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Research article

Effect of recruitment manoeuvres under lung ultrasound-guidance and positive end-expiratory pressure on postoperative atelectasis and hypoxemia in major open upper abdominal surgery: A randomized controlled trial

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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

Background: Postoperative pulmonary complications (PPCs) especially atelectasis and hypoxemia are common during abdominal surgery. Studies on the effect of either recruitment manoeuvres (RMs) or positive end-expiratory pressure (PEEP) on PPCs are controversial. The objective of this study is to evaluate the effect of perioperative lung ultrasound (LUS)-guided RMs combined with PEEP on the reduction of postoperative atelectasis and hypoxemia in major open upper abdominal surgery.

Methods: In this randomized controlled trial, 122 adult patients undergoing major open upper abdominal surgery were allocated into three groups: control (C) group (n = 42); PEEP (P) group (n = 40); RMs combined with PEEP (RP) group (n = 40). All patients were scheduled for general anaesthesia using the lung-protective ventilation (LPV) strategy. The levels of PEEP in the three groups were 0 cmH_2O, 5 cmH_2O and 5 cmH_2O. LUS examination was carried out at 3 predetermined time points in each group: 5 min after intubation (T_1), at the end of surgery (T_2) and 15 min after extubation (T_3). Patients with atelectasis on the sonogram in the RP group received LUS-guided RMs at point T_2. LUS scores were used to estimate the severity of aeration loss. The P/F ratio (PaO_2/FiO_2) at 15min after extubation was used to assess the incidence of postoperative hypoxemia. Primary outcomes were the incidences of postoperative atelectasis and hypoxemia (PaO_2/FiO_2 < 300 mmHg). The secondary outcome was the distribution of LUS scores in each lung area.

Results: From July 2021 to December 2021, 122 consecutive patients were enrolled. No typical atelectasis was observed 5 min after intubation. The incidence of atelectasis was 52.4%, 50.0% and 42.5% in the C group, P group and RP group at the end of surgery, respectively. The rate of atelectasis in the C group, P group and RP group (after RMs) was 52.4%, 50.0% and 17.5%, respectively, 15 min after extubation ($P < 0.01$). The frequency of postoperative hypoxemia was 27.5%, 15.0% and 5.0% in the C group, P group and RP group, respectively ($P < 0.017$). The increased LUS scores mainly occurred in the superoposterior and inferoposterior quadrants at the

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end of surgery. Only in the RP group demonstrated a decreased LUS score in the posteriorquadrants after extubation.

Conclusions: In patients undergoing major open upper abdominal surgery, an intraoperative mechanical ventilation strategy without PEEP or with PEEP alone did not reduce PPCs. However, PEEP of 5 cmH_2O combined with LUS-guided RMs proved feasible and beneficial to decrease the occurrence of postoperative atelectasis and hypoxemia in major open upper abdominal surgeries.

1. Introduction

Major upper abdominal surgeries include gastrectomy, hepatic resection, pancreatectomy, and splenectomy, while esophagectomy is excluded [1]. These surgeries could induce postoperative diaphragmatic dysfunction, which is a well-known cause of postoperative pulmonary complications (PPCs). PPCs, which include atelectasis, hypoxemia, pneumonia, pulmonary oedema, pulmonary thromboembolism, and acute exacerbation of chronic obstructive pulmonary disease (AECOPD), are common after major abdominal surgery and increase the need for intensive care unit (ICU) care, the length of stay (LOS) and mortality [2]. Atelectasis is among the most frequent PPCs of general anaesthesia and can occur in patients of all ages [3]. Atelectasis impairs gas exchange, thus causing hypoxemia and other respiratory disorders, such as acute lung injury and pneumonia.

Utilization of recruitment manoeuvres (RMs) may reduce PPCs and improve patient outcomes, but no consensus has been reached on the ideal recruitment strategy [4]. A meta-analysis by Cui et al. [5] found the application of RMs combined with positive end-expiratory pressure (PEEP) in patients with acute respiratory distress syndrome (ARDS) could improve oxygenation and reduce LOS albeit without beneficial effects on mortality. Moreover, the optimal PEEP needs to be further explored. Furthermore, Carlos et al. [6] showed no benefit in the groups receiving lung-protective ventilation (LPV) strategies with similarly high PPCs (approximately 45%).

Bedside lung ultrasound (LUS) has the advantages of accuracy, sensitivity, non-invasiveness, non-radiation and convenience. It has been a powerful approach for the diagnosis of atelectasis, pleural effusion and pneumothorax, and assessing aeration loss in patients exhibiting hypoxemia in anesthetized patients perioperatively [7]. In a recent randomized controlled trial, Yang et al. [3] used LUS to determine the effect of RMs on PPCs in patients undergoing laparoscopic surgery for colorectal carcinoma. Currently, a growing number of abdominal surgeries are performed with endoscopy due to minimal trauma and bleeding. However, some patients still undergo conventional open surgeries and are more likely to experience postoperative complications and delayed postsurgical recovery [8,9]. Therefore, this prospective study aimed to investigate the effect of RMs on the reduction of postoperative atelectasis and hypoxemia under the guidance of LUS in patients undergoing major open upper abdominal surgery. The secondary aim was to evaluate perioperative aeration loss by LUS examination.

