative pulmonary complications was 52.1% (25/48) and 60.4% (29/48) in the OLV and control groups, respectively (odds ratio: 0.712; 95% confidence interval: 0.317–1.600; $p = .411$). At the end of surgery, the incidence of significant atelectasis was 37.5% in the OLV group compared to 64.6% in the control group (odds ratio: 0.329; 95% confidence interval: 0.143–0.756; $p = .008$). The consolidation score of the left lung (dependent lung) in the OLV group was significantly lower than that in the control group ($p = .007$); there was no significant difference in the right lung's postoperative consolidation score between the two groups ($p = .051$).

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Conclusions There was no significant difference in the incidence of postoperative pulmonary complications within 72 h of surgery between the two groups. However, children who underwent right lateral thoracotomy cardiac surgery with CPB in the OLV group showed a low incidence of atelectasis at the end of surgery.

Trial registration ChiCTR, ChiCTR2100048720. Registered on July 13, 2021, www.chictr.org.cn.

Keywords One-lung ventilation, Lateral thoracotomy, Cardiac surgery, Child, Postoperative pulmonary complications

Background

Pediatric patients who undergo cardiac surgery with cardiopulmonary bypass (CPB) are at risk of postoperative respiratory insufficiency. Several studies have assessed the risk factors for developing postoperative pulmonary dysfunction in children undergoing median sternotomy, and some measures have proven to be effective in reducing the incidence of postoperative pulmonary complications (PPCs) [1–5]. Recently, shorter right lateral thoracotomies have been increasingly used in pediatric patients with uncomplicated congenital heart disease (CHD) [6, 7]. To achieve superior surgical and parental satisfaction, improved surgical access and rapid postoperative recovery must be optimized. One-lung ventilation (OLV) is used during right thoracotomy to facilitate surgical exposure.

Our previous study found that patients undergoing lateral thoracotomy with two-lung ventilation had a high incidence of lung atelectasis after CPB surgery, due to surgical retraction of the right lung and gravity-dependent compression of the left lung. However, no previous study has investigated the incidence of postoperative atelectasis in patients who underwent lateral thoracotomy cardiac surgery with CPB using OLV.

Hypoxemia is common in children undergoing noncardiac surgery with OLV [8]. Alterations in lung mechanics during CPB and anomalies in gas exchange leading to a high incidence of hypoxemia 2 h after CPB [9]. Some PPCs, such as atelectasis, pleural effusion, and prolonged ventilator support, are significantly associated with hypoxemia [10]. The incidence of PPCs may affect morbidity, hospital stay length, and healthcare costs [1]. In OLV, collapse and atelectasis in the non-dependent lung activate hypoxic pulmonary vasoconstriction, directing blood toward the better-ventilated lung. Meanwhile, the less-rigid cartilaginous rib cage and abdominal pressure transmitted through the diaphragm compress the dependent lung, reducing compliance and ventilation. Thus, children undergoing lateral thoracotomy cardiac surgery with OLV are at high risk of developing atelectasis and compromised pulmonary function after CPB.

This randomized controlled study was designed to assess the effect of OLV in children undergoing lateral thoracotomy cardiac surgery with CPB on postoperative atelectasis and PPCs.

Methods

This prospective randomized controlled study was conducted between June 2021 and November 2022. It was approved by the Institutional Review Board of Shanghai Children's Medical Center (No. SCMCIRB-K2021043-1) and registered with the Chinese Clinical Trial Registry (ChiCTR2100048720). This single-center study was conducted at Shanghai Children's Medical Center in China. Study personnel evaluated the eligibility of the pediatric patients, and written informed consent was obtained from the parents or legal guardians of each participant before enrollment.

Study population

Pediatric patients with uncomplicated CHD aged 6 months to 6 years with an American Society of Anesthesiology physical status of 2 or 3 scheduled for right lateral thoracotomy under CPB were included in the study. The exclusion criteria were American Society of Anesthesiology physical status > 3, previous thoracic surgery, pulmonary disease, airway anomaly, a history of respiratory tract infection within the past 4 weeks, abnormal preoperative chest X-ray or CT findings, such as atelectasis, pneumothorax, pleural effusion, or pneumonia, the presence of a tracheobronchial bronchus, current vasoactive support prior to anesthesia, and preoperative oxygen saturation below 95% in room air, as measured by pulse oximetry.

Randomization

Based on a computer-generated randomization list, participants were assigned to either the OLV or control groups in a 1:1 ratio using a sealed envelope technique. Both the lung ultrasound (LUS) operator and reviewer of the LUS images were blinded to the patients' group allocation.

