Efficacy analysis of the lung recruitment maneuver in correcting pulmonary atelectasis in neurological intensive care unit—a retrospective study

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Background: Atelectasis after supratentorial craniotomy is common. It can lead to the decrease of arterial partial pressure of oxygen (PaO_2) in patients with neurosurgical intensive care units (NICU), and the recovery of neurological function is more and more difficult. However, due to the particularity of maintaining the stability of intracranial pressure (ICP), there are few reports on effective ways to alleviate atelectasis and improve oxygenation in patients with NICU effectively.

Methods: A retrospective analysis was conducted to analyze the clinical data of patients with atelectasis who received lung recruitment maneuver in the NICU. This study collected data on 33 patients. Of these, 17 patients had traumatic brain injury and 16 patients had spontaneous intracranial hemorrhage. PaO_2, oxygenation index (OI), tidal volume, positive end-expiratory pressure (PEEP), respiratory system compliance, plateau pressure, respiratory rate, minute ventilation and chest computed tomography (CT) or portable chest X-ray images were compared before and after recruitment. As for safety evaluation indicators, we reviewed the invasive arterial blood pressure, heart rate, heart rhythm, and subcutaneous emphysema in all patients. Before and after lung recruitment, the data were compared using the paired t-test and the Wilcoxon test.

Results: Compared with tidal volume 8.1 [6.85–10.05] mL/kg, minute ventilation volume (9.3±1.3 L/min), respiratory system compliance 60 [39–80] mL/cmH_2O, respiratory rate 17 [16–21.5] breaths/min, PEEP 4 [4–6] cmH_2O, plateau pressure 19 [17–23] cmH_2O, PaO_2 (104.2±33.17 mmHg) and OI (250.6±87.65 mmHg) before lung recruitment, tidal volume 9 [8.05–10.65] mL/kg, minute ventilation (9.7±1.1 L/min), respiratory system compliance 69 [50–82.5] mL/cmH_2O, respiratory rate 17 [14–18.5] breaths/min, PEEP 4 [4–5] cmH_2O, plateau pressure 18 [16–19.5] cmH_2O, PaO_2 (127.3±34.95 mmHg) and OI (306.9±96.52 mmHg) of patients were significantly improved after recruitment after recruitment (all $P<0.05$). In all patients, chest CT showed a decrease in atelectasis area and bilateral pulmonary exudates in 25 patients after lung recruitment maneuver. X-ray after recruitment in 2 patients showed increased lung tissue transparency and decreased ground-glass shadowing, while improvements were not obvious in 6 patients.

Conclusions: For patients diagnosed with atelectasis in the NICU, lung recruitment maneuver can improve atelectasis, increase PaO_2, and improve oxygenation.

Keywords: Lung recruitment maneuver; traumatic brain injury; spontaneous intracranial hemorrhage; pulmonary atelectasis; oxygenation index (OI)

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Introduction

Neurocritical patients often have varying degrees of consciousness disturbance and poor airway self-protection ability. Vomiting and aspiration events are more common and can lead to airway occlusion. In addition, prolonged mechanical ventilation and bed rest can also cause lung infection. The exudate produced by the latter falls to the bottom of the lungs by gravity and obliterates the bronchial tubes. It can also cause or aggravate atelectasis, which may even progress after a long time. Consolidation of lung tissue leads to severely reduced oxygenation (1) and insufficient oxygen supply to the brain tissue, making the recovery of nerve function more difficult, resulting in poor patient prognosis (1-4).

The lung recruitment maneuver involves increasing the transpulmonary pressure so that the gas exchange space of the alveoli is recruited to prevent the terminal airway from closing. In turn, it prevents shear injury during alveolar opening and closing, thereby reducing ventilator-related lung injury and improving oxygenation (5). In patients other than neurosurgery, lung recruitment is often used to treat atelectasis and acute respiratory distress syndrome (ARDS) (6). There are many methods of lung recruitment. In adjusting ventilator parameters, some methods use high positive end-expiratory pressure (PEEP), and low tidal volume as lung recruitment means, while others are characterized by increasing plateau pressure. At the time of lung recruitment, each method also has different requirements. The ventilator intervention will cause the changes of the arterial partial pressure of oxygen (PaO_2), partial pressure of carbon dioxide in artery and hemodynamics, which will affect the oxygen supply of nerve cells and the changes in intracranial pressure (ICP). For example, ICP will increase with higher PEEP. Excessive ICP will lead to insufficient cerebral perfusion, which will affect patients' outcomes in the neurosurgical intensive care unit (NICU). Although there are many methods of lung recruitment, their actual impact on patients with traumatic brain injury and spontaneous intracranial hemorrhage is still unclear. Therefore, this study retrospectively analyzed the clinical response of patients with severe neurological disease and atelectasis to the lung recruitment maneuver under ventilation and explored the clinical application value of that in the NICU. We present the following article in accordance with the STROBE reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-554/rc).

