Am J Transl Res 2025;17(5):3404-3412
www.ajtr.org /ISSN:1943-8141/AJTR0163966

Original Article

Lung ultrasound score as a tool to assess pulmonary ventilation and disease severity in patients with acute respiratory distress syndrome

Zhiqi Gao[1], Kuan Lu[2], Zugeng Yang[1], Liji Xing[1], Hong Xie[1]

[1]*Department of Anesthesiology, The Second Affiliated Hospital of Soochow University, Suzhou 215004, Jiangsu, PR China;* [2]*Department of Radiology, The Second Affiliated Hospital of Soochow University, Suzhou 215004, Jiangsu, PR China*

Received February 16, 2025; Accepted April 18, 2025; Epub May 15, 2025; Published May 30, 2025

Abstract: Objective: To evaluate the effects of lung ultrasound (LUS) in assessing pulmonary ventilation status in patients with acute respiratory distress syndrome (ARDS). Methods: A total of 35 ARDS patients aged 29-93 years, admitted to the Anesthesiology Intensive Care Unit and scheduled for chest computed tomography (CT), were retrospectively analyzed. Prior to the CT scan, arterial blood gas samples were collected, and LUS scores were obtained using a Sonostar portable ultrasound device. Based on the Berlin definition, patients were categorized into mild ARDS and moderate-to-severe ARDS groups. Lung density, lung volume, proportions of lung volume in different ventilation states, and LUS scores were compared between the groups. Spearman correlation analysis was used to evaluate the relationship between LUS scores and other parameters. Results: Lung density, LUS scores, and the proportion of collapsed lung volume were significantly higher in the moderate-to-severe ARDS group than those in the mild ARDS group (all $P < 0.05$). In patients with moderate-to-severe ARDS, LUS scores showed a moderate correlation with the oxygenation index, lung density, and the proportion of collapsed lung volume. In mild ARDS patients, no significant correlation was observed between LUS scores and these parameters. Conclusion: LUS is an effective, non-invasive tool for evaluating pulmonary ventilation status in ARDS patients and is particularly reliable in assessing ventilation status in those with moderate-to-severe ARDS.

Keywords: Lung ultrasound, acute respiratory distress syndrome, pulmonary ventilation

Introduction

Acute respiratory distress syndrome (ARDS) is a critical clinical condition with alarmingly high incidence and mortality rates [1]. Mechanical ventilation remains a cornerstone of supportive treatment for ARDS patients [2], playing a vital role in correcting hypoxemia, relieving respiratory distress, and preventing or reversing atelectasis [3]. Accurate adjustment of mechanical ventilation parameters and timely weaning depend on a comprehensive assessment of pulmonary ventilation function [4].

Currently, the evaluation of pulmonary ventilation in ARDS patients relies primarily on a combination of imaging studies, respiratory mechanics, and blood gas analysis [1]. Among these, chest computed tomography (CT) is widely regarded as the gold standard, providing direct and detailed visualization of pulmonary pathology and the extent of ventilation impairment [5]. However, its clinical use is limited by the need to transport critically ill patients and by concerns about radiation exposure, which hinder frequent and dynamic bedside assessments [6, 7].

The high morbidity and mortality of ARDS, particularly in severe cases where mortality can range from 27% to 45%, highlight the importance of early detection of ventilation loss and pulmonary edema [8]. Early identification facilitates timely and appropriate interventions, potentially reducing complications, ICU length of stay, mortality, and healthcare costs. Yet, traditional physical examination lacks specificity in the early stages of ARDS [1].

https://doi.org/10.62347/MPBV9850

Lung ultrasound (LUS), as a non-invasive, radiation-free, and repeatable bedside tool, has gained increasing application in the diagnosis and monitoring of pulmonary conditions in critically ill patients [9]. Previous studies have demonstrated good agreement between LUS and CT in assessing pulmonary ventilation [10], and LUS scoring has been shown to reflect changes in lung aeration [11]. However, clinical evidence remains limited regarding the consistency of LUS in evaluating ventilatory function across different severities of ARDS [12]. Additionally, the relationship between LUS scores and key clinical parameters, such as the oxygenation index, has not been clearly established.

This study aims to explore whether LUS provides consistent and reliable assessment of ventilatory status in ARDS patients with varying disease severities by comparing correlations between LUS scores and CT-based evaluations. The goal is to enable early, simple, and accurate assessment of ARDS severity in clinical practice, thereby guiding treatment decisions and informing prognosis.