Anesthesia protocol and perioperative ventilatory settings

All enrolled children received oral midazolam (0.5 $mg\cdot kg^{-1}$) at least 20 min before induction of anesthesia. After standard monitoring was applied, all patients underwent an institutionalized general anesthetic protocol that included intravenous administration of midazolam (0.1 mg·kg^{-1}), etomidate (0.2 to 0.3 mg·kg^{-1}), sufentanil (2.0 to 2.5 μg·kg^{-1}), and rocuronium (1.0 mg·kg^{-1}). Anesthesia was maintained using continuous intravenous infusion of propofol (4.0 to 6.0 mg·kg^{-1}·h^{-1}), sufentanil (2.0 to 2.5 μg·kg^{-1}·h^{-1}), and rocuronium (0.6 mg·kg^{-1}·h^{-1}). During pre-oxygenation, all patients received 80% oxygen and pressure-controlled facemask ventilation. The fractional inspired oxygen tension (FiO_2) was then adjusted to 0.6 after successful tracheal intubation and remained unchanged throughout the operation, except in cases of a substantial drop in oxygenation, which required temporary adjustment. Mechanical ventilation was applied under pressure-controlled ventilation (PCV) mode with an inspiratory/expiratory ratio of 1:2, a tidal volume (VT) of 8 mL/kg, a respiratory frequency of 18 to 30 breaths/min based on the child's age, an oxygen flow rate of 1 to 2 L/min, and an end-tidal carbon dioxide concentration of 35 to 45 mmHg, which was maintained by adjusting the frequency.

Study protocol: OLV group

After the first recruitment maneuver (RM), if necessary, children in the OLV group were fitted with 5F bronchial blockers (BBs) (Hangzhou Tampa Medical Technology Co., Ltd.) via endotracheal tube intraluminal placement. A 2.0-mm fiberoptic bronchoscope (SEESHEEN, QG-2128; Zhuhai Shixin Medical Technology Co., Ltd., Zhuhai, China) was inserted via the endotracheal tube to visualize and guide the placement of the blocker into the right mainstem bronchus. After the children were placed in the left lateral decubitus position, the position of the BBs was confirmed and inflated under bronchoscope guidance, and OLV was initiated. Lung-protective ventilation was used during OLV (PCV mode, VT 5 mL/kg, positive end-expiratory pressure [PEEP] 6 cmH_2O). Ventilation was paused when the vena cava was blocked. Once the vena cava was reopened, OLV was resumed and maintained until CPB was achieved, using the same ventilation settings. Adequate RM was performed when switching to bilateral lung ventilation, and two-lung ventilation was resumed at the end of CPB under PCV mode, with VT 8 mL/kg and PEEP 6 cmH_2O.

Study protocol: control group

After the first RM, if necessary, children in the two-lung ventilation group were ventilated under PCV mode with VT 8 mL/kg without PEEP. Ventilation was paused when the vena cava was blocked. Bilateral lung ventilation was resumed once the vena cava was reopened after lung inflation, with the same ventilation pattern as pre-CPB. From the end of CPB to chest closure, 6 cmH_2O PEEP was applied, with VT 8 mL/kg. Temporary suspension of PEEP was necessary when dilated lung lobes obstructed the surgical field in both groups.

LUS examination and RM

Two LUS examinations were performed in all patients: 3 min after intubation and 3 min after RM at the end of surgery. All ultrasound scans were performed by a single anesthesiologist who was blinded to the group allocation and had experience with more than 100 pediatric LUS scans using a LOGIQ e ultrasound machine (GE Healthcare, Wauwatosa, WI) with a 7–12 MHz linear transducer. The patients were scanned in the supine position with their arms positioned above their heads according to the LUS examination method described by Sun et al. [11]. Each hemithorax was divided into upper and lower regions at the level of the nipples. Scans 1 and 2 were performed at the midclavicular line, scans 3 and 4 were performed at the midaxillary line, and scans 5 and 6 were performed at the 5th and 6th intercostal spaces along the posterior axillary line. Each region was assessed using a two-dimensional view with the probe placed parallel to the ribs, and 12 lung regions were scanned sequentially from left to right, cranial to caudal, and anterior to posterior. The lung sliding sign, A-lines, B-lines, consolidation, and air-bronchogram signs were recorded and assessed. The degree of consolidation and B-lines was scored from zero to three according to the grading method described by Song et al. [12]. The degree of juxtapleural consolidation was divided into four grades and scored as follows: (0) no consolidation; (1) minimal juxtapleural consolidation; (2) small consolidation; (3) large consolidation. The degree of B-lines was scored as follows: (0) fewer than three isolated B-lines; (1) multiple well-defined B-lines; (2) multiple coalescent B-lines; (3) white lung. Significant atelectasis was defined as any region with a consolidation score of ≥ 2. The graded degrees of consolidation and B-lines were scored and summed separately for each region.