2. Materials and methods

The study was approved by the review committee of the First People's Hospital of Huzhou (2021KYLL047, 2021/04/21) and registered at the Chinese Clinical Trial Registry.gov (ChiCTR2100048706, 2021/07/13) before patient enrolment. Informed consent was obtained from all patients or legally authorized representatives.

2.1. Patients

From July 2021 to December 2021, eligible patients aged 18–65 years old who were scheduled for major open upper abdominal surgery and were classified as the American Society of Anesthesiologists physical status classes (ASA) I to II were included in this study. The main types of surgery are partial gastrectomy, hepatic resection, splenectomy and pancreatectomy from tumour or trauma. Those with the following characteristics were excluded: preoperative chemotherapy, cachexia, previous thoracic procedures, preoperative abnormal computed tomography (CT) imaging such as pneumonia, atelectasis, pneumothorax and pleural effusion, current upper respiratory infection (URI), COPD, history of general anaesthesia within 2 weeks; preoperative hypoxemia, a body mass index (BMI) more than 30 kg/m^2, hemodynamic instability or non-cooperation. The exit criteria were as follows: duration of surgery less than 3 h and immediate postoperative admission to the ICU.

2.2. Anaesthesia protocol

After instituting standard pulse oximetry monitoring and electrocardiogram, invasive arterial pressure was established under local anaesthesia before anaesthesia induction and arterial blood gas analysis was completed in each patient. All patients were preoxygenated with an inspiration oxygen fraction (FiO_2) of 1.0 for 3 min. Then, anaesthesia was induced with midazolam 0.05–0.1 mg/kg, sufentanil 0.3–0.5 μg/kg, etomidate 0.2–0.3 mg/kg and cisatracurium 0.2–0.3 mg/kg for endotracheal intubation. Inhalational sevoflurane 1.5–2% combined with continuous intravenous propofol 4–10 mg/kg·h and remifentanil 2–6 μg/kg·h were utilized for anaesthesia maintenance. Supplemental cisatracurium was added for adequate muscle relaxation when needed. The depth of anaesthesia was monitored by bispectral index (BIS) with the goal between 40 and 60. Volume-controlled ventilation with a tidal volume (Vt) of 6–8 mL/kg, respiratory rate (RR) of 13–15 breaths/min, an inspiratory:expiratory ratio of 1:2 and FiO_2 of 0.5 was utilized to sustain an end-tidal carbon dioxide pressure ($P_{ET}CO_2$) of 35–40 mmHg and a peak airway pressure (P_{aw}) of less than 25 cmH_2O. All operations were conducted by the same experienced surgeon team. Postoperative regional anaesthesia was accomplished with ropivacaine (0.375%, 40 mL) through an ultrasound-guided transversus abdominis plane (TAP) in each patient. In addition, 100 μg sufentanil combined with 10 mg tropisetron was administered by continuous patient-controlled intravenous analgesia (PCIA) for 48 h. All patients were transported to the postanaesthesia care unit (PACU) after the operation. Before extubation, mechanical ventilation with the same setting as that in the operating room was used for all patients. Neostigmine 0.02 mg/kg was used for the reversal of neuromuscular blocking before extubation. Extubation was performed when the following criteria were met: RR $\geq$ 11 breaths/min, Vt $>$ 5 mL/kg, train of four stimulations (TOF) $\geq$ 0.9, haemodynamic stability and normothermia. Then, patients received O_2 via a nasal cannula at 3–5 L/min for approximately 15 min. At 15 min after extubation, each patient was performed with arterial blood gas analysis again.

2.3. Randomization and blinding

The patients were randomly allocated into the 3 groups via block randomization using computer-generated randomization software (www.Medsci.com). An independent investigator prepared the randomization list, and blocks of the group allocations were kept in concealed opaque envelopes. Each envelope was opened by the attending anaesthesiologist before general anaesthesia was induced in the operating room. Instructions for the attending anaesthesiologist were also contained in each envelope. Both the analysts and participants were blind to the control and intervention groups.

2.4. Study design

Patients were allocated into control (C) group, PEEP (P) group or RMs combined with PEEP (RP) group. With the same mechanical ventilation parameters except PEEP, patients in the C group were ventilated with zero end-expiratory pressure, while individuals in the P and RP groups received 5cmH_2O PEEP. The RP group also received RMs when atelectasis was found on the LUS examination at the end of surgery. RMs were performed under LUS monitoring. The ventilation mode was changed from VCV to PCV, with a driving pressure of 10 cmH_2O, respiratory rate of 13–15 breaths per minute, I: E of 1 : 1, and initial PEEP of 5 cmH_2O. PEEP was increased of 5cmH_2O at every step size, and 3 breaths were maintained at each step (5, 10, 15cmH_2O and so on). When the collapsed lung areas were absence on the sonogram, PEEP can no longer increase at this point. Subsequently, the pressure was maintained for approximately 10 breaths. The maximum pressure was 40 cmH_2O (10cmH_2O of driving pressure and 30cmH_2O of PEEP) [3,10]. To open the collapsed alveoli, the process of turning the patients over and patting them on the back was completed by the anaesthesia nurse in the PACU when subjects among the three groups were found by LUS to have atelectasis after extubation.

