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Effect of visual lung recruitment manoeuvres guided by trans-oesophageal lung ultrasound on atelectasis after thoracoscopic lobectomy: a randomised, single-blind, prospective study

Furong Bai[1], Mingliang Yi[1], Min Cai[1], Cong Zhao[1], Xujie Jiang[1] and Hong Yin[1*]

Abstract

Background Although the incidence of postoperative atelectasis could be reduced using lung recruitment manoeuvres, it remains high. We hypothesised that intraoperative visual lung recruitment guided by trans-oesophageal lung ultrasound would be more effective than the conventional method for managing postoperative atelectasis.

Methods In this randomised**,** controlled, prospective study, 84 patients undergoing thoracoscopic lobectomy were recruited from Affiliated Chengdu Fifth People's Hospital (teaching hospital) in China. Patients were grouped into trans-oesophageal lung ultrasound-guided (Group G, $n=42$) and control (Group C, $n=42$) groups.

Methods Lung recruitment was performed after anaesthesia induction, before chest closure and before the endotracheal tube extubation. In Group C, recruitment pressure was controlled at 30 cm H_2O for 10 s (performed thrice); in Group G, the pressure was controlled at 30 cm H_2O (performed thrice), and the tidal volume did not exceed 20 ml kg^{-1} until no atelectasis was detected by trans-oesophageal ultrasound. The primary outcome was lung ultrasound scores measured at the post anaesthesia care unit 30 min after extubation. The secondary outcomes included the oxygenation index (30 min after extubation) and the incidence of atelectasis (30 min after extubation and 3 days after surgery).

Results The final analysis included 79 patients. The lung ultrasound score was significantly higher in the control group than in the ultrasound-guided group 30 min after extubation (Group C vs. Group G, 8.6 ± 2.6 vs. 6.5 ± 2.0, $P<0.001$). No significant difference in the oxygenation indexes 30 min after extubation was observed between the groups ($P=0.074$); however, the incidence of atelectasis 30 min after extubation significantly differed between the two groups (Group C vs. Group G, 57% vs. 33%, $P=0.031$). The incidence of atelectasis 3 days after surgery did not significantly differ between the two groups (Group C vs. Group G, 45% vs. 28%, $P=0.122$).

Conclusions Lung recruitment guided by trans-oesophageal lung ultrasound can reduce lung ultrasound scores and the incidence of atelectasis at the post anaesthesia care unit 30 min after extubation. However, it does not significantly reduce the incidence of atelectasis 3 days after surgery.

Trial registration Registration number: ChiCTR2200062509. Registered on 10 /8/ 2022.

Keywords Recruitment, Lung ultrasound, Atelectasis, Thoracoscopic

*Correspondence:
Hong Yin
yinhong0912@cdutcm.edu.cn
Full list of author information is available at the end of the article

Background

Despite recent advancements in thoracoscopic surgery, one-lung ventilation can increase postoperative pulmonary complications [1]. Postoperative atelectasis is one of the most common postoperative pulmonary complications in surgical patients and serves as the pathophysiological basis for other postoperative pulmonary complications [2]. The incidence of postoperative atelectasis after general anaesthesia is 68–90% [3, 4]. Considering that atelectasis affects patient recovery and prolongs hospital stays, preventing and reducing postoperative pulmonary complications is crucial [5, 6]. Lung recruitment manoeuvres (LRMs) can reduce the incidence and extent of atelectasis during general anaesthesia [7]. However, remarkable differences exist among LRM techniques, including the optimal volume, time, and methods for recruitment [8, 9], therefore, the optimal choice for LRM remains unclear [5, 8]. The conventional LRMs mainly depend on clinical experience, which cannot provide monitoring and evaluation of the real-time effects. Furthermore, there are related risks of barotrauma and volume injury attributed to excessive recruitment or atelectasis and hypoxemia attributed to inadequate recruitment. Therefore, verifying the application of visual lung protection technology during the perioperative period can help improve LRMs, reduce postoperative pulmonary complications, and enhance recovery after surgery.