The protocol is schematically illustrated in Fig. 1. RM was performed in the supine position at the following time points: the first RM was performed only if atelectasis was detected on the first LUS examination, and the second RM was performed at the end of surgery. RM was performed in pressure-control mode, maintaining a steady pressure of 15 cmH_2O, with PEEP increased in 5 cmH_2O increments until a peak pressure of 30 cmH_2O was achieved [13]. The patients remained at each incremental PEEP step for 5 s and 10 s at peak pressure. Subsequently, PEEP was reduced in a stepwise manner at the same rate.

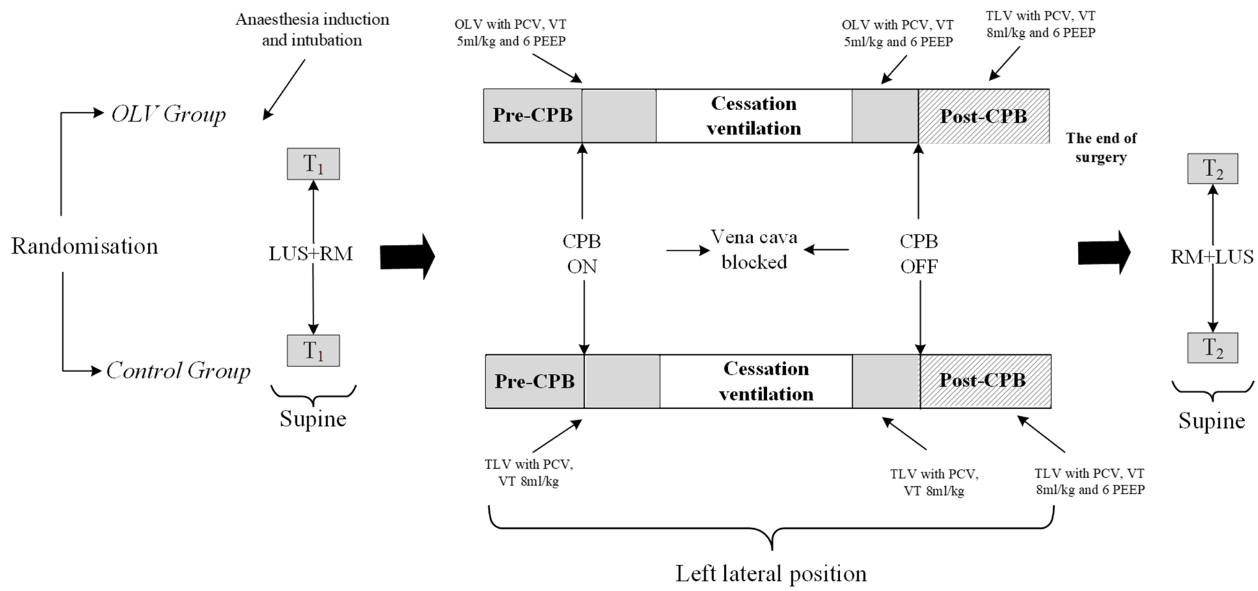

Fig. 1 Diagram of the protocol. OLV group: one-lung ventilation group patients; Control group: two-lung ventilation control patients; LUS, lung ultrasound; RM, recruitment maneuver; Pre-cardiopulmonary bypass (CPB), before CPB; Post-CPB, after the termination of CPB; T_1, 3 min after tracheal intubation; T_2, at the end of surgery

Arterial blood gas monitoring

Intraoperative arterial blood gas analysis was performed three times: 3 min after endotracheal intubation (preoperative measurement), 10 min after weaning from CPB, and 3 min after RM (at the end of surgery). Postoperative arterial blood gas analyses were performed at five time points: upon arrival at the cardiac intensive care unit (CICU), 1 h after CICU arrival, 2 h after CICU arrival, 3 h after CICU arrival, and before extubation. Hypoxemia was defined as $PaO_2/FiO_2 \leq 300$.

PPCs

PPCs were diagnosed based on clinical signs, laboratory tests, and imaging evidence, including respiratory infection, respiratory failure, pleural effusion, atelectasis, pneumothorax, and pneumonitis. Any of these conditions, alone or in combination, was considered a PPC [2, 14, 15], and modifications were made as appropriate. Respiratory infection was defined by clinical signs, fever, leukocytosis, or a positive sputum culture. Respiratory failure was defined as a postoperative $PaO_2 < 8$ kPa (60 mmHg) on room air. Pleural effusion, atelectasis, pneumothorax, and pneumonitis were defined based on chest radiography.