2.5. Lung ultrasound examination

LUS examination was performed by 2 skilled anaesthesiologists (Tao Liu and Jiahui Tu, both having at least 2 years of ultrasound training) using a 2–5 MHz convex probe in an ultrasound device (Sonosite, Shanghai, China). As previously reported in our studies [7,11], the thorax was divided into 12 quadrants, and LUS examination was performed in order. Sonograms were acquired at 3 pre-established time points: 5 min after intubation (T_1), the end of the surgery (T_2) and 15 min after extubation (T_3). We assumed that the sonogram at point T_2 could reflect the primary outcomes and that RMs under ultrasound guidance were performed at that time point when atelectasis was present in the RP group. RMs were also accomplished by the same anaesthesiologists who performed the LUS examination. The stored video of the worst pathology in each lung quadrant was analyzed offline by a third anaesthesiologist (Chen Xie, with 4 years of ultrasound training), who was blinded to the patient grouping.

2.6. Lung ultrasound score

The severity of aeration loss was evaluated by calculating the LUS score, with scores of 0–3 in each lung quadrant [11,12]. The scoring was defined as follows: 0 = equidistant A-lines parallel to the sliding pleura, normal aeration; 1 = $\leq$ 2 dispersive B lines, moderate aeration loss; 2 = presence of coalescent B lines with irregular pleural, serious aeration loss; 3 = subpleural consolidation or atelectasis, absolute aeration loss.

2.7. Data collection

Demographic and anthropometric data and preoperative imaging studies were extracted from the electronic medical records. At the bedside, we collected mechanical ventilation parameters and surgical information. Outcomes included the LUS sonograms (incidence of postoperative atelectasis) and scores, P/F ratio (PaO_2/FiO_2) from arterial blood gas, incidence of postoperative hypoxemia ($PaO_2/FiO_2 < 300$ mmHg), and duration of mechanical ventilation.

2.8. Sample size and statistical analysis

PASS software (version 22) was used to calculate the sample size before the trial. We enrolled 50 patients in our pilot trial and the incidence of postoperative atelectasis at the end of the surgery were 50.0% in the C group (9/18), 60.0% in the P group (12/20) and

33.3% in the RP group (4/12). As the sample size grow, we expected clinically incidence of atelectasis was 18.3% (a 15% reduction in atelectasis incidence was expected after the intervention of RMs) in the RP group, and the assumed occurrence in C group and P group were 60.0% and 55.0%, respectively. Then the calculated effect size was 0.298. With an α error of 0.05 and a power equal to 0.85, the sample size was 109 patients. Considering a dropout rate of 10%, the total sample size was 120 patients. Continuous variables were expressed as the mean ± standard deviation (SD) or median (interquartile range, IQR) as applicable and compared using the Mann-Whitney *U* test or repeated-measure one-way analysis of variance (ANOVA). Categorical variables are described as frequencies (percentages), and comparisons were accomplished with the chi-square test or Fisher's exact test. SPSS statistical software (version 25.0, NY, USA) and GraphPad Prism software (version 8.0) were used for data analysis. The level of statistical significance was set as a *P value* < 0.05 when compared within groups and $<0.05/3 = 0.017$ when comparing the three groups.

3. Results

From July 2021 to December 2021, 151 patients were evaluated for eligibility. A total of 127 subjects were enrolled as shown in Fig. 1. These enrolled participants were randomized into the C group, P group and RP group. Three patients in Group P and 2 patients in Group RP were excluded from analysis due to ICU admissions, hemodynamic instability and short surgery duration.

The demographic data of these patients were summarized in Table 1, and no significant difference were observed among the three groups. Perioperative surgical and anaesthetic data were shown in Table 2. The P/F ratio after extubation in the C, R and RP groups showed no significant difference (370.3 ± 29.5 vs. 392.5 ± 24.8 vs. 438.1 ± 27.9) whereas the ratio in the RP group revealed a trend of improvement when compared with the other two groups ($P = 0.026$, $P = 0.045$). The incidence of postoperative hypoxemia in the RP group (2, 5.0%) was significantly lower than that in the C group (11, 26.2%, $P = 0.014$), but no significant difference was found when compared to the P group (6, 15.0%, $P = 0.136$). Surgery type, P/F ratio before intubation, duration of surgery and anaesthesia,