Methods

Population

This retrospective study included neurocritical care patients in the NICU of the Department of Neurosurgery, Zhangzhou Municipal Hospital of Fujian Province admitted between August and December 2021. The inclusion criteria were as follows: NICU patients with stays exceeding 1 week due to severe intracranial disease, age >18 years, imaging examination findings including chest radiographs with decreased light transmittance in lung tissue and ground-glass changes (1), and lung CT showing partial infiltration of both lungs and dorsal sheet consolidation (7). The exclusion criteria were patients with hemodynamic instability [requiring vasoactive drug intervention to achieve a systolic blood pressure >90 mmHg (1 mmHg = 0.133 kPa)], severe ICP increase (ICP ≥25 cmH_2O) or manifestations of intracranial hypertension (dilated pupils, jet vomiting, etc.), pneumothorax or a history of lobectomy within 1 month, severe chronic respiratory diseases (asthma, bronchiectasis, pulmonary bullae, etc.), and lung contusion caused by trauma. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Medical Ethics Board of Zhangzhou Municipal Hospital of Fujian Province (No. 2022KYB046). Individual consent for this retrospective analysis was waived.

COVID-19

All patients were negative for SARS-CoV-2 (COVID-19) on a nucleic acid test before admission and had no clinical symptoms and pulmonary CT manifestations associated with COVID-19 infection before and during hospitalization (8,9).

Lung recruitment maneuver

All patients were mechanically ventilated under tracheotomy or tracheal intubation with continuous positive airway pressure (CPAP) to maintain the original PEEP.

The positive pressure level was set to 30–40 cmH_2O for 30 s and then adjusted to the original positive pressure level. The cycle was repeated every 30 minutes and treatment was performed 8 times daily. During the lung recruitment maneuver, attention was paid to serious adverse reactions caused by it, and if these developed, the recruitment maneuver was stopped. The adverse reactions included a decrease in arterial systolic blood pressure below 90 mmHg or a decrease of more than 30 mmHg compared to before recruitment; an increase in heart rate above 140 beats/min or an increase of >20 beats/min compared to that before recruitment, or a decrease by more than 5% compared to that before recruitment; new arrhythmia; or the development of subcutaneous emphysema.

Collected data

General information

The sex, age, body weight, Glasgow Coma Scale (GCS) score on admission, airway status, days of ventilation before the study, and length of stay in the NICU of all patients were recorded when the patients were admitted. The GCS and Glasgow Outcome Scale (GOS) score of patients undergoing lung recruitment maneuver were recorded at discharge as outcome indicators.

Subject data before and after recruitment

PaO_2 value before and 30 minutes after lung recruitment maneuver on the first day and corresponding calculated oxygenation index (OI) (defined as a ratio of partial pressure of arterial oxygen to fraction of inspired oxygen) values were recorded. Simultaneously, we recorded the ventilator parameters before and after lung recruitment, such as minute ventilation, respiratory rate, PEEP, plateau pressure, and respiratory system compliance, and calculated the tidal volume based on body weight.

Imaging examinations

Chest CT or bedside chest radiographs before recruitment were compared to those taken 3 days after the start of lung recruitment maneuver to observe whether the area of insufficiency of the lungs decreased, the transparency of the lung tissues increased, or whether the ground glass shadows were reduced.

Statistical analysis

IBM SPSS Statistics for Windows, version 25.0 was used to process the data. Measurement data (without missing data) conforming to the normal distribution are represented by means ± standard deviation. Non-normal distribution measurement data (without missing data) are represented by M [Q1–Q3]. Count data (without missing data) are represented by the number of cases (percentage).

Before and after lung recruitment, the data conforming to the normal distribution were compared using the paired *t*-test, and the data not conforming to the normal distribution were compared using the Wilcoxon test. $P<0.05$ indicated statistical significance.

Results

General clinical data

The data of a total of 33 patients were collected in this study. Among them were 17 cases of traumatic brain injury and 16 cases of spontaneous intracranial hemorrhage. The age range was 39–81 years (average 65.2±11.4 years), and 23 cases were male and 10 were female. The average weight was 63.4±9.5 kg. The GCS scores at admission and discharge were 9 [6–12.5] and 10 [8–14] points, respectively, and the GOS score at discharge was 3 [2.5–4] points. Before lung recruitment, 12 patients (36.4%) had tracheal intubation and 21 patients (63.6%) had tracheotomy. All patients had been admitted for 13 [8–23] days before recruitment. After 5 consecutive days of lung recruitment maneuver, 6 patients (18.2%) had the tracheal intubation removed, and 10 patients (30.3%) were removed from ventilation and switched to non-invasive nasal oxygen tube therapy. The total hospital stay was 24 [19–49] days (*Table 1*).

