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Optimization of lung ultrasound in ultrafast-track anesthesia for non-cyanotic congenital heart disease surgery

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A R T I C L E I N F O

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A B S T R A C T

Objective: We aimed to explore the feasibility of lung ultrasound for perioperative assessment and the optimal effect of lung ultrasound in reducing lung complications during non-cyanotic congenital heart disease (CHD) surgery using ultrafast-track anesthesia.
Methods: Sixty patients were treated at Shenzhen Children's Hospital between 2019 and 2020. Of these, 30 patients in group N had an indication for extubation and ultrafast-track anesthesia after congenital heart surgery; the tracheal catheter was removed, and the patients were sent to the cardiac intensive care unit (CICU) for further monitoring and treatment. Another 30 patients were in group L and also had an indication for extubation and ultrafast-track anesthesia; in addition we compared lung ultrasound score (LUS) before and after surgery, when we found the cases that LUS $\geq$ 15, for whom targeted optimization treatment would be carried out. The tracheal catheter was removed after LUS <15 days before the patients were sent to the CICU. In all cases, the LUS and PaO2/FiO2 ratios (P/F) of both groups were recorded at the time of anesthesia induction (T_0), before extubation (T_1), and 5 min (T_2), 1 h (T_3), and 24 h (T_4) after extubation. The incidence of pulmonary complications, LUS, and P/F were compared between the two groups.
Results: There was great consistency between LUS and radiographic findings. Comparing the data of the two groups at T_2, T_3 and T_4, the P/F was higher and the LUS was lower in group L than in group N. The incidence of lung complications in group L (18 cases, 60 %) was lower than that in group N (26 cases, 86.7 %, $\chi 2 = 5.46$, $P = 0.02$); comparing LUS between T_0 and T_3, LUS decreased in a greater number of cases in group L (15, 50 %) than in group N (7 cases, 23.3 %, $\chi 2 = 4.59$, $P = 0.032$).
Conclusion: Lung ultrasonography can effectively help assess lung conditions. Optimization guided by lung ultrasound in ultrafast track anesthesia can significantly reduce postoperative lung complications.

1. Introduction

Enhanced Recovery After Surgery (ERAS) is based on evidence-based medicine and multidisciplinary cooperation and optimizes interventions for perioperative treatment to reduce perioperative stress response and postoperative complications to accelerate recovery [1]. As an essential part of perioperative ERAS, appropriate clinical anesthesia must be continuously explored and optimized,

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particularly for the evaluation and optimization of pulmonary function [2]. With the extensive development of visualization technology in anesthesiology, the application of lung ultrasonography has attracted attention in recent years [3]. LUS has been recommended in the European point-of-care ultrasound guidelines for neonatal and pediatric intensive Care [4]. However, there were few reports on the application of lung ultrasonography for tracheal catheter extubation in the operating room. In CHD surgery with ultra-fast-track anesthesia, which requires removal of the tracheal catheter in the operating room, recovery of cardiopulmonary function is extremely important [5]. If we learn about the lung condition through lung ultrasound before removing the tracheal catheter, we can find problems in time and take optimization measures to further improve the condition of patients, which can effectively reduce postoperative pulmonary complications and promote rapid recovery. Based on the existing, relatively mature ultrafast-track anesthesia for CHD, this study further explored the application of lung ultrasound to optimize extubation conditions, improve the safety of ultrafast-track anesthesia, and enhance recovery after surgery.

2. Materials and methods

2.1. Sample size calculation

Calculating Sample Size Using PASS (V15.0.5) Software: For this study, a clinical randomized controlled trial will be conducted. The intervention group will receive optimized ultra-fast-track anesthesia (group L), while the control group will receive conventional ultra-fast-track anesthesia (group N). The outcome measure will be the LUS of the study subjects. Based on literature review and preliminary experimental results, the LUS in group N was estimated to be 15.86 ± 5.33. It was anticipated that LUS will exhibit a decrease of 4.7 points in group L compared to group N. With a bilateral $\alpha = 0.05$ and a power of 90 %, The results obtained from the PASS software indicated that each group requires a sample size of 27 individuals. In addition, factors in 10 % potential attrition, exclusions, etc, were taken into account. So it was determined that both the N group and L group would consist of 30 individuals. Therefore, the total sample size for this study will be 60 individuals.

2.2. General information

Sixty children with non-cyanotic CHD were selected under ultrafast-track anesthesia. Patients were divided into a lung ultrasound group (group L) and a normal group (group N) according to random numbers generated by a computerized random number table. Inclusion criteria: preoperative echocardiography examination was diagnosed as: Ventricular septal defect (VSD), atrial septal defect (ASD), patent ductus arteriosus (PDA), etc.; American Society of Anesthesiologists (ASA) grades I-III and cardiac function grades I-III. Exclusion criteria were cyanotic complex congenital heart disease surgery, non-cyanotic CHD with severe pulmonary hypertension, cardiac function above grade III, and expectation of requiring ventilator support after surgery. All patients were anesthetized by two anesthesiologists who were blinded to the specific grouping. Lung ultrasound and lung condition assessments were performed in all cases by one person who provided optimization treatment suggestions to anesthetists for group L. Lung ultrasound examination was then conducted, and the optimization effect was evaluated to guide the removal of the endotracheal tube.

