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Article

An Investigation Into Early Lung Recruitment and Prone Position Ventilation in Patients With Acute Respiratory Distress Syndrome After Aortic Dissection Surgery

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Abstract

Background: This study aimed to investigate the clinical effects of early recruitment maneuver (RM) combined with prone position (PP) in improving acute respiratory distress syndrome (ARDS) after aortic dissection (AD) surgery. **Methods**: A before-and-after single-arm interventional study was conducted to collect data on patients with Stanford type A aortic dissection (STAAD), who underwent surgical treatment from April 2017 to October 2023 in the Department of Cardiac Major Vascular Surgery, a teaching hospital in China. Comparisons of hemodynamic indices, changes in respiratory parameters, and adverse events were performed at six time points: before the intervention, immediately after early RM combined with PP, and at 30 min, 1 h, 2 h, and 4 h thereafter. **Results**: A total of 41 patients (80.49% male; mean age 49.05 $\pm$ 11.64 years) were included. Following early lung recruitment combined with prone positioning, PaO_2 increased from 66 mmHg at baseline to a peak of 102 mmHg post-intervention at 1 hour, and the PaO_2/FiO_2 ratio improved from 95 mmHg to 154 mmHg, indicating enhanced oxygenation. $PaCO_2$ remained stable throughout the observation period. FiO_2 initially increased from 60% to 70% and returned to baseline levels, while SpO_2 improved from 94.5% to 97%, demonstrating a sustained improvement in peripheral oxygen saturation. Hemodynamic parameters, including heart rate and central venous pressure, remained largely stable. All changes in oxygenation indices were statistically significant ($p < 0.001$ following the Friedman test). **Conclusion**: Early lung recruitment combined with prone positioning significantly improved oxygenation in post-operative ARDS patients with STAAD, as evidenced by increased PaO_2 and PaO_2/FiO_2 ratios. These benefits were achieved without significant changes in $PaCO_2$, heart rate, or lactate levels, suggesting that this strategy enhances gas exchange while maintaining hemodynamic stability.

Keywords: aortic dissection; acute respiratory distress syndrome; prone position; ventilation

1. Introduction

Aortic dissection is a condition characterized by the tearing of the intima and media of the aorta due to various causes, leading to the separation of the intima from the media. Blood flows between these layers, resulting in the division of the aortic lumen into true and false lumens. This disease progresses rapidly and has a high mortality rate [1–3]. Due to differences in the extent of involvement, aortic dissection can be classified according to the Stanford classification into Type A and Type B. Stanford type A aortic dissection (STAAD) involves the ascending aorta, whereas Type B aortic dissection (TBAD) originates from the descending thoracic aorta but does not involve the ascending aorta [4–6]. Surgical treatment is currently the most effective method for treating patients with STAAD. Research has shown that hypoxemia, characterized by respiratory failure, is a common complication of STAAD surgery. Prolonged postoperative hypoxemia (Acute Respiratory Distress Syndrome, ARDS) can lead to damage in the lungs and other organs, thereby increasing perioperative mortality [7]. Therefore, it is crucial to actively prevent hypoxemia after surgery for aortic dissection. Ventilation in the prone position (PP) is one of the important methods for treating hypoxemia [8]. Lung recruitment (Recruitment manoeuvre, RM) refers to a treatment method where, during mechanical ventilation, a pressure higher than the average airway pressure is briefly applied to expand the lungs, promoting the opening of collapsed alveoli, thus improving the patient's oxygenation and enhancing lung compliance [9]. However, there is currently controversy over whether lung recruitment can be used as a treatment method after cardiac surgery [10].

To study the clinical application effect of early lung recruitment combined with prone positioning ventilation in improving hypoxemia in patients after aortic dissection surgery, we conducted a retrospective analysis and summary of the efficacy of patients with ARDS following acute STAAD surgery who underwent early lung recruitment combined with prone positioning ventilation in our unit, in order to provide relevant experiential measures for clinical practice.