Effect of lung recruitment maneuver

After lung recruitment, the tidal volume 9 [8.05–10.65] mL/kg, minute ventilation (9.7±1.1 L/min), and respiratory system compliance 69 [50–82.5] mL/cmH_2O of patients were compared with the tidal volume 8.1 [6.85–10.05] mL/kg, minute ventilation volume (9.3±1.3 L/min), and respiratory system compliance 60 [39–80] mL/cmH_2O before lung recruitment, which were all significantly improved (all $P<0.01$; *Figure 1A-1C*). After lung recruitment maneuver, the respiratory rate 17 [14–18.5] breaths/min, PEEP 4 [4–5] cmH_2O, and plateau pressure 18 [16–19.5] cmH_2O of patients after lung recruitment were significantly lower than the respiratory rate 17 [16–21.5] breaths/min, PEEP 4 [4–6] cmH_2O, and plateau pressure 19 [17–23] cmH_2O

Table 1 Clinical data of 33 patients with severe neurological disease

Characteristics	Overall population (N=33)
Sex	
Male	23 (69.7)
Female	10 (30.3)
Age, years	65.2±11.4
Body weight, kg	63.4±9.5
GCS score on admission, points	9 [6–12.5]
GCS score at discharge, points	10 [8–14]
GOS score at discharge, points	3 [2.5–4]
Airway status	
Tracheal intubation	12 (36.4)
Tracheotomy	21 (63.6)
Days of ventilation before study	13 [8–23]
Length of stay, days	24 [19–49]

Data presented as n (%), mean ± standard deviation or M [Q1–Q3]. GCS, Glasgow Coma Scale; GOS, Glasgow Outcome Scale.

before lung recruitment (all P<0.01; *Figure 1D-1F*). The PaO_2 (127.3±34.95 mmHg) and OI (306.9±96.52 mmHg) measured after lung recruitment were significantly higher than those before lung recruitment (PaO_2 =104.2±33.17 mmHg, OI =250.6±87.65 mmHg; all P<0.01; *Figure 1G,1H*; *Table 2*).

Imaging results

Most patients showed improvements in lung imaging examination findings after lung recruitment maneuver. Chest radiographs of 25 patients after lung recruitment showed decreased or even disappeared areas of lung inflation and lung exudation compared to the previous imaging findings (*Figure 2*). The chest radiographs of 2 patients showed increased lung tissue transparency and reduced ground-glass changes after lung recruitment compared to those before recruitment. *Figure 3* shows a case of insufflation of both lungs and significant dorsal consolidation in a patient with cerebral hemorrhage before lung recruitment. *Figure 4* shows lung CT with large dorsal lungs of the patient 5 days after recruitment. The consolidation shadow decreased by more than 2/3. However, the imaging findings of 6 patients showed no obvious improvements.

Adverse reactions

In this study, no patients terminated the operation due to serious adverse reactions during the lung recruitment maneuver and all patients successfully completed it.

Discussion

Volume-controlled ventilation with low PEEP is often used in neurosurgical craniotomy to maintain a stable level of arterial carbon dioxide partial pressure ($PaCO_2$) and prevent the increase of ICP. Therefore, neurosurgical patients are prone to atelectasis (10). Neurocritical patients have varying degrees of consciousness disturbance, decreased airway protection, and decreased sputum excretion ability, along with a high incidence of secondary lung infection. Some patients require long-term mechanical ventilation (11), which can also easily lead to atelectasis. Prolonged untreated atelectasis can progress to lung consolidation, causing difficulty in oxygenation and a continuous decrease in blood oxygen content. The latter can further aggravate the intracranial situation and delay or even hinder the recovery of nerve function (12). Therefore, the timely correction of atelectasis in neurocritical patients is important for improving their prognosis.

Lung recruitment maneuver

The current commonly used lung recruitment maneuver includes sustained inflation (SI), incremental PEEP and pressure control ventilation, all of which use higher positive airway pressure levels to help alveolar recruitment, reduce pulmonary congestion and interstitial edema, and improve ventilation/blood flow ratio to improve oxygenation (13). It has been reported that lung recruitment maneuver with higher PEEP will increase the mortality of ARDS patients (14). The SI method used in this study maintained the CPAP ventilation mode of the patient, and temporarily increased the positive pressure to 30–45 cmH_2O every 30 minutes for 30–40 s before returning to the original ventilation setting (15). This method makes small changes in the settings of respiratory parameters, did not affect the PEEP setting, and was more suitable for critically ill patients with higher requirements for maintaining ICP stability.