Transthoracic lung ultrasound can accurately evaluate lung ventilation and diagnose atelectasis during the peri-operative period [10, 11]. The higher the scores, the more severe the aeration loss, and the severity of atelectasis can be indirectly assessed using lung ultrasound (LUS) scores [10, 11]. The effect of LRM guided by transthoracic LUS is better than that of conventional LRM [8, 12]. However, transthoracic LUS is affected by surgical incision and aseptic requirements during thoracic surgery and cannot be completed in real-time by dynamic monitoring. Some case reports on trans-oesophageal LUS (TE-LUS) examination [13, 14] suggest that it can evaluate heart and lung conditions and provide an imaging basis for intra-operative diagnosis and treatment decisions without affecting the surgical procedure. Our pilot study showed TE-LUS-guided LRM to be feasible: when the lung collapsed under thoracoscopy, lung consolidation could be seen on oesophageal ultrasound. However, after conventional LRM, oesophageal ultrasound showed that the lung was not fully re-expanded, but returned to preoperative lung image after oesophageal ultrasound-guided recruitment. (Fig. 1). We hypothesised that LRM guided by TE-LUS is more effective than conventional LRM and can reduce LUS scores and the incidence of atelectasis. This study aimed to evaluate the effect of TE-LUS-guided LRM on atelectasis after thoracoscopic lobectomy and provide a scientific basis for lung protective ventilation strategies in patients undergoing thoracoscopic lobectomy.

Methods

Study design

This single-centre, patient and assessor-blinded randomised controlled trial evaluated the advantages of TE-LUS-guided LRM. The study was approved by the Ethics Committee of the Chengdu Fifth People's Hospital (approval no: 2022–028 -01; approval date: 5 / 7 / 2022). It was prospectively registered with the Chinese Clinical Trials Registry (No: ChiCTR2200062509; date: 10 /8 /2022). The study was conducted at the Chengdu Fifth People's Hospital.

Fig. 1 Trans-oesophageal lung ultrasound images in different states. Trans-oesophageal lung ultrasound images in different states Left-lung oesophageal lung ultrasound image. **A** Consolidation appears after the lung collapses; **B** After conventional recruitment, the lung is not fully re-expanded; **C** After recruitment guided by oesophageal lung ultrasound, the lung image is restored to the preoperative status

Participants

Between August 2022 and May 2023, 79 patients scheduled for thoracoscopic lobectomy were enrolled. Written informed consent was obtained from all participants the day before surgery.

The inclusion criteria were an age of 18–65 years, body mass index of 18–30 kg/m^2, and American Society of Anesthesiologists (ASA) Physical Status I to III. The exclusion criteria were contraindications to the placement of oesophageal ultrasound; a history of pulmonary bullae, pneumothorax, pleural effusion, severe chronic obstructive pulmonary disease (COPD), or previous intrathoracic surgery; patient's refusal to participate; or inability to communicate. Withdrawal criteria included conversion to thoracotomy; study procedures not strictly performed; excessive interference in the ultrasound image; or unstable haemodynamics (heart rate and blood pressure fluctuated 20% above baseline despite the use of fluids and vasoactive agents).

Randomisation

SPSS 26.0 was used to generate random numbers assigned to groups in a 1:1 ratio, and sequential numbers were assigned and sealed in opaque envelopes by the corresponding author. The envelopes were only opened by anaesthesiologists once the patients had entered the operating rooms.

Blinding method

The study was blinded to patients, evaluators, and data collectors. Participating anaesthesiologists were aware of group allocation; however, they were not involved in data collection and statistical analyses.

Anaesthesia and monitoring

Preoperative preparation, anaesthesia induction, and maintenance were standardised and identical in the two groups. Anaesthesia was induced by 0.3 μg kg^{-1} sufentanil, 1.0 mg kg^{-1} rocuronium, 1.5–2 mg kg^{-1} propofol, 1–2 μg kg^{-1} remifentanil, and 0.1 μg kg^{-1} sufentanil administered before the skin incision. Remifentanil (0.05–0.2 μg kg^{-1} min^{-1}) was pumped intravenously, sevoflurane (1–2%) was inhaled, and rocuronium 0.3 mg kg^{-1} was injected intravenously when necessary for anaesthesia maintenance. The bispectral index was maintained at 40–60 during the procedure. Lactated Ringer's solution of 5–10 ml kg^{-1} h^{-1} was infused during surgery, and the colloid solution was infused if intra-operative blood loss exceeded 400 ml (colloid solution / blood loss ratio of 1:1). Urapidil, phenylephrine, and ephedrine were administered intraoperatively to maintain blood pressure within 20% of the baseline. When the heart rate was less than 45 beats min^{-1}, 0.5 mg atropine was administered intravenously.