2.3. Methods

2.3.1. Anesthesia method

After checking the basic information in the operating room, the GE Healthcare Finland Oy monitor was connected to monitor the heart rate (HR), SPO_2, electrocardiogram (ECG), and noninvasive blood pressure (BP) measurement. A general anesthetic was administered to all patients intravenously and by inhalation, in combination with endotracheal intubation. Anesthesia induction: Midazolam 0.1 mg/kg I.V., cisatracurium besylate Injection 0.1 mg/kg I.V., sufentanil Intravenous Injection 1 μg/kg I.V, propofol 2 mg/kg I.V. When the narcotic effect was favorable, and the patient's vital signs were stable, endotracheal intubation was performed and the appropriate ventilator parameters were subsequently adjusted. The pressure-controlled ventilation (PCV) mode was adopted for both groups of patients. The airway pressure was set at a tidal volume of 10 mL/kg. The respiratory rate was adjusted appropriately according to End-Tidal Carbon Dioxide ($ETCO_2$) to maintain $ETCO_2$ at 35–40 mmHg. Arterial puncture and catheterization were performed to monitor the invasively determined arterial blood pressure: systolic pressure (SBP) and diastolic pressure (DBP). Arterial blood gas analysis was used to record the arterial partial pressure of oxygen (PaO_2) and inhaled oxygen concentration (FiO_2) at the required time points. Right internal jugular vein puncture and catheterization were performed to monitor the central venous pressure (CVP). Anesthetic maintenance: sevoflurane 1–1.2 minimum alveolar effective concentration (MAC), remifentanil 0.2–0.3 μg/(kg·min) intravenous pumping, dexmedetomidine 0.5 μg/(kg·h) intravenous pumping. Depending on the progress of the surgery, cisatracurium besylate Injection or sufentanil Intravenous Injection was administered, and epinephrine, milrinone, isoprenaline, or other vasoactive drugs were administered depending on the patient's cardiopulmonary function. After surgery, the endotracheal tube was removed and the patients were sent to the CSICU for further treatment after the corresponding tests and treatment as required by the different groups.

2.3.2. ALP method of lung ultrasound for all cases

According to the ALP method [6], all 60 patients were examined and assessed by the same person using the M-Turbo Portable color ultrasound diagnostic (6–13 MHz). The patients underwent an ultrasound scan of each hemithorax and three major areas (anterior(A), lateral(L), and posterior(P)) delineated by the parasternal, anterior axillary, and posterior axillary lines (Fig. 1A). Each area can be divided into upper and lower half, creating 6 different quadrants for each hemithorax, namely anterior superior, anterior inferior, lateral superior, lateral inferior, posterior superior, and posterior inferior (Fig. 1B). Comprehensive lung ultrasound was performed in each region in three steps: Step 1 used lung ultrasound to scan each of the four regions of the anterior chest wall in the supine position; Step 2 was still in the supine position; the scan was extended from the anterior chest wall to the lateral chest wall, and the middle lung area was scanned; Step 3: The patient was lifted ipsilaterally and scanned in the posterior lung area.

2.3.3. *Lung ultrasound scoring method [7]*

The A- and B-lines can effectively assess the state of lung ventilation and lung recruitment; thus, the combination of the two will have four simple ultrasound signs of the lungs. (1) Normal A -line indicates that the pulmonary ventilation in this area is normal, record 0 point (Fig. 2A). (2) The independent presence of a single or multiple B lines, indicating that the lung ventilation in this area has decreased, and there may be interstitial pulmonary edema, which is recorded as 1 point (Fig. 2B and C). (3) B line fusion, pulmonary bronchial inflation sign, indicating that the ventilation of the lungs in the area is severely reduced, and there may be pulmonary edema or bronchial inflammation, recorded as 2 points (Fig. 2D and E). (4) Alveolar fusion, pulmonary consolidation, and atelectasis indicate the basic loss of pulmonary ventilation in this area, recorded as 3 points (Fig. 2F). Therefore, a higher LUS score indicates a worse ventilatory state of the lung. The sign of greatest severity was taken as the score of the area examined, and six areas were examined on each side of the lung so that the LUS score was between 0 and 36.

1.3.4 In a study on atelectasis, I.-K. Song et al. defined atelectasis as when the LUS $\geq$ 2 in any lung area. In this study, the LUS score 1 min after intubation was 11.5, the incidence of atelectasis was 45 %, the LUS before extubation after surgery was 15.0, and the incidence of atelectasis was 80 % [8]. Xu et al. considered patients with LUS <14 to have a low risk of extubation failure [9]. Soliman et al., who considered LUS >18 as high risk, showed that LUS predicted extubation success with a sensitivity and specificity of 91 % and 69 %, respectively, and an area under the curve (AUC) of 0.83 (CI: 0.75–0.91) [10]. Based on the above, we considered 15 points as the cut-off point in our study, which means that the tracheal catheter would not be removed with an LUS <15 in group L. When LUS $\geq$ 15 due to lung ultrasound signs such as atelectasis, lung consolidation, multiple fusion B lines, and pulmonary bronchial inflation sign detected by lung ultrasound in group L, even though they met the indications for extubation with ultrafast-track anesthesia, corresponding optimization measures should be taken accordingly.

2.3.3.1. Endotracheal sputum suctioning for group L [11]. The endotracheal sputum suctioning time should not exceed 15 s each time (suction negative pressure no more than 100 mmHg, i.e., 13.3 kPa), and the decrease in basic oxygen saturation, blood pressure, heart rates should not exceed 10 % of the basic value to avoid an impact on cardiac function and pulmonary function.

2.3.3.2. Manual hyperinflation (MH) [12,13], and sputum suction [14–16], guided by lung ultrasound for group L. MH was guided by ultrasound, and the manual pressure was adjusted to < 30 cm H_2O. MH was performed with slow and deep inspiration (2 s) to a peak, followed by an inspiratory pause (2 s) and a quick pressure release (1 s). Rest intervals of 1 s interspersed the MHI maneuvers until the collapsed lung area reopened for ventilation under ultrasound. After five MH sessions, sputum suction in the endotracheal tube was performed as required.

