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Predictive value of the combination of lung ultrasound score, extravascular lung water index, and C-reactive protein/procalcitonin ratio for acute respiratory distress syndrome in patients with severe pneumonia

Prediktivna vrednost kombinacije skora ultrazvuka pluća, ekstravaskularnog indeksa vode u plućima i odnosa C-reaktivni protein/prokalcitonin za nastanak akutnog respiratornog distres sindroma kod obolelih od teške upale pluća

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Abstract

Background/Aim. Discovering rapid and efficient biomarkers to predict the occurrence of acute respiratory distress syndrome (ARDS) is crucial for guiding subsequent treatment in patients with severe pneumonia (SP). The aim of this study was to determine the predictive value of the combination of the lung ultrasound score (LUS), the extravascular lung water index (EVLWI), and the C-reactive protein (CRP)/procalcitonin (PCT) ratio for predicting ARDS in patients with SP. **Methods.** The study included a total of 240 patients treated from January 2023 to January 2025, divided into two groups: a control group (n = 120) comprising patients with mild pneumonia and a research group (n = 120) comprising patients with SP. Comparisons of LUS, EVLWI, and CRP/PCT ratio were performed between the groups. The research group was further divided into an ARDS group (AG) and a non-ARDS group (N-AG). **Results.** Out of the 120 patients with SP, ARDS was registered in 20 (16.67%). The patients in AG exhibited significantly higher values of LUS, EVLWI, and CRP/PCT ratio in comparison to the N-AG patients ($p < 0.05$). In patients with SP, LUS, EVLWI, and CRP/PCT ratio positively correlated with the occurrence of ARDS ($r > 0$, $p < 0.05$) and were identified as independent risk factors for ARDS development (odds ratio > 1, $p < 0.05$). The areas under the receiver operating characteristic curve of LUS, EVLWI, CRP/PCT ratio, and their combination for predicting the occurrence of ARDS in patients with SP were 0.713, 0.739, 0.731, and 0.925 respectively (95% confidence interval: 0.867–0.983), with the combined model incorporating all three parameters showing the highest predictive performance. **Conclusion.** In patients with SP, LUS, EVLWI, and CRP/PCT ratio were elevated and were closely associated with the occurrence of ARDS.

Keywords:
biomarkers; c-reactive protein; pneumonia; prognosis; respiratory distress syndrome; ultrasonography.

Apstrakt

Uvod/Cilj. Otkrivanje brzih i efikasnih biomarkera za predviđanje pojave akutnog respiratornog distres sindroma (*acute respiratory distress syndrome* – ARDS) od ključnog je značaja za usmeravanje daljeg lečenja obolelih od teške upale pluća (*severe pneumonia* – SP). Cilj ovog rada bio je da se utvrdi prediktivna vrednost kombinacije skora ultrazvuka pluća (*lung ultrasound score* – LUS), ekstravaskularnog indeksa vode u plućima (*extravascular lung water index* – EVLWI) i odnosa C-reaktivni protein (CRP)/prokalcitonin (PCT) u prognozi ARDS kod obolelih od SP. **Metode.** Istraživanjem je obuhvaćeno ukupno 240 bolesnika, lečenih od januara 2023. do januara 2025. godine, koji su bili podeljeni u dve grupe: kontrolnu grupu (n = 120) u kojoj su bili oboleli od blage upale pluća i istraživačku grupu (n = 120) sa obolelima od SP. Izvršeno je poređenje vrednosti LUS, EVLWI i odnosa CRP/PCT između grupa. Istraživačka grupa je podeljena na ARDS grupu (AG) i grupu bez ARDS-a (N-AG). **Rezultati.** Od 120 obolelih od SP, ARDS je registrovan kod njih 20 (16,67%). Bolesnici iz AG imali su značajno povišene vrednosti LUS, EVLWI i odnos CRP/PCT u poređenju sa bolesnicima iz N-AG ($p < 0,05$). Kod obolelih od SP, vrednosti LUS, EVLWI i odnos CRP/PCT pozitivno su korelisali sa pojavom ARDS-a ($r > 0$, $p < 0,05$) i identifikovani su kao

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nezavisni faktori rizika od pojave ARDS-a (*odds ratio* > 1, $p < 0,05$). Površine ispod *receiver operating characteristic* krive za vrednosti LUS, EVLWI, odnos CRP/PCT i njihove kombinacije, za predviđanje pojave ARDS-a kod obolelih od SP, iznosile su 0,713, 0,739, 0,731 i 0,925 redom (95% *confidence interval*: 0,867–0,983), redom, pri čemu je kombinovani model koji je uključivao sva tri parametra pokazao najveću prediktivnu sposobnost. **Zaključak.** Kod obolelih od SP, vrednosti LUS, EVLWI i odnos CRP/PCT bili su povišeni i bili su usko povezani sa pojavom ARDS-a.