Materials and methods

Participant selection

A retrospective analysis was conducted on the medical records of mechanically ventilated patients admitted to the Anesthesiology Intensive Care Unit of the Second Affiliated Hospital of Soochow University between January and November 2019.

Inclusion criteria: (1) Age ≥ 18 years; (2) First admission to the intensive care unit; (3) Undergoing invasive mechanical ventilation; (4) Requiring chest CT scans during treatment; (5) Meeting the Berlin criteria for ARDS [13]; (6) Complete clinical records.

Exclusion criteria: (1) Conditions interfering with lung ultrasound, such as chest deformity, diaphragmatic hernia, pneumothorax, chest trauma, or skin lesions; (2) History of surgeries altering thoracic anatomy, such as esophagectomy or lobectomy; (3) Severe dysfunction of vital organs (heart, liver, kidneys) or significant hemodynamic instability; (4) Interventions between pulmonary ultrasound and chest CT that could affect imaging results, such as bronchoalveolar lavage, manual sputum clearance, or changes in positive end-expiratory pressure; (5) End-stage disease or pregnancy; (6) Incomplete clinical records.

This study protocol was approved by the Ethics Committee of the Second Affiliated Hospital of Soochow University (JD-LK-2019-009-02). The patient selection process is illustrated in **Figure 1**.

Data collection

General patient information, including sex, age, and body mass index (BMI), was obtained from the hospital's electronic medical record system. Imaging data were collected from radiological examinations.

Chest CT image analysis and index calculation

CT images were transmitted to an ADW 4.7 workstation for analysis using Thoracic VCARru software. Voxel CT values were measured in Hounsfield units (HU), with window width and level set to 1600 HU and -600 HU, respectively. Lung volumes were classified by CT value as follows: Hyperinflated: -1000 to -900 HU; Normally ventilated: -900 to -500 HU; Poorly ventilated: -500 to -100 HU; Collapsed: -100 to +100 HU.

The software automatically calculated total lung volume and the proportion of lung volume in each ventilation state. Lung tissue regions were manually delineated per CT slice, excluding the chest wall, mediastinum, major vessels, and airways. The average CT value for the entire lung was obtained by summing total CT values across slices and dividing by the total lung area.

For regions with known lung volume, the following formulas were applied [14, 15]: Lung gas volume (mL) = lung volume × (average CT value/-1000); Lung tissue volume = lung volume - lung gas volume; Lung tissue weight (g) = lung volume × (-1000 - average CT value)/-1000; Lung density (g/mL) = lung tissue weight/lung volume.

Lung ultrasound acquisition and scoring

Within four hours of the chest CT scan, lung ultrasound was performed using a Sonostar portable device. A standardized 12-zone protocol was adopted. A semi-quantitative scoring system was used to assess the degree of aeration loss in each region [16], assigning a score