2.3.3.3. Fiberoptic bronchoscopic alveolar lavage for group L [17]. If necessary, a portable fibreoptic bronchoscope (model: F1–9BS, Japan) was used to perform alveolar lavage and sputum suction under direct vision (Fig. 3A, B, C). The fibrobronchoscope has a strong target and can reach the level of each lung segment and below. Sputum can be aspirated at a fixed point under direct vision, removing local secretions, sputum clots, blood clots, and blood from the patient, effectively improving the patient's lung ventilation, and helping to correct hypoxia and carbon dioxide retention. First, we use 37 °C normal saline at about 0.5 mL/kg each time to irrigate and soften the sputum thrombus in the lung or at the opening of the bronchial segment at the atelectasis site, and then we suck out the secretion under negative pressure suction (suction negative pressure 100 mmHg, i.e., 13.3 kPa). Before performing a bronchofiberscopy, the patient must have sufficient oxygen storage, and each irrigation operation should not exceed 2 min.

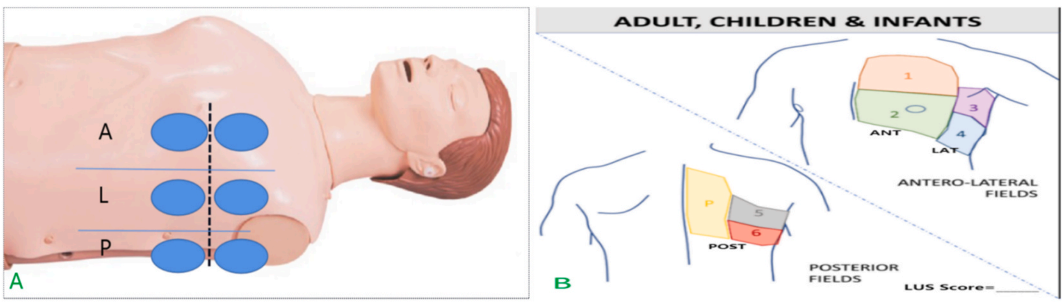

Fig. 1. Schematic Diagram of Lung Ultrasound ALP Division. (A) (B) The surface of each lung is divided into 6 areas，and the bilateral lungs are divided into 12 regions.

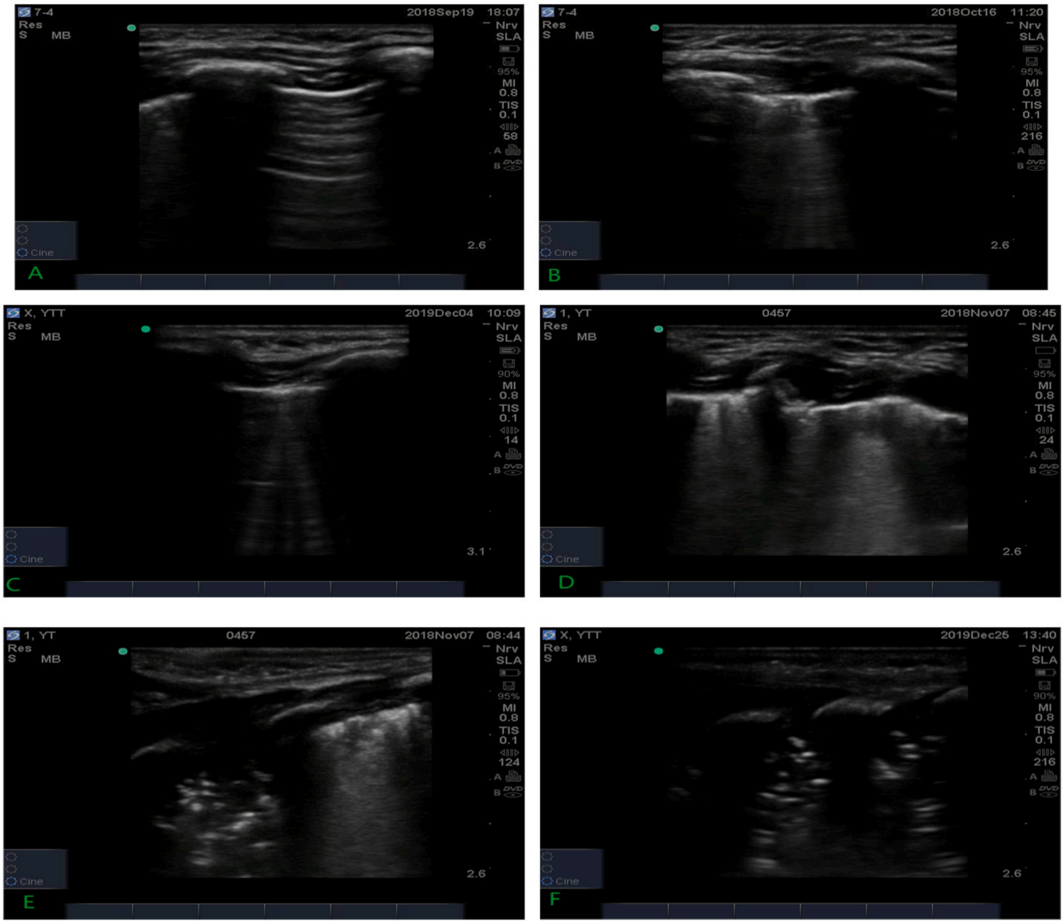

Fig. 2. Lung ultrasound scoring: (A) Normal A -line LUS = 0, (B) Independent presence of a single B-lines, LUS = 1 point, (C) Independent presence of multiple B-lines, LUS = 1 point, (D) B-Line Fusion LUS = 2 points, (E) Bronchial inflation sign, or B-Line Fusion LUS = 2 points, (F) Pulmonary consolidation or atelectasis LUS = 3 points.