Ventilation settings were as follows: volume control mode, tidal volume of 6 ml kg^{-1} of the predicted body weight for one-lung ventilation and 8 ml kg^{-1} for double-lung ventilation, ventilation rate of 12–18 breaths min^{-1} to maintain $PETCO_2$ at 35–45 mmHg, inspiratory/expiratory ratio of l:2, and 5 cmH_2 O PEEP.

Intravenous granisetron of 3 mg (to prevent vomiting), intravenous ketorolac tromethamine of 30 mg, and dezocine of 5 mg for pre-emptive analgesia were administered 30 min before the end of surgery. Patients received unified patient-controlled analgesia after surgery (self-controlled dose of 1 μg sufentanil and 1 mg ketorolac tromethamine, lock time 30 min, maintenance dose of 2 μg h^{-1} sufentanil and 2 mg ketorolac tromethamine). After surgery, the patients were sent to the post anaesthesia care unit, and the transthoracic LUS score was recorded 30 min after extubation. If the postoperative visual analogue scale scores (0 = no pain, 10 = worst pain) exceeded 3, intravenous 1 mg butorphanol was administered.

Study intervention

Eighty-four patients undergoing thoracoscopic lobectomy were randomly divided into two groups at a 1:1 ratio: a conventional LRM control group (Group C) and a TE-LUS-guided LRM group (Group G). The LRM time points were after the induction of anaesthesia, before closing the chest, and before extubation. The LRM method was as follows: in Group C, the pressure was controlled at 30 cm H_2O for 10 s, performed a total of three times; in Group G, the pressure was controlled at 30 cm H_2O, and the tidal volume did not exceed 20 ml kg^{-1} until no atelectasis was found by trans-oesophageal ultrasound, also performed a total of three times. The LRM was stopped immediately when the heart rate or mean arterial pressure fluctuated more than 20% of the baseline value or an arrhythmia occurred. Arterial blood gas was measured before extubation. The oxygenation index (OI, the ratio of PO_2 to FiO_2) and arterial pressure of carbon dioxide ($PaCO_2$) were recorded. LUS score and arterial blood gas measurements were performed 30 min after extubation. Chest computed tomography (CT) was performed 3 days after surgery, and atelectasis and other postoperative pulmonary complications were recorded.

LUS scoring method

A sonoacoustic ultrasound convex array probe was used for transthoracic LUS, as reported in the literature[8, 15, 16] The lungs were divided into 12 regions based on the nipple horizontal line, anterior axillary line, and posterior axillary line. Each region was scored from 0 to 3 points, and the sum of the scores of the 12 examination areas was the LUS score (0–36 points) (Table S1). The higher the score, the more severe the aeration loss. The LUS score was determined by two physicians with more than 1 year of experience who were blinded to the group assignments. When more than three sections (approximately 25% of total lung surface) showed any ultrasonographic sign of atelectasis (atelectasis score of ≥ 1), clinical atelectasis was considered to have occurred [15].

Definition of postoperative pulmonary complications
Postoperative pulmonary complications included atelectasis, pneumonia, acute respiratory distress syndrome, pulmonary aspiration, pleural effusion, and pneumothorax [16, 17].

Study outcomes
The primary outcome was the LUS score 30 min after extubation. The secondary outcomes included OI before extubation and 30 min after extubation, the incidence of atelectasis diagnosed by thoracic CT 3 days after surgery, the time interval for postoperative drainage tube removal, and the length of postoperative hospital stay.

Statistical analyses
The LUS score was assumed to be 9.2 (1.42) based on previous studies [11, 12]. We assumed that LRM guided by ultrasound reduced LUS by at least 1 point. Thus, we expected an LUS score of 8.2 (1.42) in the ultrasound-guided group. With a significance level of 5% (two-tailed) and a power of 80%, 33 patients were required in each group. Considering the 20% dropout rate, 84 patients were enrolled.