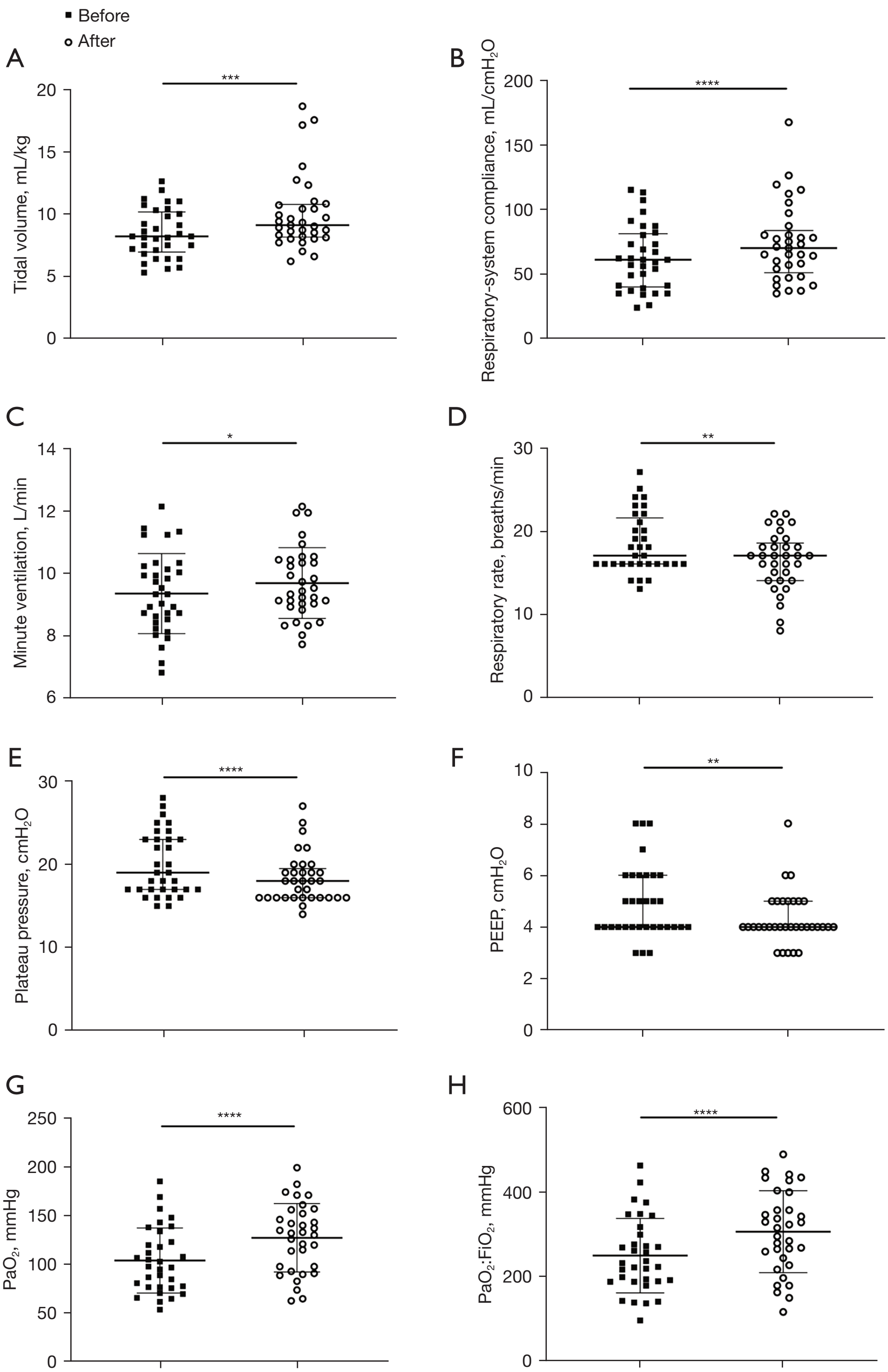

Figure 1 Respiratory parameter values of 33 patients before and after lung recruitment. The data of (A,B,D-F) are expressed by median with interquartile range, and P was calculated by the Wilcoxon test. The data of (C,G,H) are represented by mean with standard deviation, and the P value was calculated by the paired *t*-test. (A) Tidal volume, (B) respiratory system compliance, (C) minute ventilation, (D) respiratory rate, (E) plateau pressure, (F) PEEP, (G) the PaO_2, (H) ratio of PaO_2:FiO_2. *, P value <0.05, **, P value <0.01, ***, P value <0.001, ****, P value <0.0001. PEEP, positive end-expiratory pressure; PaO_2, partial pressure of arterial oxygen; FiO_2, fraction of inspired oxygen.