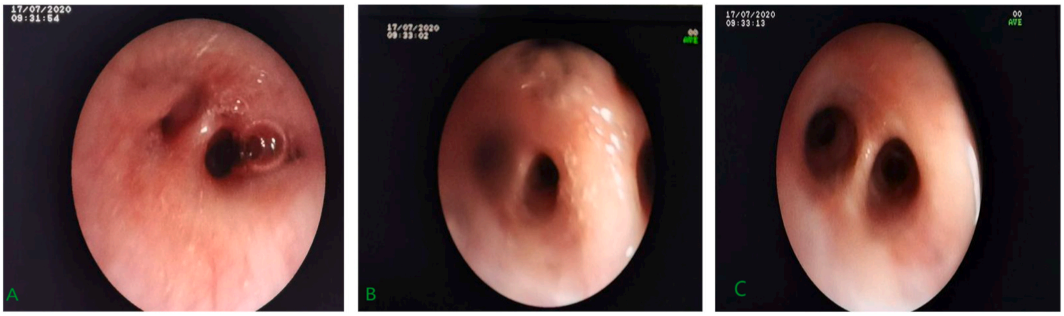

Fig. 3. (A) Before fiberoptic bronchoscope irrigation, there were many sticky secretions in the trachea, which are not easy to be sucked out , (B) Rinsed with saline to dilute the secretions, (C) The trachea was much cleaner after fiberoptic bronchoscope irrigation.

2.3.4. Optimal outcomes and assessment of lung ultrasound

With the optimization of lung recruitment for Group L, lung inspiratory and lung ventilatory functions can be improved, and the lung ultrasound image will change accordingly in group L (Fig. 4A, B, C, D, E).

2.3.5. Extubation indications for ultrafast-track anesthesia for all cases [18]

(1)Before and after extubation, the secretions remaining in the mouth, nose, throat, and trachea must be cleaned. Normal arterial blood gases, acid-base electrolyte balance, recovery of spontaneous breathing, and sufficient effective ventilation; (2) the patient's

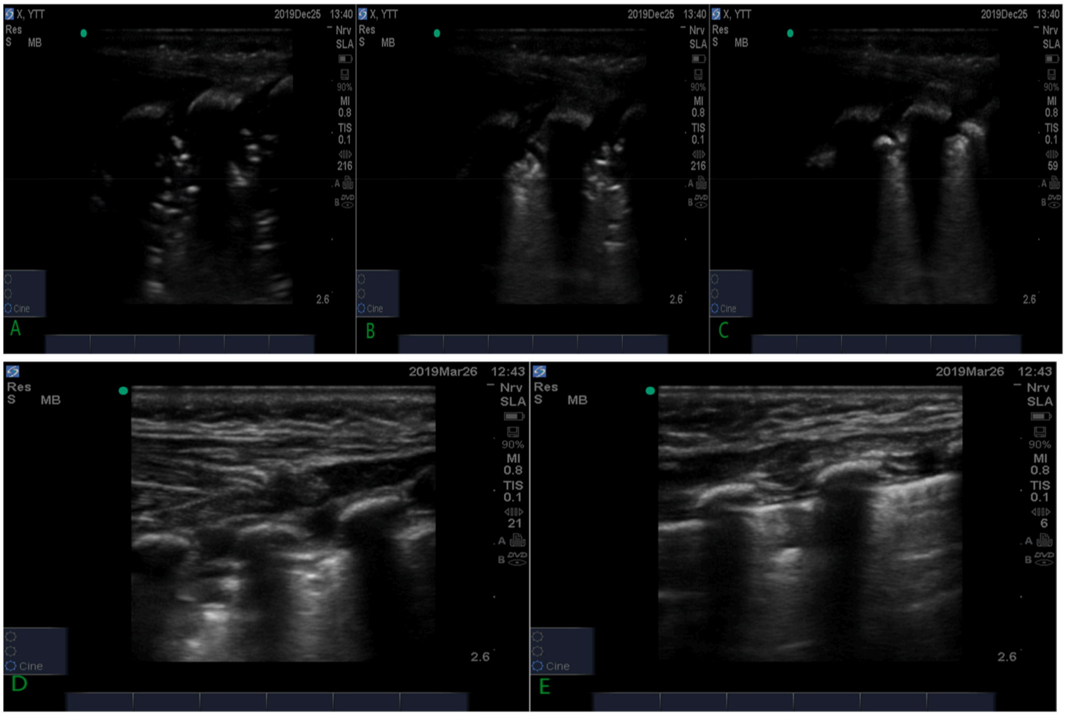

Fig. 4. (A) Before optimization of manual hyperinflation LUS = 3 points, (B) Under optimization of manual hyperinflation guided by ultrasound LUS = 2 points, (C) After optimization of manual hyperinflation LUS = 1 point, (D) Before optimization of endotracheal sputum aspiration LUS = 2 points, (E) After optimization of endotracheal sputum aspiration (A-line reappeared) LUS = 0.

consciousness recovered, and the residual effect of muscle relaxants disappeared or was reversed; (3) the respiratory inhibition of narcotic analgesics was eliminated; and (4) the cough and swallowing reflexes returned to normal, the amplitude and frequency of spontaneous respiration returned to the preoperative level, and the gas exchange volume returned to normal. $SPO_2 > 90$ % in the state of air inhalation for 5 min; (5) recovery of cough and swallowing reflexes; and (6) stable basic vital signs such as heart rate and blood pressure.