Ključne reči:
biomarkeri; c-reaktivni protein; pneumonija; prognoza; respiratorni distres sindrom; ultrasonografija.

Introduction

Severe pneumonia (SP), an infectious disease of the lungs caused by severe bacterial or viral infection, is characterized by severe clinical symptoms, rapid disease progression, and a high case fatality rate. Currently, a good prognosis is often achieved in most patients with SP following comprehensive therapies, including empirical anti-infective therapy, respiratory support (such as oxygen therapy and mechanical ventilation), and nutritional support. However, some patients still experience a poor prognosis even after comprehensive therapies and are prone to multiple severe complications [1, 2]. As a common and severe complication of SP, acute respiratory distress syndrome (ARDS) is characterized primarily by pathological alterations, including pulmonary edema (PE), alveolar capillary injury, pulmonary atelectasis, and hyaline membrane formation. Its clinical manifestations include progressive respiratory distress and refractory hypoxemia, seriously jeopardizing the life of patients [3, 4]. Clinically, therapeutic measures such as underlying disease treatment, respiratory and hemodynamic support, pulmonary protection strategies, immunomodulating therapy, and complication prevention are adopted for SP patients with ARDS, and these vary between patients with and without ARDS. Hence, discovering rapid and efficient biomarkers to predict the occurrence of ARDS in patients with SP is of great significance for guiding subsequent treatment strategies.

Previous studies have established that lung ultrasound score (LUS) reflects variations in pulmonary ventilation [5], while extravascular lung water (EVLW) index (EVLWI) quantifies PE and permeability impairment [6]. Additionally, inflammatory markers such as C-reactive protein (CRP) and procalcitonin (PCT), particularly the CRP/PCT ratio, effectively mirror the severity of systemic infection and tissue damage. While these parameters individually correlate with inflammatory lung diseases, their combined efficacy in predicting ARDS progression specifically in patients with SP remains to be elucidated.

The aim of this study was to determine the value of the combination of LUS, EVLWI, and CRP/PCT ratio for predicting the occurrence of ARDS in patients with SP.

Methods

Subjects

This study was approved by the Ethics Committee of Tianjin First Central Hospital, Tianjin, China No. (2021) GSFY [01], from January 27, 2023. The study included a total of 240 patients treated from January 2023 to January 2025. The patients were divided into two groups: a control group and a research group. The control group included 120 patients with mild pneumonia, while the research group included 120 SP patients receiving treatment therein in the same period. The mild pneumonia group was included as a reference group to compare baseline levels of LUS, EVLWI, and CRP/PCT ratio between different severities of pneumonia, whereas the primary analysis focused on ARDS prediction within the SP group.

Inclusion and exclusion criteria

The inclusion criteria for this study required that patients met the relevant diagnostic criteria of the Chinese Guidelines for the Diagnosis and Treatment of Adult Community-Acquired Pneumonia (2016 Edition) [7]. SP was defined by the presence of at least one major criterion–either the requirement for mechanical ventilation or septic shock requiring vasopressors–or at least three minor criteria, which included a respiratory rate ≥ 30 breaths/min, partial pressure of oxygen/fraction of inspired oxygen (PaO_2/FiO_2) ≤ 250 mmHg, multilobar infiltrates, or hypotension requiring intensive fluid resuscitation. Patients with confirmed pneumonia who did not meet these severe thresholds were assigned to the mild pneumonia group. Furthermore, eligible participants were required to have complete clinical and imaging data, a stable condition prior to enrollment, and no underlying history of severe immunosuppression. Finally, written informed consent was obtained from all patients or their legal representatives before participation.