Table 2 Data comparisons before and after lung recruitment

Characteristics	Before lung recruitment (N=33)	After 5 days of lung recruitment (N=33)	Effective size	P value
Tidal volume, mL/kg of body weight	8.1 [6.85–10.05]	9 [8.05–10.65]	0.6633[a]	<0.001[c]
Minute ventilation, L/min	9.3±1.3	9.7±1.1	0.8053[b]	0.017[d]
Respiratory rate, breaths/min	17 [16–21.5]	17 [14–18.5]	0.5598[a]	0.001[c]
PEEP, cm of water	4 [4–6]	4 [4–5]	0.6033[a]	0.009[c]
Plateau pressure, cm of water	19 [17–23]	18 [16–19.5]	0.8132[a]	<0.001[c]
Respiratory system compliance, mL/cm of water	60 [39–80]	69 [50–82.5]	0.8406[a]	<0.001[c]
PaO_2, mmHg	104.2±33.1	127.3±35.0	0.7573[b]	<0.001[d]
PaO_2:FiO_2, mmHg	250.6±87.7	306.9±96.5	0.7687[b]	<0.001[d]

[a], Spearman's Ranked Correlation Coefficient (rs); [b], Correlation coefficient (r); [c], Wilcoxon test; [d], paired *t*-test. P<0.05 was considered significant. Data presented as mean ± standard deviation or M [Q1–Q3]. PEEP, positive end-expiratory pressure; PaO_2, arterial partial pressure of oxygen; FiO_2, fraction of inspired O_2.

Assessment indicators for recruitment

The indicators used to evaluate the effect of lung recruitment maneuver have different characteristics. PaO_2 and OI (16-18) can directly and rapidly reflect lung ventilation. The ventilation/perfusion ratio decreases when atelectasis occurs, leading directly to decreased PaO_2. When the occluded airway and alveoli are reopened, the ventilation efficiency and PaO_2 increase. The OI value is not affected by changes in fraction of inspired oxygen (FiO_2) and is sensitive and specific for determining changes in lung gas exchange (19). Lung imaging examination is a common and intuitive method to observe the lungs. Lung CT images show the degree and range of lung expansion (7) and can be used to diagnose atelectasis and assess its severity. Although chest X-rays cannot show the texture of the lungs as accurately as CT, they can be used to indirectly assess the patient's atelectasis by observing the transparency of the lungs. If the patient cannot accept CT examination temporarily, bedside chest X-rays is also the most straightforward and effective method to evaluate atelectasis. Besides, CT combined with the helium dilution technique to calculate functional residual capacity (20), or CT combined with lung pressure-volume curve calculation (21). Such methods based on CT have higher requirements for patient status and hardware technology and are more difficult to operate for neurocritical patients. Finally, Respiratory mechanics to measure the amount of gas entering the normal lung ventilation unit and the newly opened ventilation unit (22). The evaluation idea of this kind of method is different from CT. It cannot measure collapsed and/or recruitable lung tissue like CT (23). Although it can be performed at the bedside, it also requires specific hardware technology, which limits its widespread applicability.

Analysis of arterial oxygenation and imaging

In this study, 33 patients completed SI lung recruitment maneuver, with no adverse reactions during treatment. Among them, the PaO_2, OI, and imaging manifestations of 24 patients improved after lung recruitment compared to those before lung recruitment, demonstrating that lung recruitment maneuver increased functional residual capacity, thoracic elasticity, and lung oxygenation (24). In another 3 patients, PaO_2 and OI improved after lung recruitment compared to those before lung recruitment but the imaging performance did not improve significantly. This may be because the improvement in lung imaging was slower than the change in arterial blood gas values. We observed that neither lung CT nor chest X-ray showed changes for 3–5 days even if PaO_2 was significantly increased after lung recruitment in some patients. Significant changes and improvements in lung conditions were observed in chest imaging examinations performed after 7 days of continual lung recruitment maneuver. The imaging findings of 3 patients improved after lung recruitment compared to those before lung recruitment; however, PaO_2 and OI were not significantly improved. This may be because while some patients have partial atelectasis, their lung tissue oxygen exchange can