2.4. Observations

2.4.1. Main observation index

(1) By comparing the LUS between the two groups at different time points, the higher the LUS, the more likely it was to have pulmonary complications, such as increased pulmonary exudation, pulmonary interstitial edema, atelectasis, and pulmonary consolidation, resulting in poor pulmonary ventilation; (2) The incidence of postoperative pulmonary complications was compared between the two groups before and after surgery; (3) The correlation between LUS and P/F ratio was analyzed.

2.4.2. Secondary observation index

(1) The time from anesthetic withdrawal to tracheal catheter removal was compared between the two groups. (2) P/F ratio = PaO2/FiO2 at each time point in both groups. The P/F ratio is a vital index that enables organs and tissues to obtain sufficient oxygen to generate energy. A P/F value of <3 indicates pulmonary respiratory dysfunction. (3) LUS, Arterial partial pressure of oxygen (PaO2), and concentration of oxygen uptake (FiO2) were recorded during anesthesia induction (T0), before tracheal tube removal (T1), 5 min after tracheal tube removal (T2), 1 h after tracheal tube removal (T3), and 24 h after tracheal tube removal (T4) in both groups. (4) The preoperative diagnosis, operation name, blood transfusion volume, extracorporeal circulation time, aortic occlusion time, and incidence of positive pressure ventilation/re-intubation were also recorded.

2.5. Statistical methods

SPSS22.0 was used for data analysis. LUS and P/F indicators were expressed as mean ± SD. SNK-q test was used for pairwise comparison at each time point among the groups. T test was used for normal distribution data, *U* test was used for non-normal distribution data, $\chi 2$ test was used for percentage (%) of counting data, and bivariate correlation Spearman analysis was used for LUS and P/F, and scatter plots were drawn. Statistical significance was set at $P < 0.05$; the difference was statistically significant. The Kappa consistency test was used to determine the positive and negative consistencies of the LUS and X-ray images.

3. Results

3.1. General information

Table 1 presented that there were no significant differences in sex, age, weight, surgical diagnosis, intraoperative blood transfusion, or cardiopulmonary bypass time between the groups ($P > 0.05$). The time from anesthetic withdrawal to tracheal catheter removal between group L and group N was compared [(18.70 ± 5.42 min) vs. 13.47 ± 4.73 min), $P = 0.001$]. There was no significant difference in the incidence of positive pressure ventilation/re-intubation between the two groups ($P > 0.05$).

2.2 Spearman correlation analysis between LUS and the OI═PaO2/FiO2 (P/F) ratio of all 60 patients at each time point showed a strong negative correlation (Fig. 5A, B, C, D, E). $P < 0.05$.

3.2. Main observation index

Table 2 showed a comparison between preoperative (T0) and postoperative (T3) x-ray findings showed that the number of patients with worsened radiographic findings was lower in group L (18 cases, 60 %) than in group N (26 cases, 86.7 %), including increased lung exudation, multiple consolidation shadows in the lungs, and progressive pneumonia. The number of patients with improved x-ray findings in group L (12 cases, 40 %) was higher than that in group N (4 cases, 13.3 %), and the difference between the two groups was statistically significant ($\chi2 = 5.46$, $P = 0.02$). The number of patients with decreased LUS score in group L (15 cases, 50 %) was greater than that in group N (7 cases, 23.3 %), and the number of patients with increased LUS score in group L (15 cases, 50 %) was less than that in group N (23 cases, 76.7 %), the difference between the two groups was statistically significant ($\chi2 = 4.59$, $P = 0.032$).

3.3. Secondary observation index

Table 2 also showed that there were no significant differences in P/F and LUS between the two groups at T_0 and T_1. At T_2, T_3 and T_4, the P/F ratio in group L was significantly higher than that in group N, and the LUS in group L was significantly lower than that in group N ($P < 0.05$).

2.5 We compared improved vs worsened radiographic findings or increased versus decreased LUS according to radiographic examination and LUS between T_0 and T_3 showed in Table 3. Among the 60 patients, 44 had worsened radiographic findings, and the number of cases with increased LUS was 38. The sensitivity of LUS was 86.3 % compared to X-ray findings. Sixteen patients showed improved X-ray findings, whereas 22 patients showed decreased LUS findings. The sensitivity of LUS compared to radiographic findings was 72.7 %. The Kappa consistency test revealed a kappa value of 0.77.

2.6 LUS assessment of postoperative pulmonary complications compared with radiographic findings in all 60 patients Of the 60 patients, there was decreased LUS in 22 cases while there were improved X-ray findings in 16, and 38 had increased LUS while 44 had worsened X-ray findings. Receiver operating characteristic (ROC) curve analysis showed that LUS evaluated the incidence of lung complications in 60 cases, with an area under the curve (AUC) of 0.868 (95 % confidence interval:0.769–0.968, $P < 0.001$), a sensitivity of 86.3 %, and a specificity of 72.7 % (Fig. 6). This suggested that LUS was important in the evaluation of lung complications and that the larger the AUC, the greater the diagnostic efficiency of the test.

4. Discussion

The concept of Enhanced Recovery After Surgery (ERAS) advocates multidisciplinary collaboration based on evidence-based medicine and promotes postoperative rehabilitation of patients by optimizing perioperative management measures [19]. Rapid postoperative recovery after CHD surgery is also an important aspect of ERAS. One of the most critical steps after CHD surgery is the

Table 1
Preoperative and Postoperative clinical data Values were expressed as n (percentage, %) or (mean ± SD).