The following data were collected from each patient: age, height, weight, sex, diagnosis, duration of aortic cross-clamping, duration of surgery, duration of anesthesia (min), ICU stay (h), duration of CPB (min), extubation time (from CICU arrival to extubation), length of postoperative hospital stay, and preoperative pro-BNP concentrations and postoperative plasma NT- pro-BNP concentrations.

Outcome variables and statistics

Primary outcomes were the incidence of significant atelectasis at T2 and incidence of PPCs within 72 h of surgery. Secondary outcomes included LUS scores for consolidation and B-lines at T2, intraoperative and postoperative PaO_2/FiO_2, duration of aortic cross-clamping, duration of CPB, duration of surgery, duration of anesthesia, ICU time, extubation time, postoperative hospital stay (d), and preoperative plasma pro-BNP concentrations and postoperative plasma NT- pro-BNP concentrations.

Since no studies have examined the incidence of PPCs in children undergoing lateral thoracotomy cardiac surgery, we calculated the sample size based on other studies in pediatric patients. One study demonstrated that the incidence of PPCs in infants undergoing CPB surgery for CHD via a median sternotomy was 60.5% [15]. Assuming that the incidence of PPCs in the control group was similar and that OLV would reduce PPC incidence to 30%, the required sample size was 50 patients per group, with an alpha error of 0.05, power of 80%, and allowance for a 20% dropout rate.

The data are presented as mean ± SD or median and interquartile range (25%–75%, IQR). Primary outcomes were evaluated using the chi-square test. Secondary outcomes were evaluated using Student's t-test for continuous variables and the chi-square test for categorical variables. The Wilcoxon signed-rank test was used to compare intragroup LUS scores. The Fisher's exact test was used to analyze categorical variables. Statistical analyses were performed using SPSS Statistics version 23 (IBM Corp., Armonk, NY, USA). $P < 0.05$ was considered statistically significant.

Results

Patients' characteristics

Between June 2021 and November 2022, 104 patients were enrolled and randomly divided into two groups. Two patients in each group were lost to follow-up because of residual shunts. Another two patients in each group were excluded because they were unable to undergo LUS. A total of 48 patients in the OLV group and 48 patients in the control group completed the study (Fig. 2). The baseline characteristics of the patients and intraoperative variables are shown in Table 1.

Primary outcome

There were 54 patients (56.3%) who developed PPCs within 72 h of surgery. The overall incidence of PPCs was 52.1% in the OLV group and 60.4% in the control group (odds ratio: 0.712; 95% confidence interval: 0.317–1.600; $p = 0.411$) (Table 2). All pleural effusions, pneumothorax, and atelectasis occurred on the right side of the thoracotomy, and most cases of pneumonia were also observed on the right side. Pneumonia, atelectasis, pneumothorax, and pleural effusion were detected on the day of surgery and after chest tube removal. Chest radiography was repeated until normal radiographic findings were confirmed.

The consolidation and B-line scores assessed using LUS are shown in Table 2. At the end of surgery, the incidence of significant atelectasis was 37.5% in the OLV group and 64.6% in the control group (odds ratio: 0.329; 95% confidence interval: 0.143–0.756; $p = 0.008$) (Table 2). The consolidation score of the left lung (dependent lung) in the OLV group was significantly lower than in the control group ($p = 0.007$), and there was no significant difference in the right lung postoperative consolidation score between the two groups ($p = 0.051$).

Secondary outcomes

LUS assessment

Ultrasound findings of the left lung in the control and OLV groups (dependent lungs) are shown in Fig. 3. At the end of surgery, the LUS scores (Table 2) were lower in the OLV group than in the control group for consolidation (8 [IQR, 4–12] vs. 12 [6.5–19]; $P = 0.005$) and B-lines (6 [3–9.75] vs. 8 [5.25–12]; $P = 0.024$).

PaO2/FiO2 ratio

The oxygenation index in the OLV group was lower than in the control group after chest closure ($p = 0.002$) and upon arrival at the CICU ($p = 0.011$) (Table 3). However, the difference was not statistically significant at the end of CPB and upon arrival at the CICU at 1 h. Children in the OLV group had a higher oxygenation index in the CICU at 2 h ($p = 0.022$) and 3 h ($p = 0.001$) (Table 3), but there was no significant difference before extubation. The incidence of hypoxemia in the OLV group was 68.8% and 57.9% at the end of CPB.

Data are presented as mean ± SD. T1 = preoperative measurement; T2 = 10 min after weaning from CPB; T3 = 3 min after RM (at the end of surgery); T4 = arrival at CICU; T5 = arrival at CICU at 1 h; T6 = arrival at CICU at 2 h; T7 = arrival at CICU at 3 h; T8 = before extubation.