2. Methods and Materials

2.1 Research Subject

In this before-after/single-arm interventional study, changes in respiratory parameters and hemodynamics before and after early lung recruitment and prone position ventilation were investigated in patients with acute Stanford Type A aortic dissection who underwent surgical treatment at a Hospital in China from April 2017 to October 2023.

Patients were screened for eligibility according to the following inclusion and exclusion criteria: Inclusion criteria: (1) Age $\geq$18 years; (2) Diagnosed with aortic dissection based on clinical symptoms and imaging studies, specifically Stanford Type A; (3) Postoperative ARDS: intubation and mechanical ventilation within 7 days after surgery, with a positive end-expiratory pressure (PEEP) $\geq$5 cmH_2O and an oxygenation index $\leq$150 mmHg; (4) Prone ventilation administered. Exclusion criteria: (1) Perioperative use of intra-aortic balloon pump and/or extracorporeal membrane oxygenation (ECMO); (2) Pulmonary diseases such as bullae, bronchopleural fistula, or severe emphysema; (3) Left ventricular ejection fraction (LVEF) <40%.

2.2 Early Lung Recruitment Combined With Prone Ventilation Protocol

In this protocol, selected patients underwent lung recruitment combined with prone ventilation within 6 hours after surgery. All patients underwent early lung recruitment with the PEEP titration method under ventilator assistance, combined with patient blood gas analysis results, ensuring hemodynamic stability, with one RM performed at 1 hour and 4 hours, respectively.

Patient mechanical ventilation parameter settings: The synchronized intermittent mandatory ventilation (SIMV) mode was used, with a tidal volume (VT) of 6~8 mL/kg, PEEP of 5 cmH_2O, and a respiratory rate of 12 breaths per minute.

Early Lung Recruitment Strategy: Before performing recruitment maneuvers (RM), patients should have a bedside chest X-ray or computed tomography (CT) to assess the potential for lung recruitment. Patients should be in a fully sedated state (with a richmond agitation-sedation scale (RASS) score of –3 to –5) and should not be breathing spontaneously. Set the peak pressure alarm limit to 40 cmH_2O and the PEEP alarm limit to 20 cmH_2O. In pressure-controlled ventilation (PCV), maintain the difference between inspiratory pressure and PEEP constant. Incrementally increase PEEP by 5 cmH_2O every 30 seconds up to 20 cmH_2O, maintaining ventilation for 2 minutes after each increase. Subsequently, employ a decremental method to titrate PEEP, maintaining tidal volume at 5 mL/kg. Decrease PEEP by 2 cmH_2O every 2 to 3 minutes, selecting the optimal PEEP as determined for the patient.

Prone Position Ventilation Procedure: The classical method for prone positioning is adopted for prone position ventilation [11]. Based on the actual situation in our department, the following protocol has been formulated. Once the patient is transitioned to prone ventilation and hemodynamics are stable, lung recruitment maneuvers are performed at 1 hour and 4 hours, as detailed in Table 1.

Early Lung Recruitment Combined with Prone Position Termination Criteria:

(1) Oxygen saturation decreases by more than 5% from baseline or is less than 88%;

(2) Heart rate increases by more than 5% from baseline or 15 beats per minute;

(3) Mean arterial systolic pressure drops by more than 5% from baseline or is less than 60 mmHg;

(4) New occurrences of arrhythmias, accidental extubation, drain dislodgement, cardiac arrest, or other life-threatening situations;

(5) Other circumstances determined by the clinical physician to stop treatment.

2.3 Evaluation Metrics

2.3.1 Basic Information

This includes age, gender, body mass index, smoking history, drinking history, Acute Physiology and Chronic Health Evaluation II (APACHE-II), and surgical-related information, among others.