Characteristics	lung ultrasound group (group L) (n = 30)	normal group (group N) (n = 30)	*P*-value
Gender			0.302
male	0.302	19 (63.3 %)	
female	15 (50 %)	11 (36.7 %)	
	15 (50 %)		
Age (months)	15.67 ± 2.73	20.11 ± 4.22	0.380
Weight (kg)	8.97 ± 3.76	10.00 ± 5.30	0.124
Surgical Diagnosis			
VSD (cases)	22 (73.3 %)	20 (66.7 %)	
ASD (cases)	5 (16.7 %)	7 (23.3 %)	
PDA (cases)	3 (10 %)	3 (10 %)	
Intraoperative blood transfusion (ML)	52.67 ± 3.74	63.83 ± 5.92	0.058
Cardiopulmonary bypass (min)	67.53 ± 5.30	68.00 ± 5.13	0.815
Extubation time (min)	18.70 ± 5.42*	13.47 ± 4.73*	0.001
Incidence of positive pressure ventilation/re-intubation (cases)	2 (6.67 %)	6 (20 %)	0.260

*$P < 0.05$ when compared to group N, indicating statistical significance.

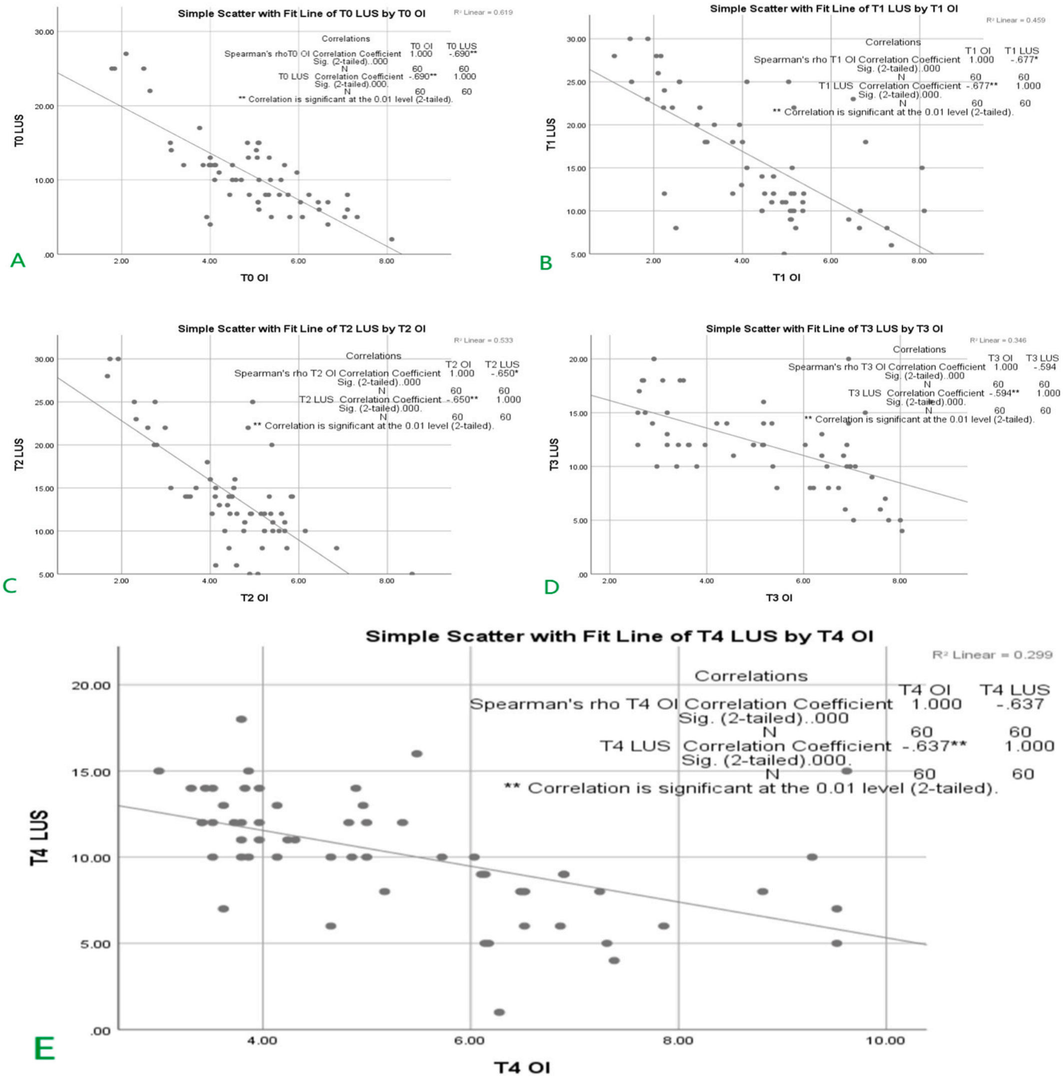

Fig. 5. Spearman correlation analysis and scatter plot between LUS and OI at each time point of all cases (n = 60). (A) Anesthesia induction (T_0), (B) before extubation (T1), (C) 5min after extubation(T_2), (D) 1 h after extubation (T_3), (E) 24 h after extubation (T_4).

Table 2
Comparison of P/F and LUS at T_0-T_4 under ultrafast-track anesthesia for congenital heart disease.