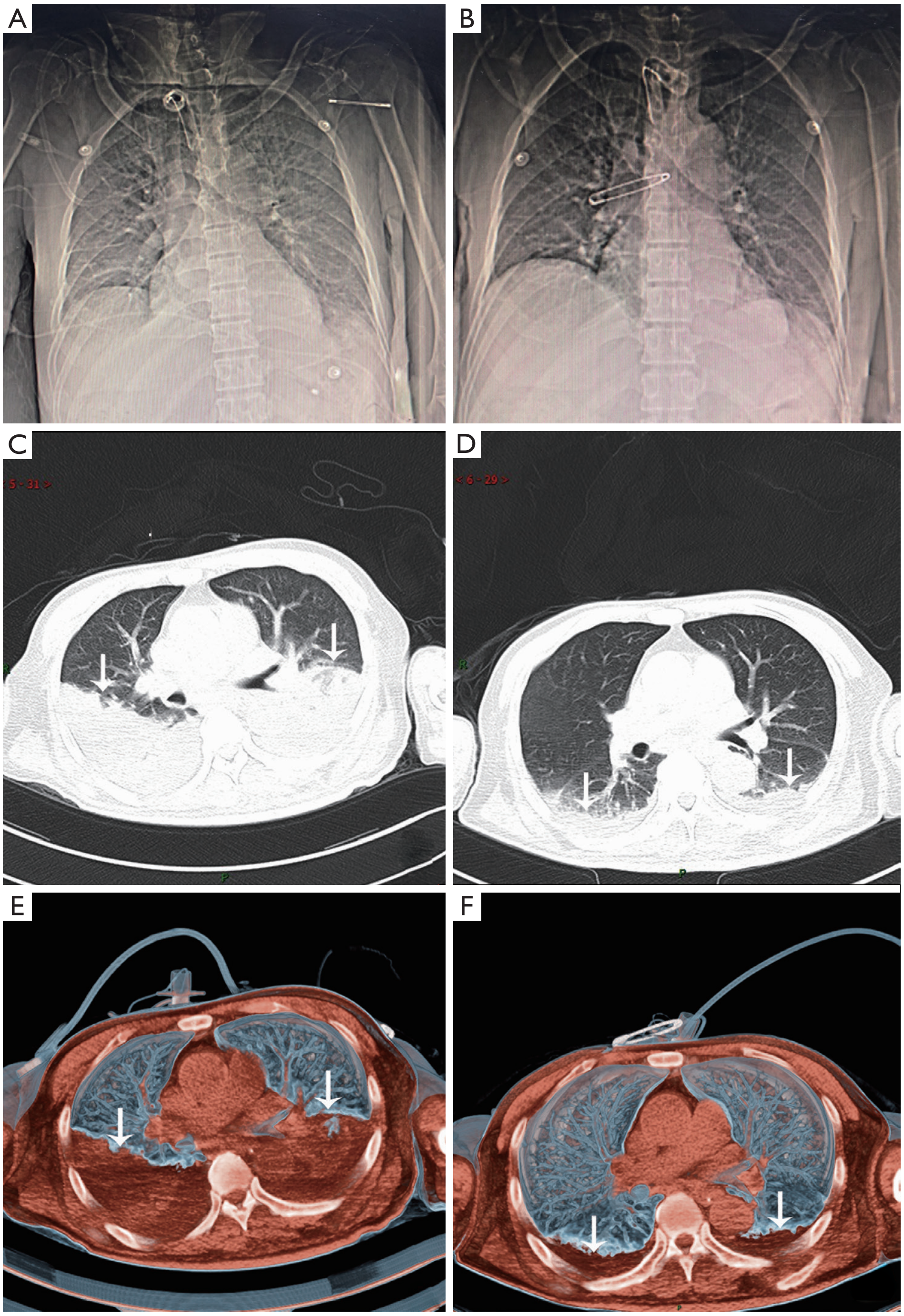

Figure 2 Comparisons of lung CT images before and after recruitment therapy. (A) Bedside chest radiographs before lung recruitment showing decreased lung tissue transmittance and ground-glass changes; (B) bedside chest radiographs 3 days after lung recruitment showing significantly increased lung tissue transmittance and reduced ground-glass changes; (C) CT image before lung recruitment showed partial swelling of the lungs and large dorsal consolidation shadows (arrow); (D) CT image 3 days after lung recruitment showing inflated parts in both lungs and dorsal consolidation contrast. The front is significantly reduced (arrow); (E) 3D reconstruction of chest CT (abdomen and lung structure rendering) before lung recruitment showing partial swelling of the lungs and large dorsal consolidation (arrow); (F) after lung recruitment, 3D chest CT reconstruction (abdomen and lung structure rendering) showing inflated parts of the lungs and reduced consolidation of the dorsal side (arrow).