OLV, one-lung ventilation; CICU, cardiac intensive care unit; CPB, cardiopulmonary bypass.

Time

The duration of aortic cross-clamping, operation duration, CPB duration, anesthesia duration, and extubation time were shorter in the OLV group, but the differences were not significant. The ICU stay was also not significantly different between the groups. The median (IQR) hospital stay was similar between the groups (both 6 [5, 6]; $P = 0.616$).

Discussion

This study demonstrated that in children undergoing right lateral thoracotomy cardiac surgery with CPB, there was no significant difference in the incidence of PPCs between the OLV and control groups. The incidence of postoperative atelectasis was significantly lower in the OLV group than in the control group. The PaO_2/FiO_2 values in the OLV group were lower than those in the control group at the end of surgery and in the CICU. Additionally, the postoperative increase in NT-pro-BNP was significantly lower in the OLV group.

No significant difference was found in the incidence of PPCs between the two groups, 52.1% in the OLV group and 60.4% in the two-lung ventilation group. The incidence of PPCs was similar to that reported by Sun et al. [15]. The patients enrolled in their study were not only uncomplicated cases but also severe CHD cases, which may have increased CPB and operative times. Another difference was that patients in our study were operated on in the left lateral decubitus position, whereas patients in their study were in the supine position.

Our previous studies [16] have shown that in children undergoing lateral thoracotomy with CPB for CHD surgery, the incidence of atelectasis was as high as 80%,