Categorical variables are reported as frequencies with proportions. Continuous variables are presented as mean with standard deviation or median (interquartile range, IQR). The normal distribution of data was evaluated using the independent sample t-test. The non-normal reported variables were calculated using the nonparametric test. Statistical significance was set at $P < 0.05$.

The primary outcome (LUS scores 30 min after extubation, normal distribution) was presented as mean with standard deviation, analysed using an independent sample t-test, Similar analyses were performed for other normal distribution data, such as heart rate (HR), mean blood pressure (MBP), peak airway pressure (*P*peak), OI 30 min after extubation, and $PaCO_2$ at the end of surgery. The other non-normal distributed data were analysed using the Mann–Whitney U test, presented as median (IQR). The incidence of atelectasis was analysed using the χ^2 test.

Results
Study patients
Ninety-six patients were assessed for eligibility between August 2022 and May 2023. Twelve patients were excluded because of surgery cancellation ($n=4$) or refusal to participate ($n=8$). The remaining 84 patients were randomly assigned to the treatment groups. Five patients dropped out of the study: one in each group owing to open conversion, two in the ultrasound-guided group owing to issues with ultrasound images, and one owing to unplanned reoperation. Finally, the data of 79 patients were analysed (Fig. 2). No patient experienced study-related adverse events. The two groups had no significant differences in baseline characteristics, ventilation data, and surgical data (Table 1).

Primary outcome
The LUS scores were higher in Group C than in Group G 30 min after extubation (Group C vs. Group G, 8.6 ± 2.6 vs. 6.5 ± 2.0, $P < 0.001$). In the posterior side between the two groups was most significant ($P < 0.001$). The OI 30 min after extubation was lower in Group C than in Group G (389 [52] vs. 407 [37]; $P=0.07$). The incidences of atelectasis diagnosed by lung ultrasonography in Group C and Group G were 57% and 33% ($P=0.031$), respectively. The incidences of atelectasis diagnosed by CT 3 days after surgery in Group C and Group G were 45% and 28% ($P=0.122$), respectively (Table 2).

Other outcomes
No significant differences were noted in the ventilation and circulation indexes, drainage tube placement time, length of postoperative hospital stay, and other postoperative complications between Groups C and G (Table S2). None of the 79 patients received ventilator support. The beneficial effect persisted, indicating that TE-LUS-guided LRM reduced the LUS score even after a post-hoc sensitivity analysis considering variables that may influence the LUS score (age, preoperative pulmonary function, body mass index, ASA physical status, or duration of surgery (Table S3). There was no significant difference in hoarseness and sore throat between the two groups. No severe TEE-related complications such as oesophageal injury, aspiration pneumonia, and dysphagia occurred in Group G; only one case had mild damage to the palate.

Discussion
The LUS score and the incidence of atelectasis diagnosed 30 min after extubation were markedly different between the control and TE-LUS-guided groups, consistent with the findings of a previous study [15]. However, the incidence of atelectasis 3 days after surgery was not