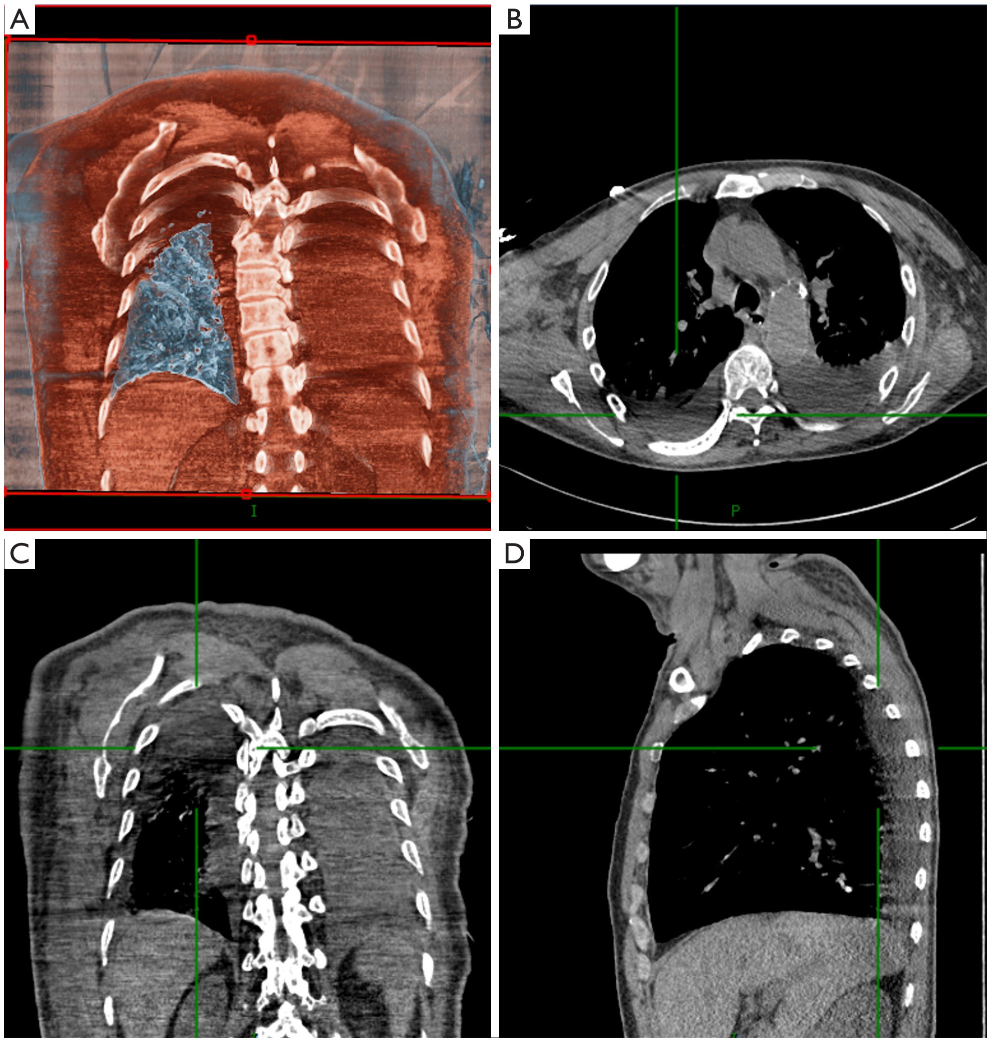

Figure 3 Lung CT plain scans and three-dimensional reconstruction before lung recruitment therapy showing partially inflated lungs and large dorsal consolidation. (A) Chest CT three-dimensional reconstruction (abdomen and lung structure rendering) in the coronal plane; (B) chest CT in the horizontal plane; (C) chest CT in the coronal plane; (D) chest CT in the sagittal plane.

still be compensated; thus, although lung recruitment maneuver reduces atelectasis, PaO_2 and OI do not increase significantly (20-22). Three patients in this study showed no improvement in PaO_2, OI, or imaging performance after lung recruitment maneuver. This may be due to functional/structural changes of alveolar surfactants, which failed to respond to the therapeutic effects of lung recruitment maneuver (6). In addition, due to the different sensitivities of patients at different PEEP levels to lung recruitment maneuver, different outcomes may occur under the same lung recruitment maneuver (25-26). The results of this study indicate that lung recruitment maneuver in patients with severe neurological conditions with atelectasis can reduce atelectasis, increase PaO_2, and improve oxygenation. Therefore, in cases with no increase in intracranial hematoma, no aggravation of edema, and stable ICP, attention should be paid to atelectasis, and timely lung recruitment maneuver should be performed to improve oxygen supply to body tissues. However, given the small sample size of this study, the clinical significance of lung recruitment maneuver in the treatment of patients with severe neurological conditions and atelectasis requires further research and exploration.

Respiratory parameters

Studies have reported that the use of airway pressure release ventilation (APRV) for the lung recruitment maneuver of