The implemented exclusion criteria were as follows: patients with comorbid bronchial asthma, chronic obstructive pulmonary disease, lung tumors, tuberculosis, or other lung diseases; those with congenital airway dysplasia; those with congenital/genetic metabolic disorders; individuals who suffer from malnutrition; those with a history of glucocorticoid, antibiotic, or immunomodulator administration within the 3 months prior to enrollment; those with infectious or hematologic diseases.

Determination of lung ultrasound score

Ultrasonography was performed using a Versana Active scanner (GE HealthCare) equipped with a convex array probe. All post-processing features, including tissue harmonic imaging and spatial compound imaging, were deactivated during the examinations. LUS was measured by

a well-trained doctor from the intensive care unit. The bilateral anterior chest walls, lateral chest walls, and back were outlined along with the parasternal, anterior axillary, and posterior axillary lines, and the region was divided into upper and lower zones using the horizontal line between the nipples, resulting in 12 zones in total. Briefly, 0–3 points were allocated for each of the 12 pre-determined anatomical regions according to ultrasound pattern: normal = 0 points, well-defined B-lines = 1 point, coalescent B-lines = 2 points, consolidation = 3 points (total score: 0–36 points). Lung consolidations (3 points) were noted only when the thickness (perpendicular from the pleura) was greater than 15 mm. Sub-pleural thickening and sub-pleural consolidations (thickness 15 mm or thinner) were assigned a score of 2 points. Due to the observational nature of this study, strict blinding procedures were not formally implemented. However, LUS assessments and laboratory testing were performed independently in routine clinical practice, and clinicians performing LUS were blinded to the corresponding laboratory results during evaluation. The scores, along with details for each zone, were recorded in a table and kept in the patient's medical record to facilitate daily monitoring. LUS was evaluated daily when possible (depending on workload and available medical staff). For the purpose of analysis, the baseline LUS obtained at enrollment was used. The sum of the highest scores of the 12 zones based on ultrasonic findings was recorded as the total LUS.

Determination of extravascular lung water index

Following femoral artery puncture and catheterization, a pulse indicator continuous cardiac output system was utilized to monitor patient hemodynamics. The EVLWI value was measured by transpulmonary thermodilution three consecutive times, and the average value was recorded. For consistency with other variables, the EVLWI value obtained at enrollment (within 24 hrs of admission) was used for analysis.

Measurement of the C-reactive protein/procalcitonin ratio

Fasting venous blood (5 mL) was harvested on the day of enrollment, left at room temperature for 30 min, and centrifuged to isolate the serum. Next, serum concentrations of CRP (Biopike, USCN-HEA821Bo, reference range: 0–5 mg/L) and PCT (EK-Bioscience, Shanghai, China, AB6036, reference range: 0–0.5 μg/L) were determined *via* a double-antibody sandwich enzyme-linked immunosorbent assay (ELISA). The CRP/PCT ratio was calculated by dividing the CRP value (mg/L) by the PCT value (μg/L), without additional unit conversion.

Determination of the occurrence of acute respiratory distress syndrome

ARDS was diagnosed according to the 2012 Berlin definition, which includes the following: acute onset within 1 week of a known clinical insult or new/worsening respiratory symptoms; bilateral pulmonary opacities on chest X-ray imaging that cannot be fully explained by pleural effusions, lobar or lung collapse, or pulmonary nodules; impaired oxygenation classified as mild (200 mmHg < PaO_2/FiO_2 ≤ 300 mmHg), moderate (100 mmHg < PaO_2/FiO_2 ≤ 200 mmHg), and severe (PaO_2/FiO_2 ≤ 100 mmHg). The diagnosis of ARDS was independently established by attending intensive care physicians. Given the observational nature of this study, the diagnosing clinicians had access to patients' routine medical records and were not strictly blinded to the baseline LUS, EVLWI, and CRP/PCT results. However, all diagnoses were strictly adjudicated according to the objective criteria of the 2012 Berlin definition [8].

Collection of general data

The gender distribution, age, body mass index (BMI), respiratory rate, heart rate, blood pressure, oxygen saturation, and arterial lactate values in the ARDS group (AG) and non-ARDS group (N-AG) were recorded. In addition, all predictor variables (LUS, EVLWI, and CRP/PCT) were measured at enrollment (within 24 hrs of admission), prior to the development of ARDS, and were used in subsequent predictive analyses. The occurrence of ARDS was prospectively monitored during hospitalization.