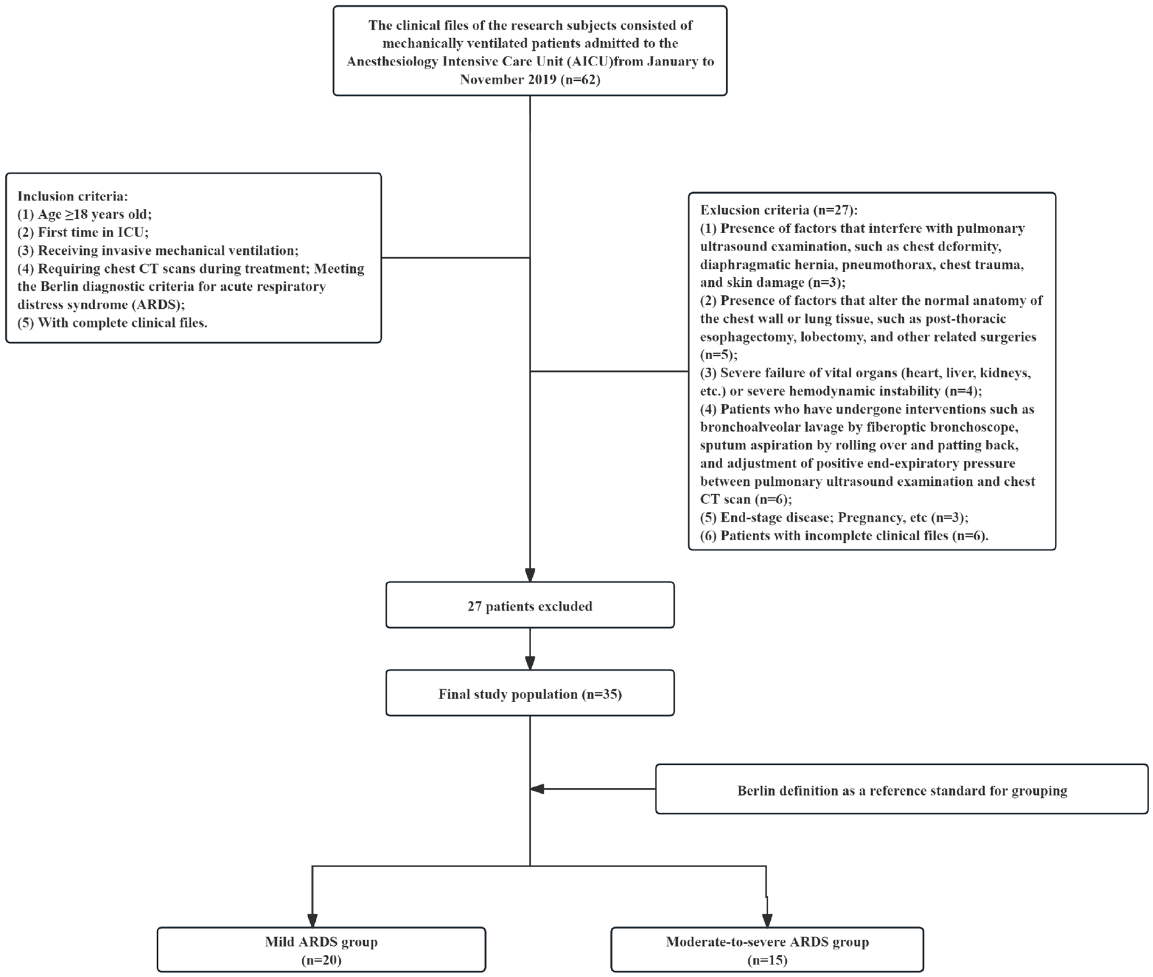

Figure 1. Flow chart for the selection of patients.

from 0 to 3 per zone. The total LUS score ranged from 0 to 36, with higher scores indicating more severe aeration loss. A score of 36 represented complete loss of aeration (**Figure 2**).

Blinding and bias control

All patients were examined using the same ultrasound and CT equipment models. Lung ultrasound imaging was performed by a single experienced anesthesiologist. Two other trained anesthesiologists independently scored the images, and the average of the two scores was used as the final LUS score. Chest CT analysis was performed by one experienced radiologist from the imaging department.

Outcome measures

Primary outcomes included lung density and LUS scores, derived from chest CT and ultrasound data. Secondary outcomes included total lung volume and the proportions of hyperinflated, normally ventilated, poorly ventilated, and collapsed lung volumes. Arterial blood gas samples were also collected prior to CT for evaluation of arterial oxygen partial pressure (PaO_2), carbon dioxide partial pressure ($PaCO_2$), fraction of inspired oxygen (FiO_2) and oxygenation index ($OI = PaO_2/FiO_2$).

Statistical analysis

Sample size was estimated based on the expected Spearman correlation coefficient (r = 0.6) between LUS scores and lung density in ARDS patients. With a power of 80% and a two-tailed alpha of 0.05, a minimum of 31 participants were required. To account for a 10% dropout rate, the target sample size was increased to at least 35 patients.