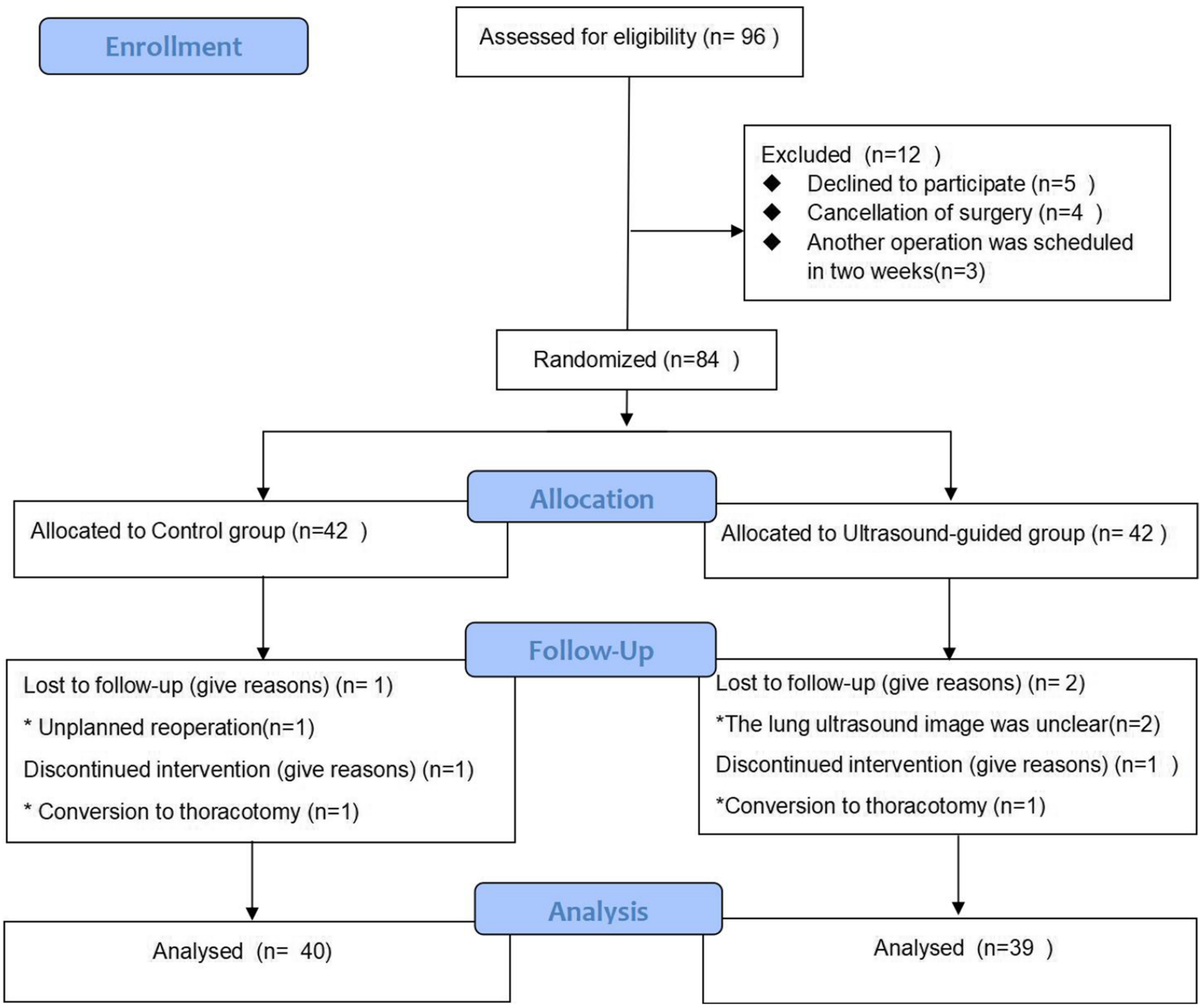

Fig. 2 Study flow diagram

significantly different between these two groups, which is inconsistent with previous findings [15]. This may be attributed to the following reasons. First, the sample size was small. Second, the criteria for diagnosing atelectasis differ and the approach to LRM is also different. Third, before extubation after LRM, the two groups underwent mechanical ventilation again, which may have caused alveolar collapse. Finally, chest CT was performed on the third postoperative day; thus, many patients with atelectasis may have recovered spontaneously.

LRMs can reduce the incidence and extent of atelectasis during general anaesthesia [7].However, these manoeuvres have obvious individual differences (different patients need different volumes, times, and methods for recruitment) [8, 9]. Transthoracic LUS-guided lung recruitment has been used in clinical practice [12, 18], and its effectiveness has been proven. Perioperative atelectasis usually involves a small range of lung tissue and is difficult to identify on a standard chest radiograph [19]. Compared to chest radiography and clinical tests, LUS has more advantages in the diagnosis and early detection of perioperative atelectasis [20]; moreover, LUS had a sensitivity of 92% and specificity of 92% in diagnosing consolidation [21]. However, performing transthoracic LUS is inconvenient owing to the interference of thoracic surgery. Oesophageal ultrasound provides preliminary understanding in lung examination [13, 14, 22] and can detect pulmonary conditions, such as pleural effusion, pneumothorax, and atelectasis. Thus, we used oesophageal ultrasound to guide lung recruitment, which is not limited by the operation and aseptic principle of the surgical site and can effectively avoid the disadvantages of transthoracic ultrasound to guide lung recruitment during thoracic surgery. Our study also demonstrated