Statistical analysis

For this analysis, SPSS 23.0 software was used. Measurement data were expressed as mean ± standard deviation and examined using the *t*-test. Continuous variables are expressed as median (interquartile range – IQR). Logistic regression (LR) analysis was conducted to identify risk factors for the occurrence of ARDS in patients with SP. The correlations between LUS, EVLWI, and CRP/PCT ratio and the occurrence of ARDS in patients with SP were evaluated using Spearman correlation analysis. Receiver operating characteristic (ROC) curves were constructed to evaluate the predictive performance of LUS, EVLWI, CRP/PCT ratio, and their combination for the occurrence of ARDS in patients with SP. Areas under the curve (AUC) > 0.90, 0.71–0.90, 0.50–0.70, and < 0.50 were considered indicative of high, fair, low, and no predictive accuracy, respectively. A p-value < 0.05 was considered statistically significant. Variables with $p < 0.05$ in univariate analysis were included in the multivariable LR model. Model calibration was evaluated using the Hosmer-Lemeshow goodness-of-fit test, with a $p > 0.05$ indicating acceptable calibration. A sensitivity analysis was conducted by forcing clinically important covariates (including age, oxygen saturation, and arterial lactate value) to assess the robustness of the primary predictors.

Results

A control group comprised 120 patients with mild pneumonia, including 68 males and 52 females aged 40–75

years (mean 50.32 ± 5.28 years), with a BMI of 20–26 kg/m^2 (mean 24.86 ± 0.55 kg/m^2). Besides, a research group was set up to incorporate 120 SP patients receiving treatment therein in the same period, including 70 males and 50 females aged 38–76 years old, with a mean of 50.36 ± 5.46 years old and a BMI of 20–26 kg/m^2 (average 25.03 ± 0.52 kg/m^2). The gender distribution, age, and BMI were comparable between the two groups ($p > 0.05$).

LUS, EVLWI, and CRP/PCT ratio were higher in the research group than in the control group ($p < 0.05$) (Table 1).

Among the 120 patients with SP, 20 (16.67%) had ARDS. Among them, the median interval from baseline predictor measurement to ARDS diagnosis was 2.3 days (IQR: 1–4 days).

The gender distribution, age, BMI, respiratory rate, heart rate, mean arterial pressure, oxygen saturation, and arterial lactate level showed no statistically significant differences between AG and N-AG ($p > 0.05$), whereas LUS, EVLWI, and CRP/PCT ratio were increased in AG compared to those in N-AG. LUS, EVLWI, and CRP/PCT ratio may provide additional predictive value ($p < 0.05$) (Table 2).

The results of Spearman's rank correlation analysis revealed that LUS, EVLWI, and CRP/PCT ratio were positively correlated with the occurrence of ARDS in patients with SP ($\rho > 0$, $p < 0.05$) (Table 3).

Table 1

LUS, EVLWI, and CRP/PCT ratio in research and control groups

Group	LUS, point	EVLWI, mL/kg	CRP/PCT ratio
Research (n = 120)	15.96 ± 2.10	13.89 ± 1.23	9.38 ± 1.03
Control (n = 120)	8.80 ± 1.15	10.75 ± 0.90	6.35 ± 0.52
p-value	< 0.001	< 0.001	< 0.001

LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin; n – number of respondents.
All values are given as mean ± standard deviation.

Table 2

Relevant indicators in ARDS and non-ARDS groups

Indicator	N-AG (n = 100)	AG (n = 20)	*p*-value*
Gender			
male	59 (59.00)	11 (55.00)	0.741
female	41 (41.00)	9 (45.00)	
Age, year	50.32 ± 3.28	51.30 ± 3.25	0.224
Body mass index, kg/m^2	24.86 ± 0.54	24.81 ± 0.52	0.705
Respiratory rate, breaths/min	37.52 ± 5.28	35.56 ± 5.27	0.132
Heart rate, beats/min	100.00 ± 15.52	98.03 ± 14.53	0.602
Mean arterial pressure, mmHg	90.50 ± 5.03	90.51 ± 5.04	0.994
Oxygen saturation, %	93.60 ± 7.04	92.59 ± 7.15	0.560
Arterial lactate value, mmol/L	2.45 ± 0.25	2.50 ± 0.26	0.419
LUS, point	15.02 ± 2.04	20.66 ± 3.20	< 0.001
EVLWI, mL/kg	13.21 ± 1.10	17.29 ± 2.08	< 0.001
CRP/PCT ratio	8.50 ± 0.96	13.78 ± 1.05	< 0.001