Data were analyzed using SPSS 23.0 software. Normally distributed quantitative vari-

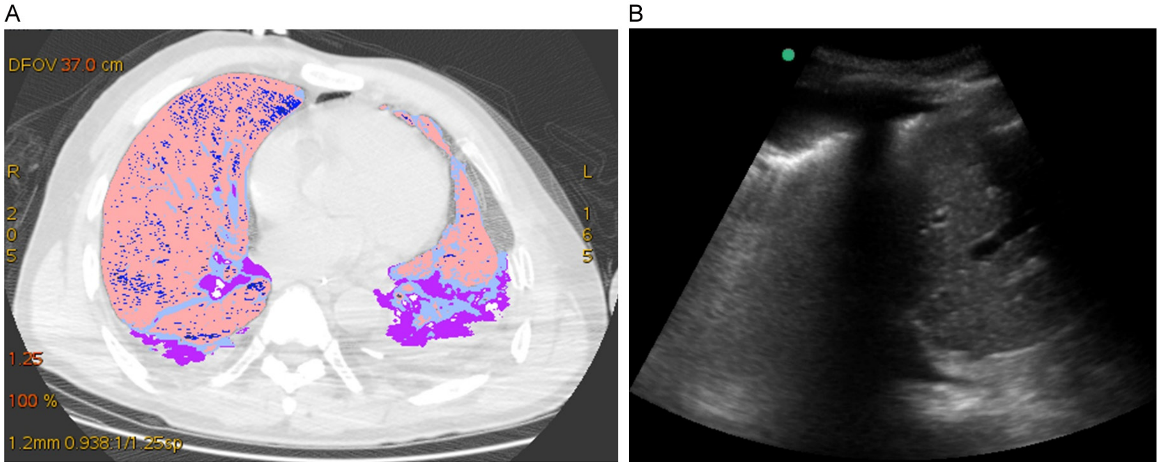

Figure 2. LUS image acquisition and scoring. A: Quantitative analysis of lung CT; B: Lung ultrasound R4 area, 3 points.

Table 1. Comparison of baseline characteristics between mild and moderate-to-severe ARDS patients (*Mean* ± SD)

Groups	Moderate-to-severe ARDS group (n = 15)	Mild ARDS group (n = 20)	χ^2/t	P
Male/female (n)	12/3	12/8	1.591	0.207
Age (years old)	74.0 ± 9.0	69.1 ± 12.4	1.294	0.205
BMI (kg/m^2)	22.4 ± 1.1	23.1 ± 2.0	1.221	0.231
OI (mmHg)	172.5 ± 18.8	258.9 ± 24.3	11.428	< 0.0001
$PaCO_2$	39.5 ± 5.8	36.0 ± 5.6	1.802	0.081
Basic disease				
Diabetes mellitus	4	6	0.047	0.829
Hypertension	5	6	0.044	0.834
Chronic nephrosis	4	3	0.729	0.393
Chronic liver disease	5	4	0.798	0.372
APACHE II	29.3 ± 3.2	27.4 ± 2.2		
pH	7.3 ± 0.2	7.2 ± 0.3	1.116	0.272

Note: ARDS, acute respiratory distress syndrome; BMI, body mass index; OI, oxygenation index; $PaCO_2$, arterial carbon dioxide partial pressure.

ables were expressed as mean ± standard deviation ($\overline{x}$ ± sd), and group comparisons were conducted using independent samples t-tests. Categorical variables were presented as frequencies (%) and compared using Fisher's exact test. Spearman's rank correlation was used to assess relationships between LUS scores and CT-derived indices. A *P*-value < 0.05 was considered statistically significant.

Results

Comparison of general information

No statistically significant differences were found between mild and moderate-to-severe ARDS groups in terms of baseline characteristics, including gender, age, BMI, and $PaCO_2$ levels (all P > 0.05). However, the OI was significantly higher in patients with moderate-to-severe ARDS compared to those with mild ARDS (P < 0.05) (**Table 1**).

Comparison of pulmonary imaging features and LUS scores

Patients with moderate-to-severe ARDS had significantly higher lung density and a greater percentage of collapsed lung volume than those with mild ARDS (P < 0.05). However, there were no statistically significant differenc-

Table 2. Comparison of pulmonary imaging features and LUS scores between mild and moderate-to-severe ARDS patients (*Mean* ± SD)

Groups	Lung density (g/ml)	LUS score	Lung volume (L)	Lung gas volume (L)	Percentage of poorly ventilated lung volume (%)	Percentage of collapsed lung volume (%)	Percentages of poorly ventilated lung volume and collapsed lung volume (%)	Percentage of hyperinflated lung volume (%)
Moderate-to-severe ARDS group (n = 15)	0.4 ± 0.1	16.7 ± 2.3	1.7 ± 0.6	0.8 ± 0.3	10.7 ± 3.0	14.2 ± 7.0	23.6 ± 7.1	6.0 ± 4.2
Mild ARDS group (n = 20)	0.3 ± 0.1	13.6 ± 3.8	1.8 ± 0.7	1.0 ± 0.4	11.2 ± 3.4	9.7 ± 3.2	21.9 ± 8.1	5.9 ± 4.8
t	2.928	2.793	0.444	1.622	0.452	2.521	0.647	0.006
P	0.006	0.009	0.660	0.114	0.654	0.017	0.522	0.949

Note: LUS, lung ultrasound; ARDS, acute respiratory distress syndrome.