2.3.2 Hemodynamic and Respiratory Parameters

Dynamic monitoring of the patient's heart rate (HR), oxygen saturation (SpO_2), and central venous pressure (CVP). Records are kept for HR, SpO_2, and CVP, as well as lactate levels at various time points: before and after early lung recruitment plus prone ventilation at 30 minutes, 1 hour, and post-ventilation at 2 hours and 4 hours.

2.3.3 Adverse Events

Occurrences of respiratory or cardiac arrest, incidence of pressure ulcers, and accidental extubation rates are tracked.

2.4 Statistical Analysis

Statistical analyses were performed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). Categorical variables are presented as frequency and percentage [n (%)], whereas continuous variables are expressed as mean $\pm$ standard deviation (SD) for normally distributed data or median with interquartile range (IQR) for non-normally distributed data. Normality was assessed using the Shapiro–Wilk test. For repeated measurements at different time points, the Friedman test was used for non-normally distributed variables. A p-value $\leq$ 0.05 was considered statistically significant.

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Table 1. Team roles and responsibilities in classic prone positioning.

Standing position	Character	Division of labor and responsibilities
Position 1	Physician or Respiratory Therapist	Stand at the head side of the patient, responsible for commanding the team and coordination, securing the tracheal intubation, and protecting the ventilator tubing.
Position 2	Charge Nurse	Stand on the right side of the patient's neck and shoulder, responsible for protecting the drainage tubing, such as central venous catheters, chest drainage tubes, and arterial catheters. Also, monitor the patient's monitoring equipment and changes in the ventilator.
Position 3	Nurse	Stand on the left side of the patient's neck and shoulder, responsible for protecting the drainage tubing, such as central venous catheters, chest drainage tubes, arterial catheters, and urinary catheters.
Position 4	Nurse	Stand on the right side of the patient's hip and thigh root, assisting in the protection of catheters and drainage tubes such as urinary catheters, abdominal drainage tubes, and thoracic drainage tubes.
Position 5	Nurse	Stand on the left side of the patient's buttocks and thigh root to assist in protecting the urinary catheter, abdominal drainage tube, and thoracic drainage tube.

3. Result

During the study period, researchers conducted a comprehensive analysis of acute aortic dissection surgeries, treating a total of 224 cases. The severity of this condition was evident from the outset, with 5 cases resulting in preoperative mortality due to the critical nature of the dissection itself. Postoperatively, an additional 14 patients succumbed to complications arising from multi-organ failure, highlighting the challenges and risks associated with this complex surgical intervention. In addressing the critical issue of ARDS complicating aortic dissection surgeries, researchers implemented a protocol involving early lung recruitment combined with prone ventilation. This intervention was applied to 41 patients, as detailed in Table 2 of the study. Fig. 1 shows the flowchart of patient selection.

Table 2 summarizes the baseline characteristics and perioperative clinical data of the study cohort (n = 41). The mean age of patients was 49.05 ± 11.64 years, with a predominance of males (80.49%). The average body mass index (BMI) was 28.71 ± 4.28 kg/m^2. More than half of the patients had a history of smoking (53.66%), while 34.15% reported alcohol consumption. Diabetes was present in 21.95% of cases, and 4.88% had pre-existing lung disease.

Regarding perioperative outcomes, the mean duration of mechanical ventilation was 58.89 ± 47.48 hours, and the average intensive care unit (ICU) length of stay was 182.5 ± 175.4 hours. The median aortic cross-clamp time was 116 minutes (IQR 85–145), and the median cycle arrest time was 13 minutes (IQR 9.5–23.5). The median LVEF was 60% (IQR 59–61). Postoperative 24-hour drainage averaged 457.1 ± 304.9 mL, with a total bleeding volume of 2225.1 ± 1320.9 mL. Two patients (4.9%) died during the study period. The median APACHE II score was 18 (IQR 17–20), and the median transfer time was 201 minutes (IQR 169.5–236.5).