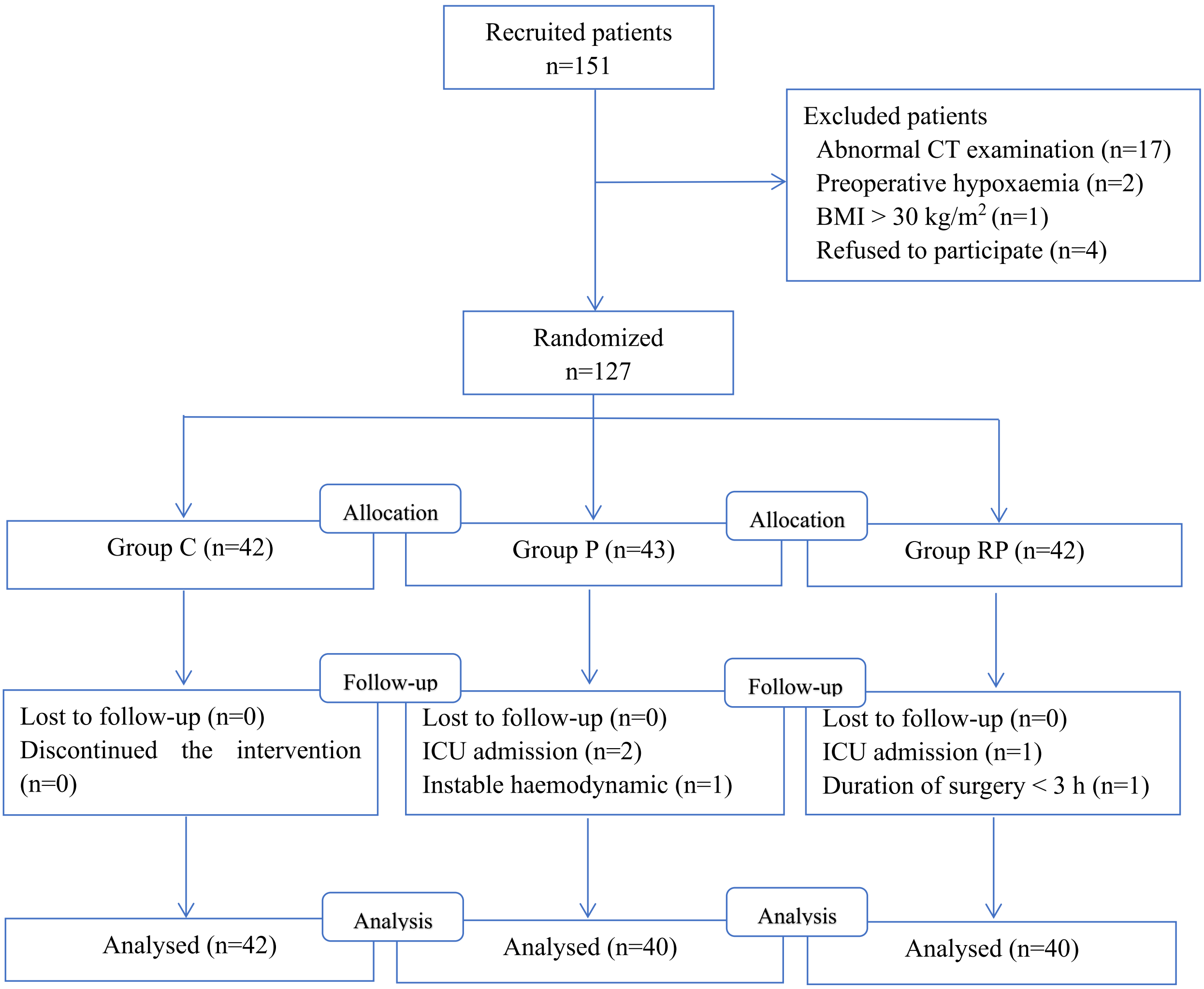

Fig. 1. Flow diagram of patient enrolment.

Table 1
Demographic data in the three groups.

Variables	Groups			P value		
	C (n = 42)	P (n = 40)	RP (n = 40)	$P_{C\text{-}P}$	$P_{C\text{-}RP}$	$P_{P\text{-}RP}$
Sex, M/F (n)	22/20	18/22	23/17	0.504	0.641	0.655
Age (y)	55.6 ± 4.4	54.5 ± 5.2	50.7 ± 4.2	0.519	0.144	0.251
Height (cm)	161.3 ± 2.5	164.2 ± 3.2	164.7 ± 4.1	0.427	0.276	0.709
Weight (kg)	60.7 ± 5.6	64.2 ± 3.5	59.1 ± 4.5	0.334	0.471	0.124
BMI (kg/m^2)	23.2 ± 1.3	23.7 ± 1.1	21.7 ± 1.6	0.838	0.189	0.080
ASA, I/II (n)	11/31	13/27	8/32	0.530	0.507	0.808

Data are described as the mean ± standard deviation (SD) or median (interquartile range, IQR), as appropriate.
Abbreviations: M, male; F, female; BMI, body mass index; ASA, American Society of Anesthesiologists classification.

Table 2
Perioperative operational and anaesthesia data in the three groups.

Variables	Groups			P value		
	C (n = 42)	P (n = 40)	RP (n = 40)	$P_{C\text{-}P}$	$P_{C\text{-}RP}$	$P_{P\text{-}RP}$
Type of surgery, n (%)				0.330	0.782	0.830
Gastrectomy	9 (22.5)	10 (25.0)	9 (22.5)			
Hepatic resection	17 (40.5)	10 (25.5)	12 (30.0)			
Splenectomy	9 (22.5)	14 (35.0)	11 (27.5)			
Pancreatectomy	7 (17.5)	6 (15.0)	8 (20.0)			
P/F Ratio before intubation (mmHg)	431.8 ± 26.2	441.3 ± 22.9	441.1 ± 28.1	0.447	0.596	0.953
Duration of surgery (min)	200.0 (183.8, 231.3)	202.5 (190.0, 236.3)	190.0 (158.8, 288.8)	0.649	0.848	0.585
Duration of anaesthesia (min)	235.0 (200.0, 268.8)	250.0 (226.25, 277.5)	250.0 (206.3, 291.3)	0.164	0.243	0.969
Intraoperative crystalloid administration (ml)	1500.0 (1500.0, 2000.0)	1750.0 (1500.0, 2000.0)	1500.0 (1125.0, 2000.0)	0.662	0.638	0.433
Estimated blood loss (ml)	100.0 (50.0, 200.0)	150.0 (50.0, 275.0)	125.0 (100.0, 200.0)	0.676	0.948	0.905
Urine output (ml)	500.0 (400.0, 600.0)	400.0 (400.0, 500.0)	400.0 (300.0, 500.0)	0.134	0.438	0.293
P/F Ratio after extubation (mmHg)	370.3 ± 29.5	392.5 ± 24.8	438.1 ± 27.9	0.396	0.026	0.045
Incidence of hypoxemia, n (%)	11 (26.2)	6 (15.0)	2 (5.0)	0.211	0.014	0.136
Length of PACU stay (min)	47.5 (43.8, 50.0)	45.0 (40.0, 50.0)	40.0 (40.0, 48.8)	0.188	0.052	0.355
Length of stay (d)	7.0 (6.0, 10.3)	9.0 (7.0, 11.0)	7.0 (6.0,12.0)	0.208	0.620	0.723