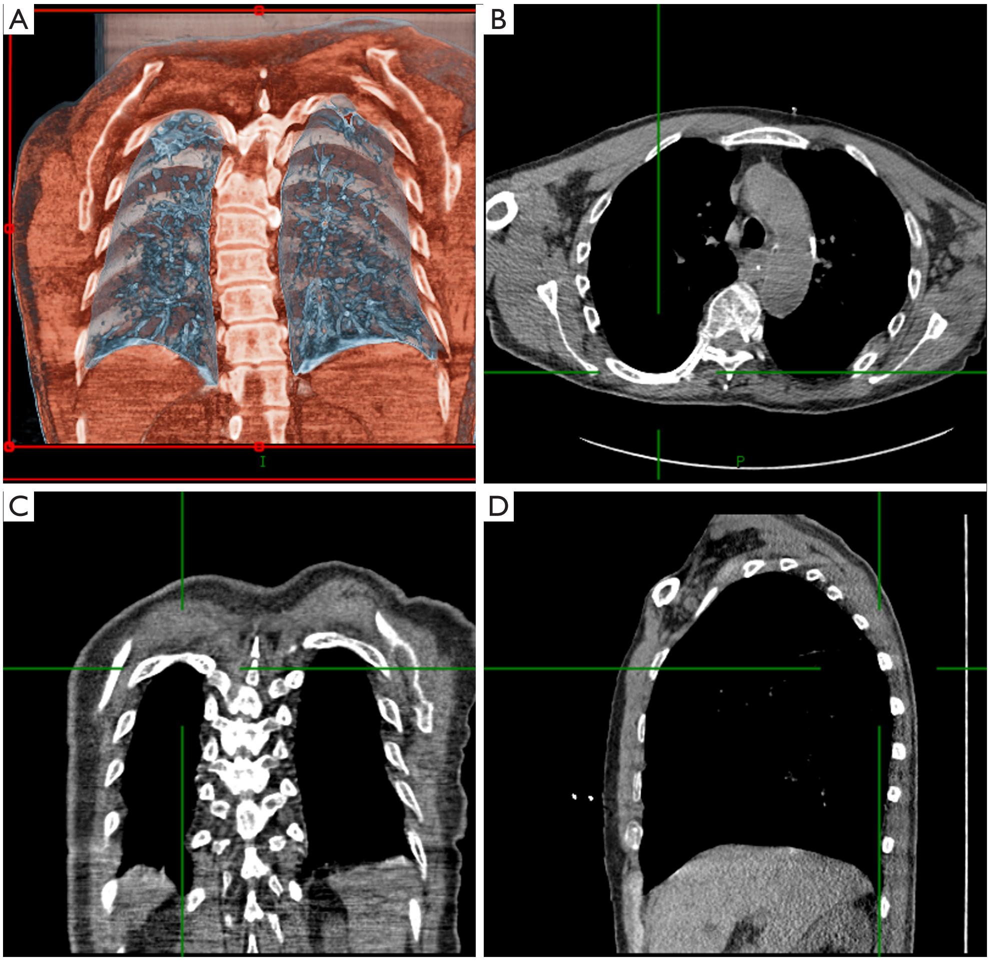

Figure 4 Lung CT plain scans and three-dimensional reconstruction after lung recruitment therapy showing the inflated part of the lungs and significantly reduced consolidation of the dorsal side compared to the previous scan. (A) Chest CT three-dimensional reconstruction (abdomen and lung structure rendering) in the coronal plane; (B) chest CT in the horizontal plane; (C) chest CT in the coronal plane; (D) chest CT in the sagittal plane.

patients with ARDS can reduce plateau pressure, increase average airway pressure, and improve oxygenation and respiratory system compliance (27-29). The appropriate PEEP and tidal volume should be selected according to the recruitment potential of ARDS patients to maximize the protection of normal alveoli and closed alveoli (30,31).

In this study, based on the protection of ICP, we did not adjust PEEP, but intermittently and briefly increased tidal volume to cause alveolar recruitment. Too low $PaCO_2$ can cause intracranial vasoconstriction and insufficient perfusion of brain tissue, while too high $PaCO_2$ will lead to intracranial vasodilation, excessive perfusion of brain tissue, and an increase of ICP. All these are disadvantageous to the recovery of neurological function (32). Therefore, we adjusted the patient's minute ventilation to keep $PaCO_2$ within the range of 35–45 mmHg. The results are consistent with previous reports. Lung recruitment maneuver can reduce atelectasis in neurosurgery. The patient's required respiratory rate, PEEP, and plateau pressure decrease, while improving tidal volume, minute ventilation, and lung compliance, thereby increasing oxygenation.

This study has some limitations. The number of enrolled patients was small, and the data of each patient may have a significant impact on the results. In addition, the study lacked a control group. There may be bias in comparing data before and after lung recruitment. A sufficient number of control measures will make these findings more convincing.

In summary, the incidence of atelectasis in critically ill patients is high. Without timely correction, atelectasis can lead to lung consolidation, persistent dyspnea, and prolonged hospital stay in the ICU. Severe cases can even lead to poor recovery of neurological function. The functional prognosis of patients is poor. Lung recruitment maneuver have been widely used in the ICU and have obvious effects on curing or reducing atelectasis. This study is a novel attempt to apply the method of lung recruitment maneuver to neurocritical care patients. We applied an SI method to treat neurocritical care patients with lung recruitment, resulting in significant improvements in PaO_2, OI, and imaging manifestations. These findings indicate that the SI method is suitable for the treatment of lung recruitment maneuver in NICU.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://atm.amegroups.com/article/view/10.21037/atm-22-554/rc

Data Sharing Statement: Available at https://atm.amegroups.com/article/view/10.21037/atm-22-554/dss

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://atm.amegroups.com/article/view/10.21037/atm-22-554/coif). All authors report that this study was supported by the Fujian Natural Science Fund (No. 2020J011305). The authors have no other conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Medical Ethics Board of Zhangzhou Municipal Hospital of Fujian Province (No. 2022KYB046). Individual consent for this retrospective analysis was waived.

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