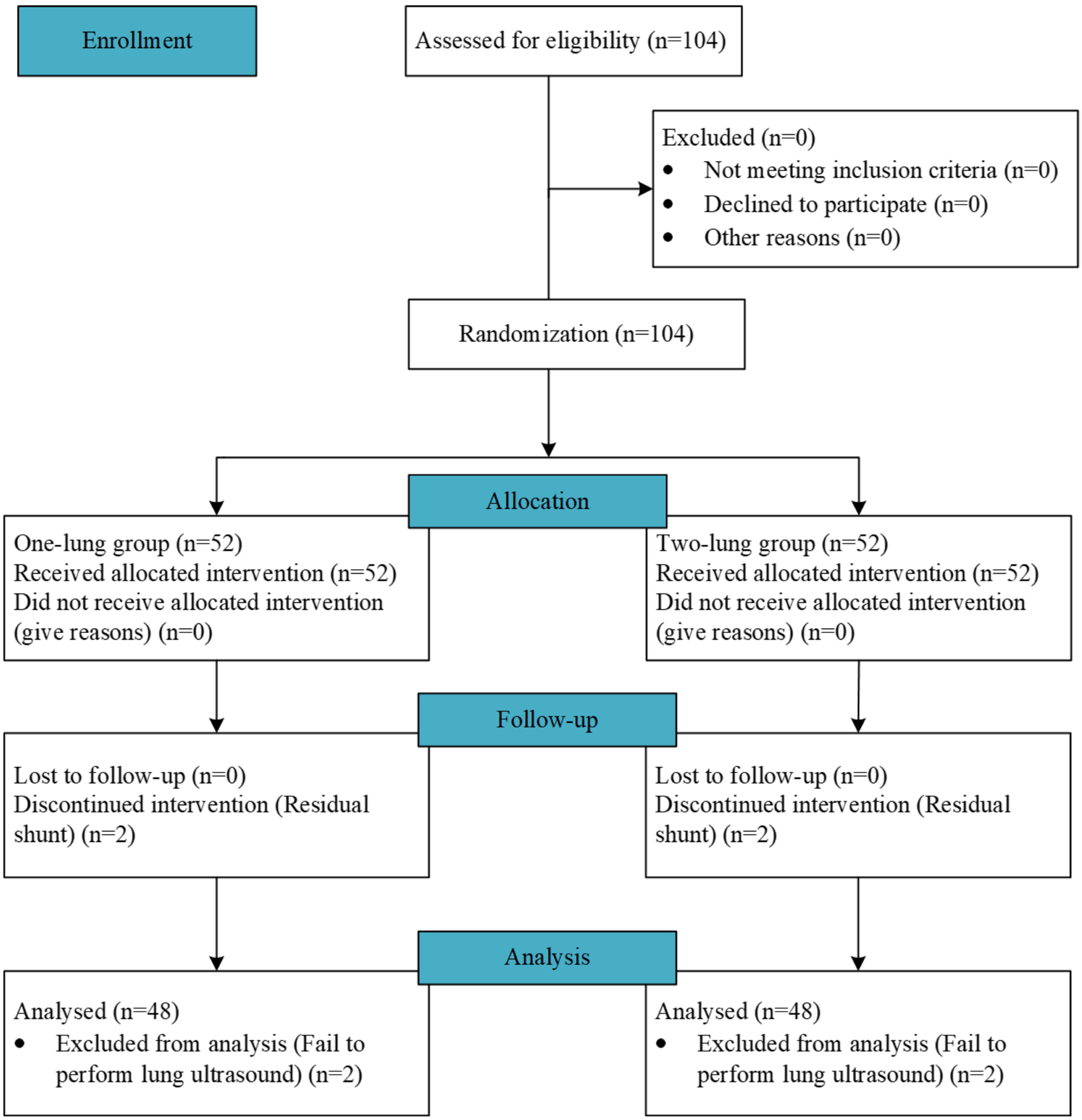

Fig. 2 CONSORT diagram. CONSORT, Consolidated Standards of Reporting Trials

whereas the incidence of atelectasis in the two-lung ventilation group of this study was 60.4%. This difference was primarily due to the varying ages of the children included in the two studies. The patients enrolled in the present study were aged 6 months to 6 years, whereas those in our previous study were 3 years old or younger. Atelectasis is more likely to occur at younger ages.

Midline sternotomy is a conventional approach to the heart. Currently, an alternative surgical approach via the lateral axilla is used for better cosmetic outcomes (avoiding midline sternotomy) and greater parent/patient satisfaction [6, 7, 17]. Lung separation has been suggested to improve surgical access to the heart and is widely used in clinical practice [18]. Since there are no uniformly sized tracheal tubes or double-lumen tubes available for children under 8 years of age in China, single-lumen tracheal tubes advanced into either the bronchus or BBs are chosen for this age group. Recently, a multicenter cohort

Table 1 Demographic data and surgical characteristics

	OLV group (*n* = 48)	Control group (*n* = 48)	*P-value*
Age (month)	34.2 (14.5)	28.9 (16.0)	0.092
Gender (M/F)	22/26	22/26	1.000
Weight (kg)	14.1 (3.8)	12.8 (3.4)	0.064
Height (cm)	94.2 (11.6)	89.5 (12.0)	0.055
Type of surgery (n)			0.704
ASD	19 (39.58%)	19 (39.58%)	
VSD	28 (58.33%)	26 (54.17%)	
ASD + PDA	1 (2.08%)	2 (4.17%)	
PAPVC	0 (0%)	1 (2.08%)	
Duration of aortic clamping (min)	29.1 (15.2)	32.5 (19.2)	0.343
Duration of surgery (min)	124.6 (25.8)	131.9 (32.8)	0.225
duration of CPB (min)	47.7 (17.0)	50.8 (22.0)	0.435
duration of anesthesia (min)	169.1 (28.0)	174.1 (36.9)	0.453
ICU stay time (h)	43.8 (2.1)	43.1(2.4)	0.124
extubation time	280.4 (105.2)	308.5 (142.2)	0.274
Hospital stays postoperative (days)	6 (5–6)	6 (5–6)	0.616
Preoperative pro-BNP	116.8 (172.3)	124.9 (138.3)	0.803
Postoperative NT- pro- BNP	1675.1 (852.0)	2351.5 (1531.5)	0.009

Data are presented as mean (SD), median (IQR), or number of patients (%)

Abbreviations: *ASD* Atrial septal defect, *CPB* Cardiopulmonary bypass, *F* female, *M* male, *VSD* ventricular septal defect, *PDA* Patent ductus arteriosus, *PAPVC* Partial anomalous pulmonary venous return, *OLV* One-lung ventilation, *ICU* Stay time (h), duration of pediatric patient stays in the ICU

study found that the use of a BB was associated with a lower risk of hypoxemia than that of endobronchial intubation in young children undergoing OLV [8]. Therefore, a BB is the preferred method for OLV.

We also found that the incidence of postoperative atelectasis in the OLV group was significantly lower than in the control group. In infants and young children, atelectasis and alveolar collapse readily occur in ventilated lungs during anesthesia, OLV, and the lateral decubitus position. There are multiple reasons for this phenomenon. The weight of the mediastinum, less rigid cartilaginous rib cage, and abdominal pressure transmitted through the diaphragm impede the expansion of the dependent lung [19]. Additionally, stopping ventilation during CPB is associated with the development of microatelectasis and reduced surfactant diffusion. Reducing the occurrence of atelectasis in the dependent lung is important because alveolar collapse in the dependent lung activates hypoxic pulmonary vasoconstriction, which diverts more perfusion to the non-ventilated lung and increases the shunt fraction. Therefore, a ventilation strategy that included a small VT of 5 mL/kg during OLV, with 6 cmH_2O PEEP maintained throughout, was used in the OLV group in the current study, while in the bilateral lung ventilation group, PEEP was only used after CPB, considering its impact on surgical exposure. The results showed that the postoperative consolidation score evaluated using lung ultrasonography for the left lung (dependent lung) in