Table 3. Comparison of LUS score between pulmonary endogenous and pulmonary extrinsic ARDS patients (*Mean* ± SD)

Groups	Number	LUS score	OI (mmHg)
Pulmonary endogenous ARDS group	19	16.1 ± 3.9	215.3 ± 46.3
Pulmonary extrinsic ARDS group	16	13.6 ± 2.7	228.8 ± 51.3
t	-	2.162	0.818
P	-	0.038	0.419

Note: LUS, lung ultrasound; ARDS, acute respiratory distress syndrome.

es between the two groups regarding total lung volume, lung gas volume, percentage of hyperinflated lung volume, or percentage of poorly ventilated lung volume (all P > 0.05). In addition, LUS scores were significantly higher in the moderate-to-severe ARDS group compared to the mild ARDS group (P < 0.05) (**Table 2**). In addition, we divided the patients into pulmonary endogenous ARDS group and pulmonary extrinsic ARDS group according to the etiology, and compared the LUS score and oxygenation index between two groups. The results showed that LUS score was significantly lower in pulmonary extrinsic ARDS group than in pulmonary endogenous ARDS group (P < 0.05), while the OI between two groups showed no significant differences (P > 0.05, **Table 3**).

Comparison of LUS score and oxygenation index

A significant negative correlation was observed between the LUS score and OI in the overall ARDS cohort (r = -0.489, P < 0.05). In mild ARDS patients, no significant correlation was found (r = -0.154, *P* = 0.518), whereas a significant negative correlation was observed in moderate-to-severe ARDS patients (r = -0.553, *P* = 0.033) (**Figure 3**).

Comparison of LUS score and lung density

In all ARDS patients, the LUS score showed a significant positive correlation with lung density (r = 0.427, P = 0.011). Among patients with mild ARDS, this correlation was not statistically significant (r = 0.313, P = 0.180). However, in the moderate-to-severe ARDS group, a significant positive correlation was identified (r = 0.634, P = 0.011) (**Figure 4**).

Comparison of LUS scores and the percentage of collapsed lung volume

In patients with mild ARDS, there was no significant correlation between the LUS score and the percentage of collapsed lung volume (r = 0.252, *P* = 0.283). In contrast, a strong positive correlation was found in patients with moderate-to-severe ARDS (r = 0.605, *P* = 0.017). This relationship is further illustrated in **Figure 5** for intuitive visualization.

Discussion

Mechanical ventilation is a cornerstone supportive therapy for patients with ARDS [2]. Accurate and timely assessment of ventilatory status is essential for optimizing mechanical ventilation settings, evaluating therapeutic effi-

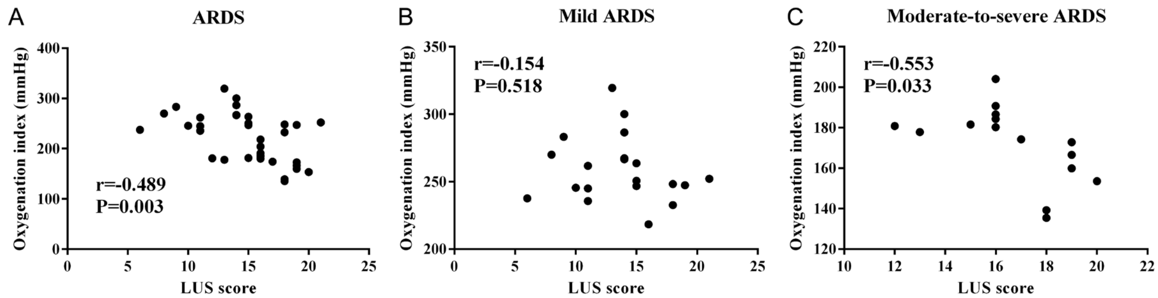

Figure 3. Correlation between LUS score and OI in ARDS patients. A: Correlation between LUS score and OI in all ARDS patients; B: Correlation between LUS score and OI in mild ARDS patients; C: Correlation between LUS score and OI in moderate to severe ARDS patients. LUS, lung ultrasound; OI, oxygenation index; ARDS, acute respiratory distress syndrome.