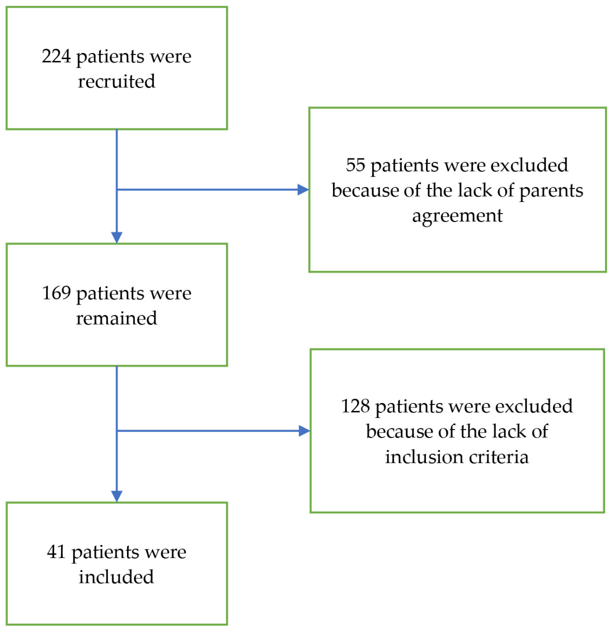

Fig. 1. The flowchart of the participant recruitment.

Table 3 presents the temporal changes in respiratory parameters measured at six time points before, during, and after early lung recruitment combined with prone positioning. All values are expressed as median with IQR. Since the majority of variables did not follow a normal distribution (Shapiro–Wilk test), the Friedman test was applied for repeated measures comparisons.

A significant overall effect of time was observed for PaO_2, PaO_2/FiO_2 ratio, FiO_2 requirement, SpO_2, and CVP ($p < 0.001$ for all). These parameters showed marked improvement in oxygenation indices, particularly within the first 1–4 hours after initiation of the intervention, with sustained effects up to 4 hours after completion.

Table 2. Baseline clinical and perioperative characteristics of the study population.

Characteristics	Data
Age (years)	49.05 ± 11.64
Gender	
Male	33 (80.49%)
Female	8 (19.51%)
Height (cm)	172.66 ± 5.78
Weight (kg)	85.70 ± 14.08
BMI (kg/m^2)	28.71 ± 4.28
History of smoking	22 (53.66%)
History of drinking	14 (34.15%)
Basic lung disease	2 (4.88%)
Diabetes	9 (21.95%)
Mechanical ventilation time (h)	58.89 ± 47.48
Postoperative ICU hospitalization time (h)	182.54 ± 175.42
24-hour drainage (mL)	457.08 ± 304.85
Total bleeding volume (mL)	2225.11 ± 1320.90
Death rate	2 (4.88%)
Aortic cross clamping time (min)	116 (85, 145)
LVEF (%)	60 (59, 61)
Cycle stop time (min)	13 (9.5, 23.5)
Transfer time (min)	201 (169.5, 236.5)
APACHE II score (Score)	18 (17, 20)

Values are expressed as mean ± standard deviation (SD) for normally distributed variables, median (Q25, Q75) for non-normally distributed variables, and n (%) for categorical variables. BMI, body mass index; ICU, intensive care unit; LVEF, left ventricular ejection fraction; APACHE II, Acute Physiology and Chronic Health Evaluation II.

Table 3. Changes in respiratory parameters before and after early lung recruitment combined with prone positioning.