Characteristics	T_0	T_1	T_2	T_3	T_4	Positive(cases)	Negative(cases)
P/F ratio						improved x-ray findings	worsened x-ray findings
Group N	4.82 ± 1.32	4.35 ± 1.95	4.06 ± 1.26	4.64 ± 1.82	4.99 ± 1.98	4 (13.3 %)	26 (86.7 %)
Group L	4.94 ± 1.41	4.22 ± 1.45	4.85 ± 1.18*	5.74 ± 1.69*	5.70 ± 1.48*	12 (40 %)	18 (60 %)
Z/χ2- value	0.39	0.05	0.56	2.08	2.07	5.46	
P - value	0.695	0.959	0.05	0.04	0.04	0.02	
LUS						LUS decreased	LUS increased
Group N	11.23 ± 5.85	16.67 ± 7.01	16.60 ± 7.11	13.46 ± 3.62	11.3 ± 3.76	15 (50 %)	15 (50 %)
Group L	10.43 ± 5.02	15.57 ± 6.95	12.00 ± 3.64*	10.80 ± 3.69*	9.27 ± 3.62*	23 (76.7 %)	7 (23.3 %)
Z/χ2- value	0.45	0.56	2.73	2.43	2.19	4.59	
P - value	0.66	0.58	0.01	0.02	0.03	0.03	

*P < 0.05 when compared to group N, indicating statistical significance.

recovery of cardiopulmonary function, which requires multi-sectoral cooperation for good implementation [20]. The management of perioperative anesthesia in noncyanotic CHD has made great progress from conventional to fast-track and ultra-fast-track anesthesia. Under conventional ultrafast-track anesthesia, anesthesiologists perform extubation based on clinical experience and extubation

Table 3
LUS and X-ray examination at T_0 and T_3, consistency test between positive and negative results.

	worsened x-ray findings/increased LUS (cases)	improved x-ray findings/decreased LUS (cases)	Kappa consistency test Kappa-value	*P*-value
Cases (n = 60)			0.77	P = 0.001
X-ray	44 (73.3 %)	16 (26.7 %)		
LUS	38 (63.3 %)	22 (36.7 %)		

*P < 0.05 when compared to group N, indicating statistical significance.

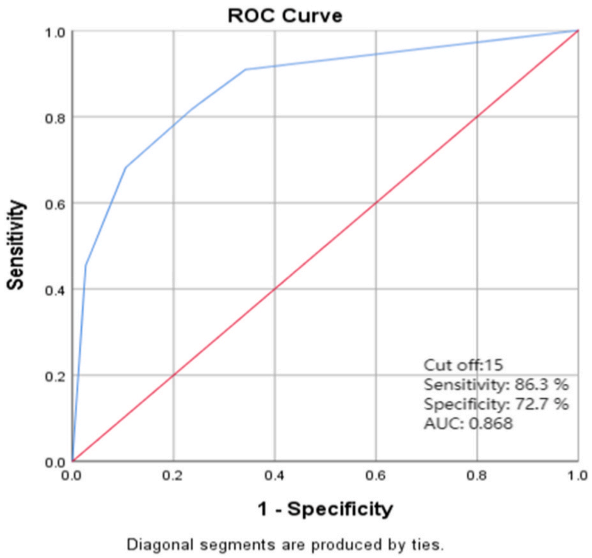

Fig. 6. ROC analysis of lung ultrasound score (LUS) to predict the occurrence of pulmonary complications.

indications. Although the technology is quite mature, there is a lack of objective and accurate assessments of lung recovery before and after extubation. Therefore, there are still some cases of increased pulmonary exudation, atelectasis, pulmonary consolidation, and other complications after tracheal catheter extubation. In these cases, because of the removal of the tracheal catheter, endotracheal sputum aspiration, manual lung recruitment, or other targeted and accurate treatments for pulmonary complications cannot be performed. Patients await self-absorption and recovery. Therefore, safety problems remain that can lead to failure of ultrafast track anesthesia in severe cases [21,22]. A study on early extubation strategies after congenital heart surgery by Simeonov et al. also showed that re-intubation was still necessary in 4.7 % of patients with early extubation due to respiratory reasons or hemodynamic instability [23]. Therefore, accurately determining the timing of extubation and reducing lung complications requires further exploration. With the extensive use of visualization techniques in clinical medicine, lung ultrasonography has attracted considerable attention in recent years. Lung ultrasound enables the timely, convenient, rapid, and effective evaluation of local and global lung ventilation.

This study further explored the application of lung ultrasound to optimize extubation conditions to ensure the efficacy and safety of ultrafast-track anesthesia. There were no significant differences in sex, age, weight, surgical diagnosis, intraoperative blood transfusion, or cardiopulmonary bypass time. Primary observational indicators were analyzed and compared with X-ray findings between postoperative (T_3) and preoperative (T_0) periods. According to the X-ray findings at T_3, lung conditions improved compared to those at T_0. The number of cases in Group L was greater than that in Group N. The number of cases of LUS that decreased at T_3 compared with that at T_0 in group L was also greater than that in group N ($P < 0.05$). This was because patients in Group L underwent lung ultrasound examination before extubation. For the cases with LUS $\geq$ 15 points due to B-line fusion, atelectasis or lung consolidation, targeted optimization treatment would be adopted, including endotracheal tube sputum aspiration, manual hyperinflation and sputum aspiration, ultrasound-guided lung recruitment, bronchoscopic alveolar lavage and other optimization treatments. The tracheal catheter was removed until LUS was <15 points, as evaluated by lung ultrasonography. Group L received targeted optimization guided by lung ultrasound to reopen the atelectasis to improve lung ventilation and lung gas distribution, reduce pulmonary shunts, and improve the ventilation-perfusion ratio, effectively increase lung compliance, and improve lung oxygen supply. Therefore, by analyzing the P/F and LUS scores at each time point, it was observed that before extubation (T_0 and T_1), there was no statistically significant difference in the P/F and LUS scores between the two groups ($P > 0.05$). However, after extubation (T_2, T_3, and T_4), the P/F in group L was higher than that in group N, whereas the LUS in group L was significantly lower than that in group N ($P < 0.05$). This could be reflected in the fact that after the adoption of the optimization measures, patients in Group L were able to achieve greater improvement in various ventilation metrics because of greater improvement in lung ventilation and oxygenation. However, owing to the need for comprehensive lung ultrasound examination and evaluation of both lung regions, the problems found need to be optimized accordingly.