Table 2 Lung ultrasound scores and incidence of postoperative pulmonary complications in patients

	OLV group (*n* = 48)	Control group (*n* = 48)	Odds ratio (95% CI)	*P-value*
Postoperative Consolidation score	8 (4–12)	12 (6.5–19)		0.005
Consolidation score ≥ 2	18 (37.5)	31(64.6)		0.008
R-scans	3 (1–5)	4 (2–7)		0.051
L-scans	5 (2–7)	8(2.25–12.75)		0.007
B-lines score	6 (3–9.75)	8 (5.25–12)		0.024
R-scans	3 (0.25–5)	3.5 (2–5)		0.293
L-scans	3 (1–5)	5 (2–8)		0.011
Postoperative pulmonary complications	25 (52.08)	29 (60.42)	0.71(0.32–1.60)	0.411
Respiratory infection	11 (22.9)	15 (31.3)		
Respiratory failure	0	1 (2.1)		
Pleural effusion	1 (2.1)	3 (6.3)		
Atelectasis	1 (2.1)	0		
Pneumothorax	1 (2.1)	6 (12.5)		
Pneumonia	13 (29.2)	14 (31.2)		

Data are presented as median (interquartile range) or n (%)

OLV one-lung ventilation, *CI* confidence interval

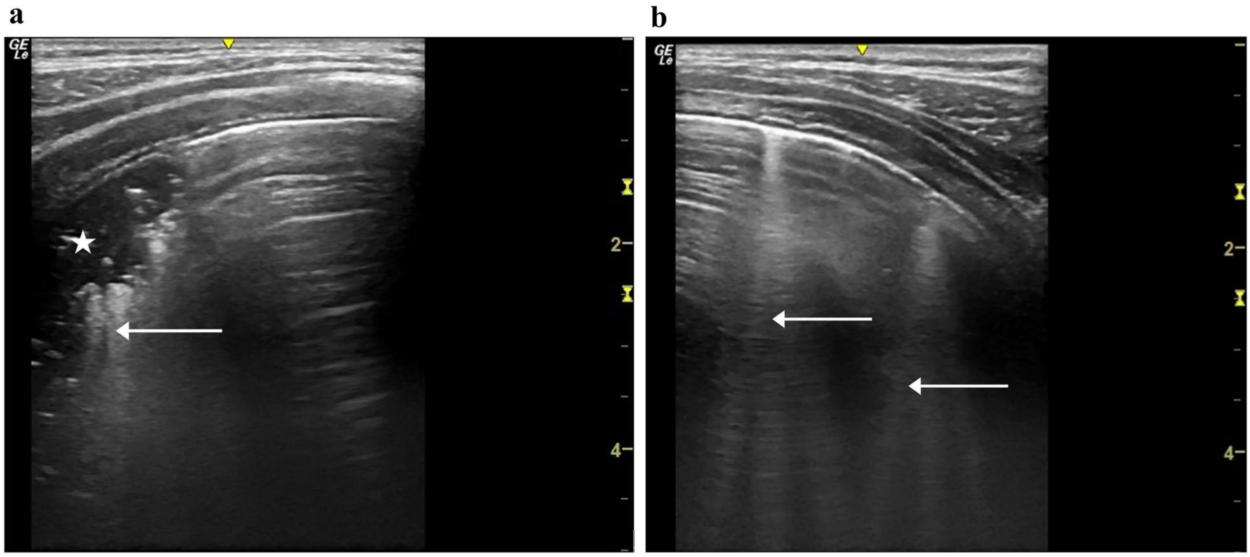

Fig. 3 Lung ultrasound findings of the left lung in the control and one-lung ventilation (OLV) groups (dependent lung). Images were obtained from the 5th and 6th intercostal spaces along the posterior axillary line. In the control group (**a**), large juxtapleural consolidation and multiple coalescent B-lines were observed. In the OLV group (**b**), two coalescent B-lines without juxtapleural consolidation were observed. Asterisks indicate juxtapleural consolidation, and arrows indicate B-lines

Table 3 Differences in PaO_2/FiO_2 ratio between the two groups at different time points

	OLV group (*n* = 48)	Control group (*n* = 48)	*P-value*
PaO_2/FiO_2 ratio			
T1	478.0 (77.7)	490.4 (63.8)	0.394
T2	249.1 (118.1)	267.8 (120.4)	0.445
T3	300.4 (112.9)	372.3 (105.4)	0.002
T4	404.2 (123.7)	460.6 (93.4)	0.011
T5	403.6 (110.6)	412.7 (64.7)	0.625
T6	466.6 (68.1)	434.0 (68.5)	0.022
T7	466.7 (68.4)	415.8 (73.6)	0.001
T8	455.4 (66.6)	447.6 (165.1)	0.761

the OLV group was significantly lower than that in the two-lung ventilation group. There was no significant difference in the right lung postoperative consolidation scores between the two groups. This was mainly attributable to the continuous application of PEEP in children in the OLV group throughout the lateral position.