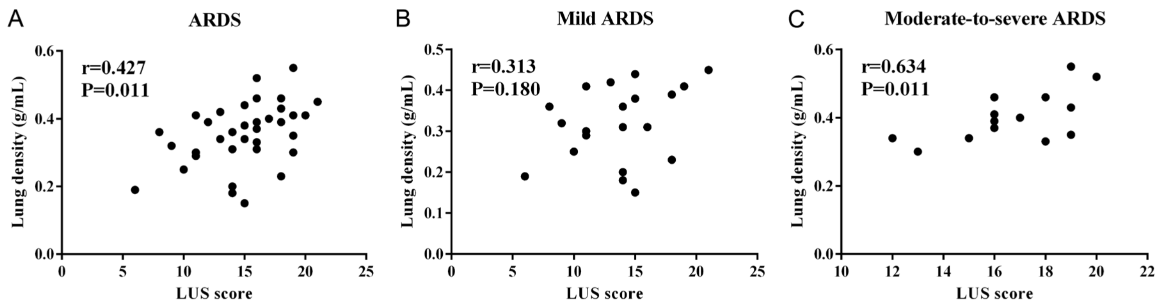

Figure 4. Correlation between LUS score and lung density in ARDS patients. A: Correlation between LUS score and lung density in all ARDS patients; B: Correlation between LUS score and lung density in mild ARDS patients; C: Correlation between LUS score and lung density in moderate to severe ARDS patients. LUS, lung ultrasound; ARDS, acute respiratory distress syndrome.

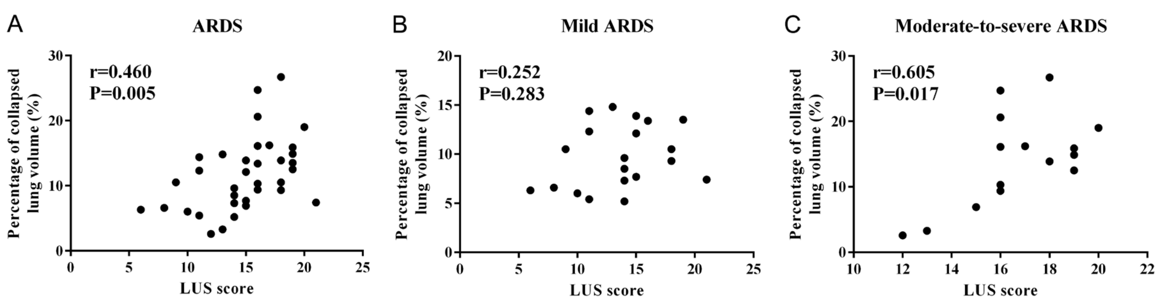

Figure 5. Correlation between LUS score and the percentage of collapsed lung volume in ARDS patients. A: Correlation between LUS score and the percentage of collapsed lung volume in all ARDS patients; B: Correlation between LUS score and the percentage of collapsed lung volume in mild ARDS patients; C: Correlation between LUS score and the percentage of collapsed lung volume in moderate to severe ARDS patients. LUS, lung ultrasound; ARDS, acute respiratory distress syndrome.

cacy, and predicting patient outcomes [1]. LUS, with its non-invasive nature and bedside applicability, has been widely used in diagnosing and managing pulmonary conditions in critically ill patients [17, 18]. Previous studies have shown that LUS is highly valuable in assessing pulmonary ventilation in ARDS patients and demonstrates strong concordance with CT in evaluating lung aeration [19]. The LUS score has been recognized as a robust indicator of both global and regional lung aeration [20]. However, its reliability across varying severities of ARDS remains insufficiently explored. The primary objective of this study was to determine whether LUS maintains consistent accuracy in evaluating pulmonary ventilation in

ARDS patients with different disease severities. Our findings suggest that LUS provides more reliable assessments in patients with moderate-to-severe ARDS than those with mild ARDS.