Table 1 Paricipants'baseline characteristics, ventilation data, and operative data

Variables	Group C, *n* = 42	Group G,*n* = 42
Sex(male)	16(38%)	17(40%)
Age(yr)	54[44 to 59]	55[49 to 58]
ASA Physical Status ≥ III	9(21%)	8(19%)
body mass index(kg/m^2)	23.3 ± 2.7	23.1 ± 2.5
Smoking history	6(14%)	8(19%)
Comorbid condition		
Diabetes mellitus	4(10%)	4(10%)
Hypertension	9(21%)	5(12%)
cardiovascular diseases	4(10%)	3(7%)
Heart rate(beats/min)	73 ± 8	70 ± 9
Mean arterial pressure(mmHg)	85[81 to 93]	84[78 to 91]
Peak airway pressure(cm H_2O)	16 ± 2.3	16 ± 2.1
end-tidal carbon dioxide pressure(mmHg)	40 ± 3.6	39 ± 2.8
Duration of surgery(min)	150[120 to 181]	165[120 to 187]
Type of surgery		
Lobectomy	25(60%)	24(57%)
Radical resection	17(40%)	18(43%)
estimated blood loss(ml)	50[20 to 90]	50[20 to 100]
Intraoperative fluid infusion(ml/min)	1600[1100 to 1700]	1600[1100 to 1700]

ASA American Society of Anesthesiologists

* All data presented as mean (standard deviation), n (%), or median [interquartile range]

Table 2 Main outcomes and other related indicators of patients

Variables	Group C, *n* = 40	Group G,*n* = 39	*P* value
Lung ultrasound scores 30min after extubation			
Lung consolidation score	5.2 ± 2.1	3.4 ± 2.2	0.001
B-lines score	4[3 to 6]	4[2 to 5]	0.601
Lung ultrasound scores	8.6 ± 2.6	6.5 ± 2.0	0.000
Anterior	1[0 to 2]	1[0 to 2]	0.249
Lateral	3[2 to 4]	3[2 to 3]	0.056
Posterior	4[3 to 5]	3[2 to 4]	0.000
OI 30 min after extubation	389 ± 52	407 ± 37	0.074
PCO2 30 min after extubation	43 ± 5.7	42 ± 4.6	0.094
Atelectasis diagnosed by lung ultrasonography	23(57%)	13(33%)	0.031
Atelectasis diagnosed by CT of chest	18(45%)	11(28%)	0.122

OI Oxygenation index, *PaCO2* Arterial partial pressure of carbon dioxide

* Data are presented as mean (standard deviation), n(%), or median [interquartile range]. Independent sample t-test was used for Lung consolidation score, Lung consolidation score,Lung ultrasound scores, OI and PaCO2; Rank sum test was used for the other lung ultrasound scores; Pearson's chi-square test was used for the incidence of atelectasis

that LRM guided by TE-LUS is feasible: when the lung collapsed under thoracoscopy, we scanned the consolidation image using oesophageal ultrasound; when the lung was recruited, oesophageal ultrasound could capture the image of the lung before the collapse.

This study demonstrated that although visual lung recruitment improved early lung ventilation in the post anaesthesia care unit, it did not significantly improve the incidence of postoperative pulmonary complications 3 days after surgery. This could be attributed to the following reasons. First, lung recruitment may cause barotrauma and volutrauma, and the clinical symptoms caused by the trauma may be delayed. Second, exposure to high concentrations of oxygen increases the risk of atelectasis [23–25]. Some patients may not be able to maintain oxygenation above 90% during one-lung ventilation; therefore, there is a need to increase inhaled oxygen concentration. Third, the oesophageal ultrasound probe was inserted through the mouth, which may cause throat injury and infection, leading to pulmonary complications [26]. In this light, TE-LUS is not mandatory or commonly applied during thoracic surgery and not all the anaesthetists are able to perform this kind of advanced exam. There was no significant difference in hoarseness and sore throat between the two groups. No severe TE-LUS-related complications such as oesophageal injury, aspiration pneumonia, and dysphagia occurred in Group G. Only one case had mild damage to the palate. The possible reason for this good result is that we have optimised its use, the inclusion of patients with healthy lungs, the use of a newer smooth probe rather than a rough old probe, the use of a "two-handed jaw thrust manoeuvre" to reduce insertion resistance, and the exclusion of high-risk populations.