Data are described as the mean ± standard deviation (SD), median (interquartile range, IQR) or frequency (percentage), as appropriate.
Abbreviations: P/F ratio, PaO_2/FiO_2 extracted from arterial blood gas analysis PACU; postanaesthesia care unit; length of stay, hospital length after the date of operation.

transfusion and output volume, length of PACU stay and LOS showed no difference among the three groups.

All LUS examinations were completed with an average of 9.6 ± 1.9 min per time point during the study. A total of 4392 cine-loops were stored. Fig. 2 showed representative LUS images at various time points of the three groups. The incidence of atelectasis at different points was summarized in Table 3. LUS revealed only irregular pleural lines but no typical atelectasis at point T_1. Before RMs, 22 (52.4%), 20 (50.0%) and 17 (42.5%) patients exhibited similar atelectasis rates in the C group, P group and RP group, respectively, at the end of the surgery. However, postoperative atelectasis after extubation was detected in 22 (52.4%), 20 (50.0%) and 7 (17.5%) patients in the C, P and RP groups, respectively and RP group demonstrated statistically less atelectasis than C or P group ($P < 0.017$). No statistically significant difference was found between the Cand P group. Only RP group demonstrated less atelectasis after extubation than at the end of surgery ($P = 0.027$).

Fig. 3 showed LUS scores in each lung quadrant of all patients. After intubation, no significant difference in LUS scores among the three groups was observed (Fig. 3A). At the end of surgery and after extubation, the increased LUS scores were mainly found in the superoposterior and inferoposterior zones, with no significant difference among the other areas (superoanterior, inferoanterior, superolateral and inferolateral). At the end of surgery, the scores of the posterior zones had significantly increased, and no difference was observed among the three groups (Fig. 3B). After extubation, only the RP group showed significant decrease in the LUS scores of posterior zones ($P < 0.05$), with no difference found in either the C group or P group (Fig. 3C).

In the RP group, 19 patients (42.5%) experienced transient hypotension, 13 (32.5%) patients were associated with transient bradycardia during RMs. Both the hypotension and bradycardia were self-limited without any organic damage. Under the guidance of lung ultrasound, no barotrauma was found during the RMs.

4. Discussion

In this randomized prospective study, we found a high incidence of atelectasis in patients undergoing major open upper abdominal surgery. Our previously studies established the feasibility and sensitivity of LUS for diagnosing postoperative pulmonary diseases perioperatively and continuously evaluating aeration loss in the perioperative period [7,11]. This study is an extension of our previous research and aimed to investigate the effect of RMs on the reduction of atelectasis as measured by LUS. The incidence of atelectasis in