Respiratory parameters	Time 0	Time 1	Time 2	Time 3	Time 4	Time 5	*p*-value
PaO_2 (mmHg)	66.29 ± 9.76	84.31 ± 27.22	102.34 ± 34.26	94.83 ± 18.69	94.54 ± 21.36	90.83 ± 10.76	<0.001
$PaCO_2$ (mmHg)	40.83 ± 9.72	39.56 ± 5.95	38.39 ± 4.73	39.81 ± 5.30	38.95 ± 6.47	37.85 ± 4.68	0.594
PaO_2/FiO_2 (mmHg)	98.51 ± 22.80	125.95 ± 48.79	153.98 ± 58.61	156.34 ± 41.50	158.24 ± 45.25	158.47 ± 26.41	<0.001
FiO_2 (%)	60 (60, 80)	70 (60, 80)	60 (60, 72.5)	60 (60, 60)	60 (55, 70)	60 (50, 60)	<0.001
SPO_2 (%)	94 (92, 95)	96 (94, 98)	97 (96, 98.75)	98 (95.5, 98)	98 (96, 98)	97 (96.5, 98)	<0.001
HR (minute)	85.29 ± 9.52	85.71 ± 10.41	85.85 ± 11.41	83.76 ± 10.60	84.42 ± 11.89	84.63 ± 9.86	0.816
CVP (cmH_2O)	12.88 ± 1.23	12.81 ± 2.24	12.15 ± 1.97	12.46 ± 2.20	12.07 ± 1.92	11.63 ± 1.56	<0.001
Lac (mmol/L)	1.5 (1.0, 5.7)	1.5 (1.0, 2.8)	1.3 (0.9, 2.45)	1.3 (1.0, 2.55)	1.3 (1.0, 1.95)	1.2 (1.0, 1.9)	0.904

Time 0: before early lung recruitment, Time 1: 30 minutes After Initiation, Time 2: 1 Hour After Initiation, Time 3: 4 Hours After Initiation, Time 4: 2 Hours After Completion, Time 5: 4 Hours After Completion. Values are expressed as mean ± standard deviation (SD) for normally distributed variables, median (Q25, Q75) for non-normally distributed variables. HR, heart rate; CVP, central venous pressure.

In contrast, $PaCO_2$, HR, and lactate levels did not change significantly across time points (p = 0.594, p = 0.816, and p = 0.904, respectively), indicating stability of ventilation, hemodynamic status, and metabolic response during the study period.

The line graph depicts the changes in PaO_2 (mmHg), $PaCO_2$ (mmHg), and PaO_2/FiO_2 ratio (mmHg) across six time points before, during, and after early lung recruitment combined with prone positioning. PaO_2 increased from 66 mmHg at baseline (Time 0) to 77 mmHg at Time 1 and peaked at 93 mmHg at Time 2, then remained elevated around 90–94 mmHg at subsequent time points. $PaCO_2$ remained relatively stable throughout the observation period, ranging from 37 to 40 mmHg. The PaO_2/FiO_2 ratio showed a marked improvement from 95 mmHg at baseline to 118 mmHg at Time 1 and progressively increased to 154–157 mmHg by Time 5, reflecting enhanced oxygenation following the intervention (Fig. 2).

The line graph illustrates the changes in FiO_2 (%) and SpO_2 (%) at six consecutive time points during and after early lung recruitment combined with prone positioning. FiO_2 initially increased from 60% at baseline (Time 0) to