Therefore, in terms of time comparison, the extubation time of group L was much longer than that of group N, $P < 0.05$.

A low oxygenation index (OI)$=PaO_2/FiO_2$ (P/F), precisely reflects lung injury. Whether the LUS of the two groups accurately reflects the lung conditions requires a correlation analysis between LUS and P/F. In this study, the LUS and P/F of the two groups at each time point presented a non-normal distribution; therefore, bivariate correlation Spearman analysis was conducted, and the results showed that the LUS of the two groups presented a significant negative correlation at each time point ($P < 0.05$), indicating that the higher the LUS, the lower the P/F, that is, the worse the lung oxygenation condition. It was confirmed that LUS magnitude calculated using LUS can accurately and effectively evaluate pulmonary ventilation and oxygenation in patients with congenital heart disease during the perioperative period under ultrafast track anesthesia.

As the application of lung ultrasound has become increasingly extensive, it has gradually become an alternative to CT or X-ray owing to its advantages of convenience, speed, lack of radiation, and simple operation. The sensitivity and accuracy of lung ultrasound diagnosis have also been widely recognized [24–26]. We demonstrated the objectivity and accuracy of LUS for the diagnosis of lung conditions in 60 patients. In this study, we compared radiographic findings and LUS between the postoperative (T_3) and preoperative (T_0) periods. Among the 60 patients in total, 44 had worsened radiographic findings, while 38 had increased LUS findings. The sensitivity of LUS was 86.3 % compared with X-ray findings. Sixteen patients showed improved X-ray findings, whereas 22 patients showed decreased LUS findings. The sensitivity of LUS compared to radiographic findings was 72.7 %. A Kappa consistency test showed a kappa value of 0.77, indicating good consistency between the diagnostic results of lung ultrasound and radiography. The results of ROC curve analysis in this study showed that the AUC was 0.868 (95 % confidence interval:0.769–0.968, $P < 0.001$), sensitivity was 86.3 %, and specificity was 72.7 %, indicating that lung ultrasound could effectively detect lung consolidation, atelectasis, or other lung complications, and its diagnostic sensitivity and accuracy were both high, similar to the results of a study by Wang et al. [27].

It should be pointed out that we expected initially that on-table extubation could result in decreased CICU stay and hospital stay. However, we found that due to process of clinical diagnosis and treatment factors, patients were typically transferred to the general ward the following day, regardless of when they were sent to the CICU. Therefore, when calculating the length of stay in the CICU and hospital, it did not accurately represent the actual time required for patients to remain in the CICU.

Conclusion: 1. Lung ultrasonography can be used to effectively assess the pulmonary condition of children with CHD during perioperative procedures. 2. Optimization of lung ultrasound under ultrafast-track anesthesia for noncyanotic CHD can significantly reduce postoperative lung complications, improve postoperative lung imaging findings, and contribute to the postoperative rehabilitation of patients, which is worthy of clinical application.

Disadvantages: (1) Lung ultrasound itself has certain limitations: on the one hand, lung ultrasound is a surface imaging technology, can only find surface lesions, not effectively find those deep lung tissue lesions covered by more superficial areas of good ventilation, and the feasibility of performing detailed lung ultrasounds intraoperatively within workflow constraints as another potential limitation; On the other hand, it takes a long time to perform a full and detailed lung ultrasound for each segment. We believe that, as technology matures and experience accumulates, time taken will improve considerably. (2) Visualization technology is the trend and hotspot of perioperative anesthesia management, but the application of lung ultrasound in the operating room and perioperative anesthesia management is still in the exploratory stage, including the understanding of the principle of lung ultrasound, and the experience needs to be further improved. (3) Although this study proved that optimization measures under the guidance of lung ultrasound could effectively improve the efficacy and safety of ultrafast-track anesthesia, almost 50 % of the 30 patients in group L had increased LUS scores (i.e., negative results). This suggests that there is still much room for improvement in the optimization effects of optimized treatment measures, such as manual lung sputum aspiration, ultrasound-guided lung recruitment, and bronchoscopic alveolar lavage. More efficient optimization approaches are also discussed.

Ethics declarations

This study was reviewed and approved by the Clinical Trial and Biomedical Ethics Committee of Shenzhen Children's Hospital, Guangdong, China, with the approval number: No-2018028.

All patients (or their proxies/legal guardians) provided informed consent to participate in the study.

All patients (or their proxies/legal guardians) provided informed consent for the publication of their anonymised case details and images.

Data availability statement

Data included in article/supplementary material/referenced in article.

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Yuetao Xie: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Lin Ma:** Writing – original draft, Investigation, Data curation, Conceptualization. **Huatian Lin:** Writing – original draft, Software, Methodology, Investigation. **Caiqi Yang:** Writing – original draft, Methodology, Data curation. **Xueqing Wang:** Writing – original draft, Methodology, Data curation. **Taohua Peng:** Writing – original draft, Methodology, Data curation. **Lixin Wu:** Writing – original draft, Methodology, Data curation. **Fang Chen:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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