ARDS – acute respiratory distress syndrome; N-AG – non-ARDS group; AG – ARDS group; n–number of respondents; LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin.
All values are given as numbers (percentages) or mean ± standard deviation.
***Note*: *Continuous variables were compared using the *t*-test, whereas categorical variables were compared using the chi-square test.**

Table 3

Correlations analysis of LUS, EVLWI, and CRP/PCT ratio with the occurrence of ARDS in patients with severe pneumonia

Coefficient	LUS	EVLWI	CRP/PCT
ρ	0.561	0.603	0.646
p-value	< 0.001	< 0.001	< 0.001

LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin; ARDS – acute respiratory distress syndrome.

Table 4

Results of logistic regression analysis on the occurrence of ARDS in severe pneumonia patients

Item	B	SE	Wald	*p*-value	OR	95% CI
LUS	1.005	0.226	19.845	< 0.001	2.733	1.756–4.253
EVLWI	2.130	0.541	15.521	< 0.001	8.416	2.917–24.285
CRP/PCT	0.577	0.121	22.559	< 0.001	1.780	1.403–2.258

ARDS – acute respiratory distress syndrome; SE – standard error; OR – odds ratio; CI – confidence interval; LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin.

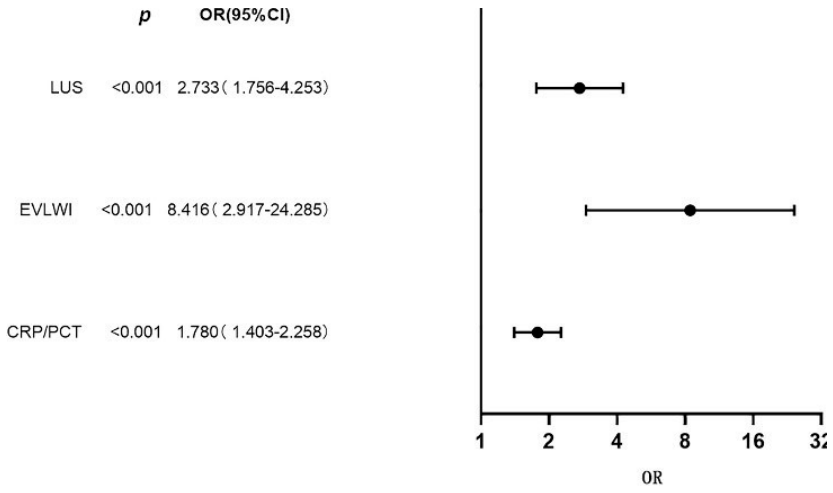

Fig. 1 – Forest plot of clinical characteristics based on multivariate logistic regression analysis. OR – odds ratio; CI – confidence interval; LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin.

Table 5

Value of LUS, EVLWI, CRP/PCT ratio, and their combination for predicting the occurrence of ARDS in patients with severe pneumonia

Item	Optimal cut-off value	AUC	SE	*p*-value	95% CI	Sensitivity	Specificity	Youden index
LUS	16.955 points	0.713	0.076	0.003	0.563–0.862	0.700	0.730	0.430
EVLWI	14.690 mL/kg	0.739	0.073	0.001	0.596–0.883	0.800	0.770	0.570
CRP/PCT	10.635 ratio	0.731	0.072	0.001	0.590–0.872	0.850	0.740	0.590
Combination	-	0.925	0.030	< 0.001	0.867–0.983	0.900	0.840	0.740

LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin; ARDS – acute respiratory distress syndrome; AUC – area under the curve; SE – standard error; CI – confidence interval.

According to LR analysis, LUS, EVLWI, and CRP/PCT ratio served as risk factors for the occurrence of ARDS in patients with SP [odds ratio (OR) > 1, $p < 0.05$].