Post-CPB hypoxemia is common after pediatric CHD surgery. All patients enrolled in our study had uncomplicated CHD, and none had preexisting intracardiac right-to-left shunting. CPB stimuli, surgical procedures, and anesthesia decrease pulmonary surfactant levels. Although CPB techniques have improved, a recent study revealed that the overall incidence of post-CPB hypoxemia in pediatric cardiac surgery was as high as 48.4% [9]. Moreover, OLV may further worsen oxygenation due to OLV and inevitable transpulmonary shunting. In the present study, all patients underwent right thoracotomy, and the smaller left lung served as the dependent, ventilated lung. Because the left lung is smaller than the right lung, oxygenation during OLV was worse during right thoracotomy than during left thoracotomy. Slinger et al. found that the operative side was one of the most important factors in predicting hypoxemia during OLV [20]. In our study, the incidence of post-CPB hypoxemia was 68.8%, which was significantly higher than that in the control group and in Sun's study [9]. The oxygenation index of patients in the OLV group was lower than that of patients in the control group, both at the end of surgery and upon arrival at the CICU. Although the overall incidence of hypoxemia was higher in the OLV group, this condition resolved before extubation. Furthermore, the oxygenation index of patients in the OLV group was higher than that of the control group at 2 and 3 h after arrival at the CICU. This may have been due to a lower incidence of atelectasis in the left lung and less compression in the right lung in the OLV group.

NT-pro-BNP is a cardiac neurohormone secreted from the ventricles in response to ventricular wall stretching or myocardial ischemia [21]. Our results showed that the postoperative NT-pro-BNP level was significantly lower in the OLV group than in the two-lung ventilation group. This may be attributed to an increased operative space with single-lung ventilation, which reduces ventricular wall stretch. However, whether a reduction in NT-pro-BNP levels leads to better clinical outcomes requires further investigation. This study has several limitations. First, lung ultrasonography was performed only in the operating room, and chest radiography was used to assess PPCs in the CICU within 72 h of surgery. In fact, a reproducible bedside pulmonary ultrasound is more sensitive in detecting early extravascular water accumulation and more accurate in diagnosing pneumonia than conventional radiography [22, 23]. Second, all patients in this study underwent intraluminal BB placement. Therefore, the results may not apply to children undergoing OLV with extraluminal BB placement or endobronchial intubation. Third, some studies have suggested that maintaining ventilation or using continuous positive airway pressure during CPB is associated with better outcomes in pediatric patients undergoing cardiac surgery. Our study did not use continuous positive airway pressure or other ventilation modes in the dependent lung during CPB, which should be addressed in future research. Finally, in the current study, IL-6 was measured clinically in some cases as an inflammatory biomarker; however, because of incomplete data, this study did not use an inflammatory biomarker to assess lung damage directly.

Conclusions

Children undergoing lateral thoracotomy cardiac surgery with CPB in the OLV group had a lower incidence of atelectasis at the end of surgery than that of those undergoing two-lung ventilation. However, there was no significant difference in the incidence of PPCs between the two groups. The application of OLV in pediatric patients undergoing lateral thoracotomy cardiac surgery with CPB is relatively new. As an invasive procedure, the risk–benefit or cost–benefit of OLV in these patients requires further evaluation.

Abbreviations

BBs	Bronchial blockers
CHD	Congenital heart disease
CPB	Cardiopulmonary bypass
FiO_2	Fractional inspired oxygen tension
LUS	Lung ultrasound
OLV	One-lung ventilation
OR	Odds ratio
PCV	Pressure-controlled ventilation
PPCs	Postoperative pulmonary complications
VT	Tidal volume

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Authors' contributions

Study design/planning: H. L. C, T. L, Y. S. Study conduct: H. L. C, T. L, Y. S, W. D. Data analysis: H. L. C, T. L, Y. S. Writing the manuscript: H. L. C, T. L, Y. S.

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Data availability

The datasets used or analyzed in the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Shanghai Children's Medical Center (No. SCMCIRB-K2021043-1) and registered in the Chinese Clinical Trial Registry (ChiCTR2100048720). Written informed consent was obtained from the parents of each child.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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