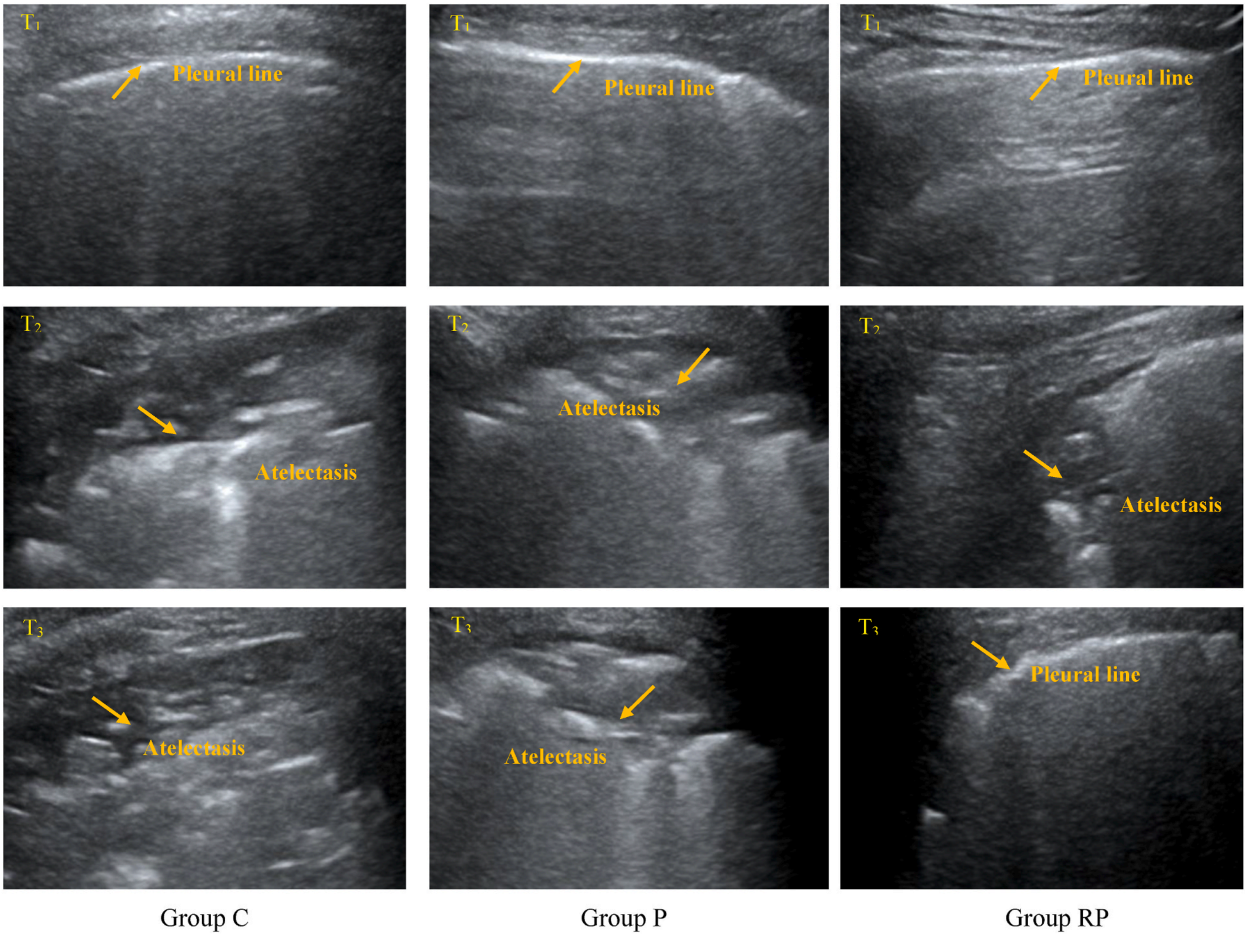

Fig. 2. Representative lung ultrasound images from each group at the various time points.

Table 3
Incidence of atelectasis per group by lung ultrasound at each protocol time point.

Time point	Group C (n = 42)	[a]P value	Group P (n = 40)	[a]P value	Group RP (n = 40)	[a]P value	[b]P value		
							$P_{C\text{-}P}$	$P_{C\text{-}RP}$	$P_{P\text{-}RP}$
T_1	0 (0)		0 (0)		0 (0)		–	–	–
T_2	22 (52.4)	<0.001	20 (50.0)	<0.001	17 (42.5)	<0.001	0.829	0.370	0.654
T_3	22 (52.4)	>0.99	20 (50.0)	>0.99	7 (17.5)	0.027	0.829	0.001	0.004

T_1, 5 min after intubation; T_2, the end of the surgery; T_3, 15 min after extubation.
[a] Chi-square test comparing differences within the individual study groups at successive time points, T_1 *vs*. T_2, T_2 *vs*. T_3.
[b] Chi-square test for comparisons between groups in each protocol step.

the C group, P group and RP group was 52.4%, 55.0% and 42.5% at the end of surgery, respectively. Interestingly, the occurrence of atelectasis in the RP group decreased to 17.5% after RMs under LUS guidance, while no significant improvement was found in either the C group or the P group. The incidence of postoperative atelectasis was similar to that in a previous study [14] but lower than that in Yang et al.'s reports. We believe that the pneumoperitoneum of laparoscopic surgery in Yang et al.'s [3] study may be the primary cause of this phenomenon, as carbon dioxide can cause weaknesses of the diaphragm's muscle fibres. However, patients with major upper abdominal surgery have worse preservation of lung function and higher rates of PPCs due to the invasive procedures, post-operative pain and other factors [15,16]. To our knowledge, this is the first randomized controlled study to investigate the use of LUS-guided RMs combined with PEEP in major open upper abdominal surgery.

Blum et al. [17,18] found that the incidence of hypoxemia ranges from 20.6% to 50.0% after general anaesthesia. In this study, the incidence of postoperative hypoxemia was 26.2%, 15.0% and 5.0% in the C group, P group and RP group, respectively. Hypoxemia is primarily triggered by atelectasis, but not all patients with atelectasis present with hypoxemia. The implementation of intraoperative lung protection ventilation and postoperative oxygen use may cause hypoxemia. The significantly less hypoxemia in the RP group was