Twenty ARDS events and three predictors were included in the primary LR model, resulting in an events-*per*-variable ratio of approximately 6.7.

EVLWI showed the strongest association [OR = 8.416, 95% confidence interval (CI): 2.917–24.285], followed by LUS (OR = 2.733, 95% CI: 1.756–4.253) and CRP/PCT ratio (OR = 1.780, 95% CI: 1.403–2.258) (Table 4 and Figure 1). Furthermore, an exploratory sensitivity analysis was performed by additionally adjusting for clinically important covariates, including age, oxygen saturation, and arterial lactate value. In this adjusted model, LUS, EVLWI, and the CRP/PCT ratio remained independently associated with the occurrence of ARDS ($p < 0.05$), and the direction of the associations was consistent with that observed in the primary model, supporting the robustness of these predictors after adjustment for selected baseline clinical covariates.

The ROC curves were plotted using the presence/absence of ARDS in patients with SP (0 = absence, and 1 = presence) as the state variable, together with LUS, EVLWI, and CRP/PCT ratio as the test variables. The results uncovered that the AUCs of LUS, EVLWI, CRP/PCT ratio, and their combination were 0.713 (95% CI: 0.563–0.862), 0.739 (95% CI: 0.596–0.883), 0.731 (95% CI: 0.590–0.872), and 0.925 (95% CI: 0.867–0.983), respectively (Table 5 and Figure 2). The Hosmer-Lemeshow goodness-of-fit test showed no significant evidence of poor calibration for the combined prediction model, with no significant difference between the observed and predicted probabilities ($\chi^2 = 5.684$, $df = 8$, $p = 0.683$).

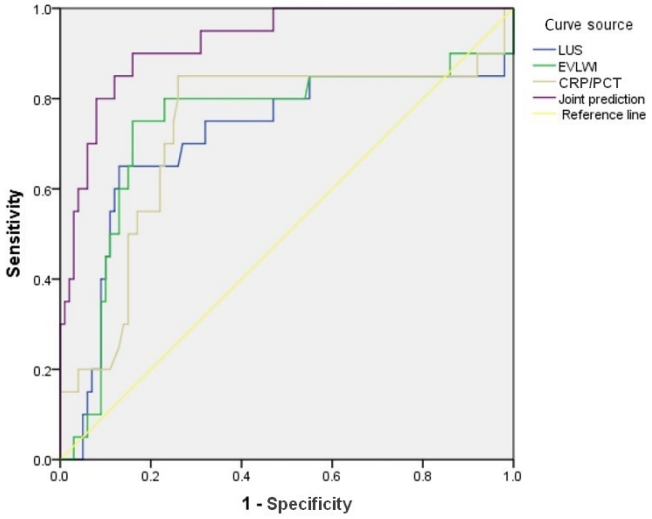

Fig. 2 – ROC curves of LUS, EVLWI, CRP/PCT ratio, and their combination for predicting the occurrence of ARDS in patients with severe pneumonia. ROC – receiver operating characteristic curves; LUS – lung ultrasound score; EVLWI – extravascular lung water index; CRP – C-reactive protein; PCT – procalcitonin; ARDS – acute respiratory distress syndrome.

Discussion

As a serious lung infection, SP covers extensive inflammation and damage to the lungs, which can result in severe complications and enhance the medical and economic burdens. As a common complication of SP in the clinic, ARDS can significantly worsen the illness, enhance the difficulties in infection control and clinical treatment, and increase the mortality rate [9]. Therefore, discovering biomarkers for efficient prediction of ARDS in patients with SP is of great significance for guiding the selection of clinical therapeutic regimens.

LUS, EVLWI, and CRP/PCT ratio were increased in AG, suggesting that conventional clinical indicators alone may be insufficient to distinguish ARDS risk. However, the combination of LUS, EVLWI, and CRP/PCT ratio may provide additional predictive value ($p < 0.05$).