A few studies have examined oesophageal LUS and its role in lung protective ventilation. We demonstrated the feasibility and advantages of TE-LUS in diagnosing atelectasis under intraoperative direct vision. Our study found that the most effective area of TE-LUS was in the posterior (gravity-dependent region—where atelectasis is most likely to occur). TE-LUS avoids the disadvantages of empirical lung recruitment and does not affect the procedure; moreover, it can dynamically monitor the heart and lungs in real time. Furthermore, we speculate that TE-LUS will provide insights for the intraoperative diagnosis of atelectasis in the future and provide a basis for visual lung protection, especially for obese and older patients and those with heart diseases.

The LUS scores range from 0 to 36, with higher scores indicating more severe aeration loss. The LUS scores of the experimental and control groups were 8.6 ± 2.6 and 6.5 ± 2.0 respectively, which were lower than those in patients with severe pneumonia but slightly higher than those in patients undergoing non-thoracic surgery [15, 27]. The higher LUS scores compared with those in patients with non-thoracic surgery could be attributed to the lung injury being caused by the surgery; moreover, thoracic surgery had higher lung recruitment pressure than non-thoracic surgery, which may have caused barotrauma. The lower LUS scores compared with those in patients with severe pneumonia could be attributed to the exclusion of patients with severe pulmonary dysfunction and the enrolment of young and non-obese patients with low risk of pulmonary complications.

This study has certain limitations. First, this study was a small single-centre study. Second, transthoracic LUS and TE-LUS depend on the clarity of the ultrasound machine, the surgeon's skill, and patient cooperation. TE-LUS is affected by the spine, heart, and air, and transthoracic lung ultrasound is affected by the heart, liver, subcutaneous fat or gas, drainage tube, and operation. These factors may have affected the accuracy of the ultrasound diagnosis. Third, this study was performed in young patients with healthy lungs who were at relatively low risk for postoperative pulmonary complications. Therefore, it is unclear whether TE-LUS-guided lung recruitment is more clinically valuable in high-risk patients with COPD, obesity, and older age.

Conclusions

In conclusion, lung recruitment guided by TE-LUS during thoracoscopic lobectomy reduced the LUS scores and the incidence of early postoperative atelectasis (especially the posterior region). Whether it can reduce the incidence of long-term atelectasis needs to be confirmed by a larger sample. Future studies should use large sample sizes and conduct validation studies in high-risk patients, such as those with COPD, older age, or obesity, to reduce postoperative pulmonary complications and improve patient prognosis.

Abbreviations

ASA	American Society of Anesthesiologists
COPD	Chronic obstructive pulmonary disease
CT	Computed tomography
HR	Heart rate
IQR	Interquartile range
LRM	Lung recruitment manoeuvre
LUS	Lung ultrasound scores
MBP	Mean blood pressure
OI	Oxygenation index
$PaCO_2$	Arterial pressure of carbon dioxide
*P*peak	Peak airway pressure
TE-LUS	Trans-oesophageal LUS

Supplementary Information

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Supplementary Material 1. Lung ultrasound scoring system.

Supplementary Material 2. Other outcomes of Participants.

Supplementary Material 3. Logistic Regression Analysis of Factors Associated with LUS score.

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Authors' contributions

F.B-Methodology, Supervision, Formal analysis, Writing-original draft. M.Y-Methodology, Supervision, Writing-original draft. M.C-Investigation, Data curation. C.Z-Formal analysis. X.J- Supervision, Data curation. H.Y-Conceptualization, Methodology, Writing - review & editing.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was approved by the ethics committee of Chengdu Fifth People's. Hospital with approval number(2022–028(Study)-01). All patients have given informed consent to participate in the trial.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Anesthesiology, Chengdu Fifth People's Hospital, 33 Mashi, Road, Wenjiang District, Chengdu 611130, China.

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