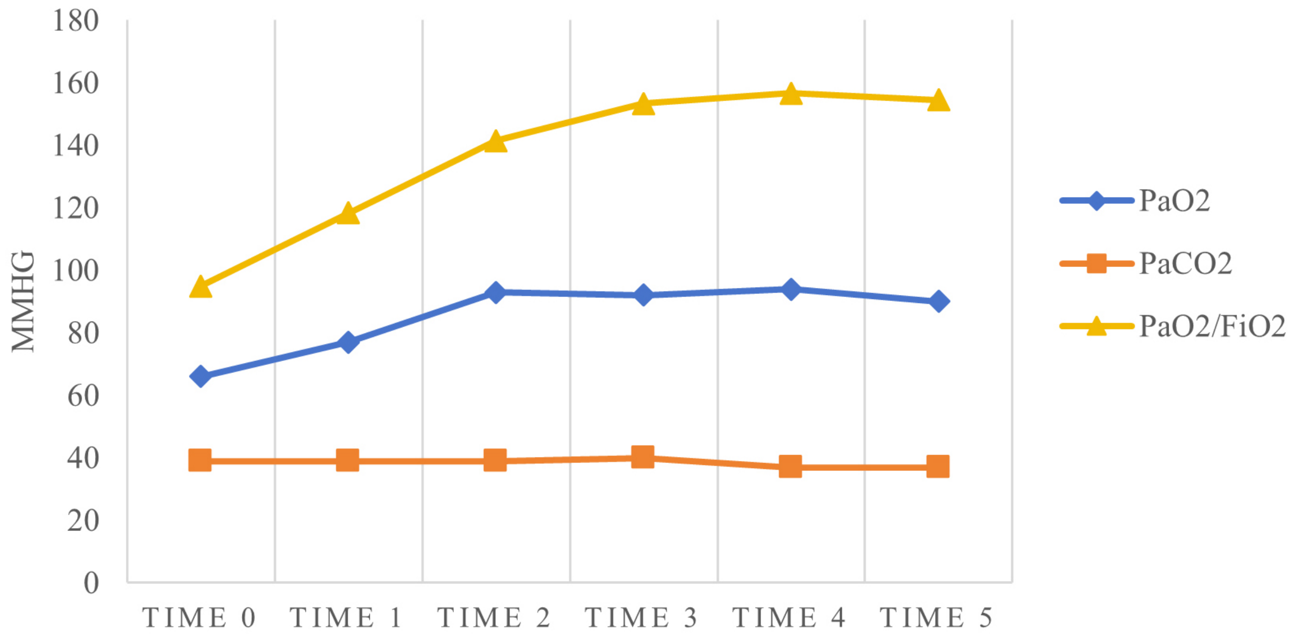

Fig. 2. Temporal changes in PaO_2, $PaCO_2$, and PaO_2/FiO_2 ratio following early lung recruitment and prone positioning.

70% at Time 1 and remained slightly elevated at 69% at Time 2, before returning to 60% from Time 3 onward. Correspondingly, SpO_2 improved from 94.5% at baseline to 96% at Time 1 and 97% at Time 2, followed by minor fluctuations at later time points, reaching 97% at Time 5. These trends indicate an early improvement in oxygenation after the intervention, which was largely maintained throughout the subsequent time points (Fig. 3).

4. Discussion

Postoperative complications from STAAD surgery have become a significant cause of patient mortality, with ARDS being one of the main complications. In this study, all included patients met the diagnostic criteria for moderate to severe ARDS [12]. The risk factors for ARDS after STAAD surgery are associated with interleukin-6 and systemic inflammatory response [13]. In addition, a risk factor analysis for STAAD identified obesity as a relevant factor [14–16]. It is related to young age, anemia, and the extensive transfusion of blood products [17].

Early lung recruitment combined with prone positioning can improve postoperative hypoxemia in patients with aortic dissection. The results of this study show that early lung recruitment combined with prone positioning can improve postoperative hypoxemia in patients with aortic dissection. The main reason may be attributed to extensive alveolar collapse in ARDS, which reduces the effective lung volume. Early lung RM combined with prone positioning can more effectively reopen collapsed alveoli while also increasing lung volume, thereby improving oxygenation [18–20]. However, it is important to note that the persistent effect of early RM on alveolar opening is limited, only improving oxygenation for a period. This study only explored changes in respiratory parameters at 30 minutes, 1 hour, 4 hours after the maneuver, and 2 hours, 4 hours post-procedure; further investigation into the duration of effects is warranted. Zhang *et al*. [21] suggested lung recruitment if the patient's lungs are recruitable. However, Nielsen *et al*. [22] indicated that if ARDS patients have acute pulmonary heart disease, especially involving right heart function, the implementation of lung recruitment might affect the patient's venous return and thereby right heart function. Considering this, the recruitment pressures PEEP in this study were all $\leq$20 cmH_2O. Although oxygenation parameters showed significant improvement in this study, changes in FiO_2, CVP, and lactate were minimal. These findings suggest that while early RM and PP may rapidly enhance oxygenation, their impact on other physiological markers may be limited or delayed. Additionally, due to the retrospective nature of the study, we did not perform correlation analysis between the intervention and outcomes such as ICU stay or mortality, which should be explored in future studies. Ding *et al*. [23] also reported the efficacy of early prone positioning in Acute Type A Aortic Dissection (TAAD) patients. In line with this study, they support the role of PP in postoperative management, though our combined RM + PP approach may offer additional benefits. The implementation of lung protective ventilation strategies has been the dominant approach in recent years. However, for some patients with refractory hypoxemia, the effectiveness of these strategies has not been satisfactory [24]. In another randomised controlled study by Martinsson *et al*. [25], RM + PP increased lung aeration and oxygenation after cardiac surgery. In another study by Zhang *et al*. [26], blood gas