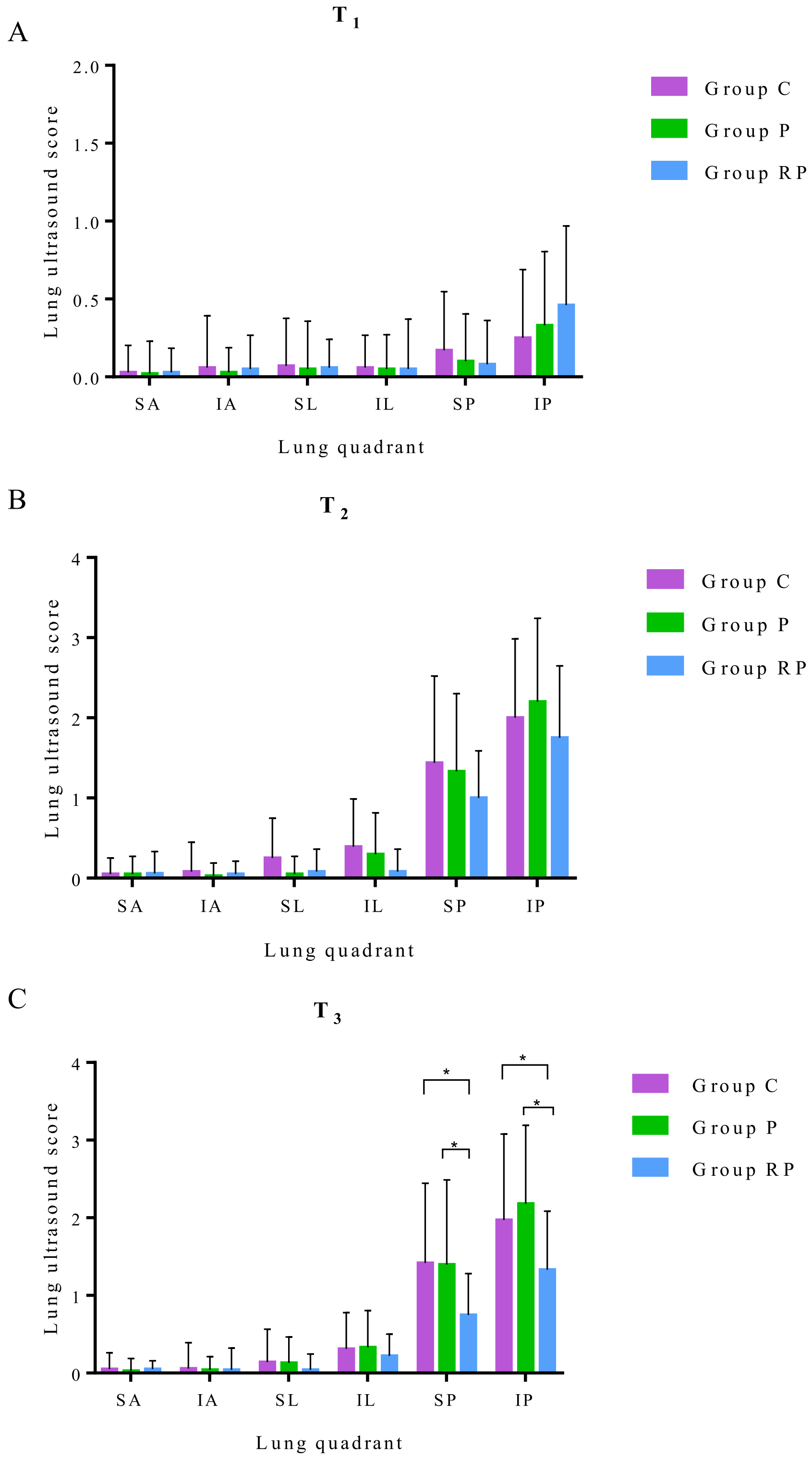

Fig. 3. Lung ultrasound score of each lung quadrant in the three groups.

due to the effective RMs combined with PEEP under direct LUS visualization.

Consistent with previous results [13], the main areas of atelectasis located in the superoposterior and inferoposterior zones in our study. This is primarily due to gravity in the supine position. Compression of the lung tissues by the mediastinum, heart and viscera is inevitable, and therefore, alveolar closure is more likely to occur in posterior regions [19,20]. There was no significant decrease between the rate of atelectasis in the C group and P group at the end of surgery and after extubation, indicating that postoperative atelectasis will not resolve quickly without intervention. Patients suffered from atelectasis in the RP group received RMs under LUS guidance until atelectasis disappeared at the end of surgery; however, 17.5% of patients still developed atelectasis after extubation. The following factors may contribute to this observation. First, the combined effect of general anaesthesia and the supine position lead to an immediate decline in functional residual capacity and gas exchange as well as an impaired immune response [21]. Second, surgical intervention, blood loss, and local ischemia–reperfusion due to low-perfusion periods might cause the release of inflammatory mediators that can provoke further lung injury [22,23]. Third, the combined effect of other factors, such as neuromuscular blockade, cough and pain, can also affect postoperative respiratory function. It is worth noting that the RMs did not translate into shorter LOS in the RP group. Partly because patting these patients suffered from atelectasis on the back regularly by the nurses in the PACU and the ward. Spontaneous respiration, cough and expectoration, walk and functional exercise were also efficient for the treatment of atelectasis. Besides, RMs were implemented only once after surgery while the effect of the of the RMs seemed to be transient. Intraoperative continuous positive airway pressure (CPAP) or postoperative nasal high-flow oxygen therapy (HFNC) could expand alveolar to some extent, and the application of CPAP or HFNC might prolong the effect of the RMs. We think these comprehensive factors are the primary reason for no difference of LOS between the three groups.

The protective effect of PEEP on PPCs is a matter of intense debate, while the optimal level to minimize atelectasis remains uncertain. Adequate PEEP (7 or 9 cm H_2O) in Östberg et al.'s [24] study was advocated as sufficient to minimize atelectasis in healthy lungs without the need for RMs. However, randomized controlled trials by Hemmes et al. [25,26] showed no difference in the development of PPCs after intraoperative ventilation with either high (12 cmH_2O) or low levels ($\leq$2 cmH_2O) PEEP. A PEEP of 5 cmH_2O in the intervention group in our study is based on the method of previous studies. In our study, 5 cm H_2O PEEP alone did not provide significant benefits in reducing postoperative atelectasis. The most likely explanation for the lack of benefit from PEEP alone is PEEP may result in an increase in the driving pressure [27], which is associated with more PPCs.