LUS evaluates pulmonary ventilation by detecting characteristic ultrasound findings corresponding to different degrees of lung edema or consolidation [21]. The scoring system quantifies four distinct sonographic patterns, with higher scores reflecting greater loss of aeration due to tissue edema or consolidation [22]. Thus, LUS provides an indirect yet informative assessment of lung ventilation status. Our results demonstrated a significant correlation between LUS scores and both lung density and OI, indicating that LUS can effectively reflect the extent of lung pathology in ARDS. Moreover, the consistency between LUS and CT in evaluating lung aeration further supports the clinical utility of LUS in ARDS management [5].

Pulmonary edema and consolidation disrupt lung volume and ventilation-perfusion balance, serving as major contributors to respiratory failure in ARDS patients [23, 24]. As lung tissue edema or consolidation worsens, respiratory failure becomes more severe [2]. In our study, patients with moderate-to-severe ARDS had significantly higher lung density and lower OI than those with mild ARDS. Correspondingly, LUS scores were also significantly elevated in the moderate-to-severe ARDS group. These findings are consistent with those of Li et al. [25], who reported higher LUS scores in pulmonary ARDS compared to extrapulmonary ARDS and a progressive increase in LUS scores with increasing ARDS severity.

We further compared the proportions of hyperinflated, poorly ventilated, and collapsed lung volumes between the two ARDS severity groups. While the percentages of hyperinflated and poorly ventilated lung volumes did not differ significantly between groups, the proportion of collapsed lung volume was significantly higher in the moderate-to-severe ARDS group. Given that LUS scores closely reflect the degree of lung edema or collapse [26], this finding may explain the higher LUS scores observed in the more severe group. However, the lack of significant difference in the percentage of poorly ventilated lung volume contrasts slightly with the significant difference in LUS scores, suggesting that collapsed regions may have a more substantial impact on LUS scoring than poorly ventilated areas.

Pulmonary edema results in impaired gas exchange due to ventilation-perfusion mismatch and intrapulmonary shunting, inactivation of surfactant leading to alveolar collapse, reduced lung compliance, increased inspiratory pressure requirements, and heightened work of breathing [27]. Consequently, more severe ARDS is associated with greater degrees of lung collapse and dysfunction. In line with this, we observed a significant negative correlation between LUS score and OI in both overall ARDS patients and those with moderate-to-severe ARDS. This trend was also noted in the study of Li et al. [25], reinforcing the utility of LUS as a clinical tool for evaluating ARDS severity and respiratory compromise.

Furthermore, the findings of this study clearly demonstrated a significant correlation between LUS scores and lung density in patients with moderate-to-severe ARDS. In contrast, no such correlation was observed in patients with mild ARDS. This disparity suggests that the LUS score more accurately reflects the extent of pulmonary edema and consolidation in moderate-to-severe ARDS compared to mild cases, thereby offering greater clinical utility in assessing ventilation status in more severe disease.

Additionally, our results showed a strong positive correlation between LUS scores and the percentage of collapsed lung volume in moderate-to-severe ARDS patients. Based on this finding, it is reasonable to infer that as lung collapse increases, the LUS score also rises significantly. This indicates that the reliability of LUS in evaluating pulmonary consolidation may be closely related to the extent of lung tissue collapse.

However, this study has several limitations. First, LUS is a semi-quantitative technique that relies on ultrasound artifacts to indirectly assess pulmonary lesions. Unlike CT imaging, it cannot directly visualize morphological changes in lung tissue, limiting its accuracy in evaluating disease progression and identifying etiologies. Second, the sample size was relatively small, and we did not conduct further regression analyses to explore other potentially influential factors, such as the distribution of poorly ventilated regions or specific ARDS etiologies. Therefore, it remains uncertain whether additional variables may impact the reliability of LUS in assessing pulmonary ventilation, which warrants further research.

In conclusion, LUS is an effective tool for evaluating pulmonary ventilation status in ARDS patients. Its reliability is notably higher in moderate-to-severe ARDS than that in mild ARDS, and this reliability appears to increase in parallel with the degree of lung tissue collapse.

Disclosure of conflict of interest

None.

Address correspondence to: Hong Xie, Department of Anesthesiology, The Second Affiliated Hospital of Soochow University, Suzhou 215004, Jiangsu, PR China. Tel: +86-13962161588; E-mail: hongx2016@126.com

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