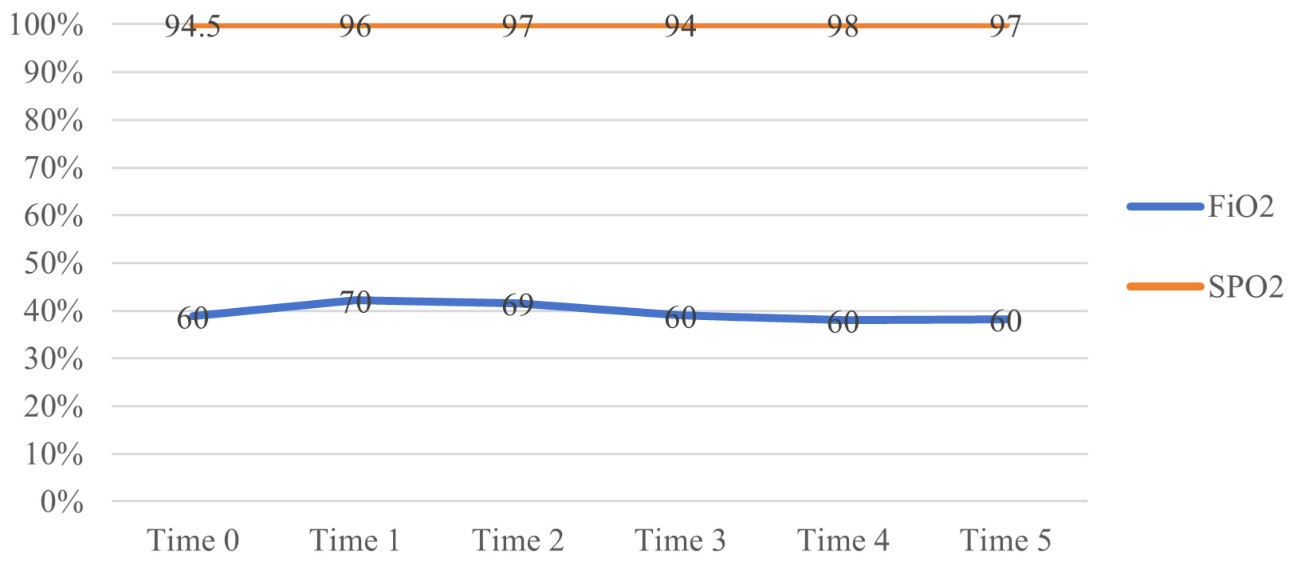

Fig. 3. Temporal changes in FiO_2 (%) and SpO_2 (%) following early lung recruitment and prone positioning.

parameters, hypoxemia, and respiratory mechanics indices improved after prone ventilation in patients with ARDS after cardiac surgery. ARDS is defined as a clinical syndrome of acute hypoxemic respiratory failure caused by lung inflammation, distinct from cardiogenic pulmonary edema [27]. The pathophysiological differences between postoperative cardiac surgery ARDS and general ARDS may exist. However, RM and PP are effective in the management of both conditions.