Advantages of RMs for preventing postoperative alveolar collapse and improving oxygenation in patients undergoing general anaesthesia have been confirmed in an increasing number of reports [28,29]. Nevertheless, the clinical benefit of RMs is still conflicting, as high away pressure might overexpand aerated alveoli, leading to ventilator-induced lung injury [30]. The application of stepwise RMs (increased by 3 cmH_2O every three breaths) combined with LPV was found to improve patient outcomes in Kung and colleagues' [31] study. The RMs surpass the lung's opening pressure, and the PEEP should be high enough to prevent re-collapse of the lungs [14]. Based on recent studies [3,10], we gradually increased the airway pressure from 10 cmH_2O to 40 cmH_2O (5 cmH_2O increments every time) until no collapsed lung areas were visible on the sonogram. Without the LUS real-time guidance, the recruitment pressure might be imprecise. Too much recruitment pressure might lead to pneumothorax especially in old patients with pulmonary bullae, while low recruitment pressure could result in insufficient pulmonary re-expansion. To minimize the drawbacks and maximize the benefits of RMs, adequate monitoring of recruitment at the bedside is necessary. Using LUS as real-time guidance during RMs has improved patient safety, owing to its advantages such as accuracy, sensitivity, repeatability, portability, non-invasiveness, non--radiation and easy applicability. RMs were only performed in these patients with postoperative atelectasis found on the LUS examination at the end of surgery in the RP group. This study design could prevent patients without atelectasis to get RMs or avoid unnecessary recruitment for lung injury. The results of this study indicated that RMs under LUS guidance played a key role in improving postoperative oxygenation by eliminating atelectasis effectively when combined with a PEEP of 5 cmH_2O. Although side effects such as hypotension of RMs have been reported, the rate was very low [32], and hemodynamic effects were self-limited and transient. The postoperative transient hypertension and kidney failure were mainly considered to be caused by stress reaction.

This study also has several limitations. First, we did not perform RMs in the C group, and consequently, the study could not reveal whether RMs effectively reduced PPCs in patients with zero PEEP. Second, the RMs had not been conducted after intubation as no atelectasis was found in any participant at the time point. We think the possible causes may be as follows: although a high concentration of oxygen ($FiO_2 = 1.0$) was used during anaesthesia induction, we adjusted the FiO_2 to 0.5 immediately after endotracheal intubation while atelectasis has not yet formed. The participants were aged 18–65 years old while atelectasis are more common after induction of pediatric anaesthesia. Few small atelectasis might has formed, but the lung ultrasound failed to identify it as the diagnostic accuracy of lung ultrasound was 97.2% [7] when compared to thorax computerized tomography (golden standard, diagnostic accuracy 100%). The implementation of RMs (at the end of surgery) seemed delayed, whereas it is based on the results of lung ultrasound in our present study. If atelectasis was found after intubation, the RMs would be performed immediately at this time point. In clinical practice, whenever atelectasis is detected, related measures should be taken immediately. Third, the present study demonstrates the usage of LUS had save some patients (no atelectasis) from RMs. No group performed RMs without LUS, the study had failed to demonstrate the advantage of LUS in the current settings. As the method to perform RMs using LUS was based on published data, whether the recruitment pressure under LUS guidance was lowered need furthercontrolled study. Last, the present study did not record postoperative pain score. Postoperative pain is one of the main causes of pulmonary atelectasis. In the present study, postoperative analgesia was accomplished with TAP and PCIA in each patient. At the same time, intraoperative sufentanil had also take analgesic effect after surgery. So these patients were not suffering from significant pain in the PACU. The postoperative pain might change within 48 h, however, the lung ultrasound had not exam in this period. This need to be improved in our future study.

5. Conclusions

Patients undergoing major open upper abdominal surgery had a high incidence of postoperative atelectasis. An intraoperative mechanical ventilation strategy with or without 5 cmH_2O PEEP alone did not reduce postoperative ateletasis. Combined with 5 cmH_2O

PEEP, perioperative lung ultrasound-guided recruitment manoeuvres proved feasible and beneficial to decrease the incidence of postoperative atelectasis, hypoxemia and aeration loss in the posterior lung quadrants.

Author contribution statement

Tao Liu, M.D.: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Jiapeng Huang M.D.Ph.D.: Conceived and designed the experiments; Wrote the paper.

Xinqiang Wang, M.D; Jiahui Tu, M.D; Yahong Wang, M.D.: Performed the experiments.

Chen Xie, M.D.: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

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List of abbreviations

PPCs	postoperative pulmonary complications
RMs	recruitment manoeuvres
PEEP	positive end-expiratory pressure
LUS	lung ultrasound
AECOPD	acute exacerbation of chronic obstructive pulmonary disease
ICU	intensive care unit
LOS	length of stay
ARDS	acute respiratory distress syndrome
LPV	lung-protective ventilation
ASA	American Society of Anesthesiologists physical status classes
CT	computed tomography
URI	upper respiratory infection
BMI	body mass index
FiO_2	inspiration oxygen fraction
BIS	bispectral index
Vt	tidal volume
RR	respiratory rate
$P_{ET}CO_2$	end-tidal carbon dioxide pressure
P_{aw}	peak airway pressure
TAP	transversus abdominis plane
PCIA	patient-controlled intravenous analgesia
PACU	postanaesthesia care unit
TOF	train of four stimulations

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