EVLWI is an important parameter for assessing PE and pulmonary permeability impairment, and provides useful information for lung status evaluation and fluid management. A recent systematic review and meta-analysis showed that higher EVLW measured by transpulmonary thermodilution was associated with increased mortality in critically ill patients, supporting the prognostic value of EVLWI in acute lung injury and ARDS-related conditions [10]. EVLWI has also been reported to predict prognosis in patients with acute lung injury in China [11]. In the present study, EVLWI was higher in AG than in N-AG and was positively associated with the occurrence of ARDS. LR analysis further showed that EVLWI was an independent risk factor for ARDS in patients with SP. This may be explained by the disruption of the alveolar-capillary barrier in SP, which increases vascular permeability and promotes PE formation [12–14]. As a quantitative indicator of EVLW, EVLWI reflects the degree of lung water accumulation and pulmonary permeability impairment [15, 16], making its association with ARDS biologically plausible.

LUS is a noninvasive tool for evaluating changes in pulmonary aeration by quantifying lung ultrasound findings. A previous study has shown that LUS changes with the progression of pneumonia and the extent of pulmonary involvement, and may be useful for prognostic assessment [17]. In this study, LUS was significantly higher in AG than in N-AG and was positively associated with the occurrence of ARDS. LR analysis also identified increased LUS as a risk factor for ARDS. These findings are consistent with previous evidence and may be explained by the ability of LUS to reflect diffuse alveolar damage, loss of aeration, and fluid accumulation in the lungs [18–20]. Therefore, a higher LUS may indicate more severe pulmonary involvement and a greater likelihood of progression to ARDS.

CRP and PCT are commonly used inflammatory biomarkers. CRP is an acute-phase protein synthesized by the liver in response to inflammatory stimuli, whereas PCT increases mainly in bacterial infection and systemic inflammatory responses. In the present study, the CRP/PCT ratio was higher in AG than in N-AG and was identified as a risk factor for ARDS. This may be because CRP and PCT reflect different aspects of inflammatory and infectious responses, and an elevated CRP/PCT ratio may indicate aggravated inflammation, tissue injury, and infection burden in SP [21, 22].

With disease progression, this inflammatory imbalance may further contribute to the development of ARDS [23, 24].

In the present study, the AUCs of LUS, EVLWI, CRP/PCT ratio, and their combination for predicting ARDS in patients with SP were 0.713, 0.739, 0.731, and 0.925, respectively, indicating that the combined model exhibited superior predictive performance compared with any individual indicator. This result appears favorable compared

with previously published models. For example, a multicenter lung ultrasound-based ARDS model reported an AUC of 0.90 in the derivation cohort and 0.80 in the validation cohort [5]. In contrast, a nomogram for predicting ARDS in patients with bacterial pneumonia achieved an AUC of 0.794 [25]. A sepsis-associated ARDS prediction model reported AUCs of 0.811 and 0.812 in the training and testing sets, respectively [26]. Although direct comparisons across studies should be interpreted with caution due to differences in study populations, predictor composition, and validation strategies, the combined model in the present study showed promising predictive performance. Clinically, this combination may help identify patients with SP who are at high risk of ARDS and may benefit from closer respiratory and hemodynamic monitoring, earlier optimization of fluid management, and timely escalation of supportive care.

Limitation of the study

This study has several limitations. First, although LUS and EVLWI can be dynamically monitored during clinical management, only baseline measurements obtained at enrollment were included in the present analysis. Therefore, the potential effects of treatment interventions, such as fluid management, ventilatory support, and anti-infective therapy, were not evaluated. Second, although several baseline clinical variables were collected, residual confounding could not be completely excluded. Third, the relatively small number of ARDS events may have affected model stability. In this study, 20 ARDS events and 3 predictors were included in the primary LR model, resulting in an events-*per*-variable ratio of approximately 6.7, which is fewer than the traditionally recommended threshold of 10. Therefore, the model may be at risk of overfitting and should be interpreted as exploratory. In addition, internal validation using bootstrapping was not performed, and an independent external validation cohort was not available. Finally, strict blinding was not formally implemented in this real-world clinical setting, which may have introduced potential observational bias.

Conclusion

The present findings suggest that elevated lung ultrasound score, extravascular lung water index, and C-reactive protein/procalcitonin ratio are associated with the occurrence of acute respiratory distress syndrome in patients with severe pneumonia. Their combined use may enhance predictive accuracy for the occurrence of acute respiratory distress syndrome in these patients. Future studies with larger cohorts, bootstrapping-based internal validation, and multicenter external validation are warranted to confirm the robustness and generalizability of the model.

Conflicts of interest

The authors declare no conflict of interest.

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