Early lung recruitment combined with prone positioning is relatively safe for ARDS patients with aortic dissection. In this study, only one patient was allowed to prematurely terminate prone ventilation due to arrhythmia as permitted by the attending physician, indicating a certain level of safety with early lung recruitment combined with prone positioning. However, some studies have reported that the incidence of cardiac arrest during prone ventilation is 6.75% [12]. Additionally, Schmidt *et al*. [28] pointed out that lung recruitment might cause barotrauma, exacerbating injury in non-collapsed alveolar regions, and that not all alveoli in consolidated areas can be fully recruited. Therefore, assessing the recruitable nature of the lungs in the early recruitment process is particularly important. This study confirms that early lung recruitment combined with prone positioning is relatively safe for ARDS patients with aortic dissection. However, since this procedure requires significant manpower and has a higher incidence of complications, it necessitates an assessment by the attending physician regarding the necessity of a second operation. This study did not evaluate the need for a second prone ventilation operation; future studies could design strict randomized controlled trials to analyze the safety and effectiveness of this approach in patients with moderate to severe ARDS after STAAD surgery. Safety remains a critical concern in postoperative cardiac patients. Although only one patient in our cohort experienced arrhythmia requiring early termination, potential risks such as barotrauma and hemodynamic instability must be considered. Our protocol employed conservative PEEP limits ($\leq$20 cmH_2O) and continuous monitoring to mitigate these risks. Nonetheless, further studies are needed to evaluate long-term safety outcomes. In this study, we can not evaluate the mortality, ICU stay, and ventilation duration after the intervention due to the lack of a control group.

The findings from this study underscore the critical role of early lung recruitment combined with prone ventilation in managing ARDS following acute aortic dissection surgeries. By systematically evaluating respiratory parameters at multiple time points, researchers elucidated the protocol's effectiveness in enhancing oxygenation, optimizing respiratory mechanics, and mitigating postoperative complications. The observed improvements in oxygenation and respiratory metrics highlight the protocol's potential to reduce the incidence and severity of ARDS, thereby improving patient outcomes and overall surgical success rates. These findings contribute valuable insights into evolving perioperative strategies aimed at enhancing respiratory support and minimizing the physiological burden associated with complex cardiovascular surgeries.

This study is limited by its single-center retrospective design and relatively small sample size. Furthermore, the absence of a control group (e.g., RM alone or PP alone) restricts the ability to attribute improvements solely to the combined intervention. Future prospective randomized controlled trials are warranted to confirm these findings and enhance their generalizability.

5. Conclusion

In summary, the use of early lung recruitment combined with prone positioning in postoperative STAAD patients with moderate to severe ARDS can improve oxygenation and is relatively safe, which can guide its application in clinical treatment. The documented improvements in respiratory parameters underscore the protocol's efficacy in optimizing lung function and mitigating respiratory complications, thereby enhancing patient safety and recovery outcomes. Moving forward, continued research and clinical application of such protocols hold promise in advancing perioperative care practices and improving outcomes for patients facing the challenges of acute aortic dissection surgeries and associated respiratory complications. However, further research is still needed on the timing and duration of lung recruitment combined with prone positioning. Additionally, further investigation is required to determine whether this approach can be applied to other major cardiovascular diseases.

Availability of Data and Materials

The data are available from the corresponding author on reasonable request.

Author Contributions

XL: Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing. SL: Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing. GL: formal analysis, writing—review and editing. AM: formal analysis, writing—review and editing. XG: formal analysis, writing—review and editing. SJ: investigation, writing—review and editing. JZ: Conceptualization, methodology, writing—review and editing. All authors have read and agreed to the published version of the manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was carried out in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of The Provincial Hospital affiliated with Shandong First Medical University (Protocol No. 2020-4007). All participants in the study provided their written informed consent.

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Conflict of Interest

The authors declare no conflict of interest.

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