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Lung Ultrasound in Pediatric ARDS: Associations with Oxygenation Impairment, RALE Score, and ICU Mortality

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Abstract

Purpose

This study evaluated the associations of lung ultrasound score (LUS) and Radiographic Assessment of Lung Edema (RALE) score with oxygenation index (OI) in children with acute respiratory distress syndrome (ARDS) and explored their apparent prognostic performance for ICU mortality.

Methods

This prospective observational study included children aged 2 months to 16 years with ARDS defined by the Pediatric Acute Lung Injury Consensus Conference-2 criteria in a tertiary pediatric intensive care unit in Vietnam. LUS, RALE score, and OI were assessed within 48 h of ARDS diagnosis (T1) and 48 h later (T2). Associations among LUS, RALE score, and OI were evaluated using Spearman correlation and multivariable linear regression. Exploratory logistic regression models were used to assess ICU mortality.

Results

Forty-two children were included. LUS correlated significantly with OI at both T1 ($r = 0.65$, $p < 0.001$) and T2 ($r = 0.74$, $p < 0.001$). RALE score was also correlated with OI at T1 ($r = 0.41$, $p = 0.007$) and T2 ($r = 0.65$, $p < 0.001$). LUS and RALE score were significantly correlated at both time points. In multivariable linear regression, both LUS and RALE score were independently associated with log-transformed OI. In exploratory mortality models, pre-existing comorbidity was the only independent predictor of ICU mortality.

Conclusion

In children with ARDS, LUS was significantly associated with oxygenation impairment and RALE score. Structured lung ultrasound may serve as a radiation-free bedside adjunct to chest radiography for serial assessment of pediatric ARDS.

What is Known

- Lung ultrasound and RALE score are used to assess lung injury severity in ARDS.
- Pediatric data comparing LUS, RALE score, and oxygenation index remain limited.

What is New

- In children with ARDS, LUS was associated with both oxygenation index and RALE score.
- LUS may serve as a radiation-free bedside adjunct to chest radiography for serial assessment of pediatric ARDS.

Introduction

Pediatric acute respiratory distress syndrome (ARDS) remains a major cause of morbidity and mortality in pediatric intensive care units (PICUs) worldwide. Accurate bedside assessment of lung injury severity and oxygenation impairment is therefore essential for clinical decision-making and prognostication. Chest radiography (CXR) has traditionally been used to evaluate pulmonary involvement in ARDS. The Radiographic Assessment of Lung Edema (RALE) score provides a semi-quantitative method for grading radiographic opacities and has been associated with disease severity and outcomes in adult ARDS as well as with clinical outcomes in pediatric ARDS [1–3]. However, CXR is limited by radiation exposure, inter-observer variability, and limited sensitivity to dynamic changes in lung aeration–limitations that are particularly relevant in pediatric patients requiring frequent reassessment [4]. Lung ultrasound (LUS) has emerged as a bedside, radiation-free imaging modality capable of real-time evaluation of lung aeration. In adult ARDS, LUS has demonstrated strong correlations with oxygenation indices and radiographic severity scores [1,5,6].

Despite increasing adoption of lung ultrasound in pediatric critical care, data regarding the associations of lung ultrasound scores with radiographic edema scoring and pediatric–specific oxygenation metrics remain limited. In particular, the relationship between lung ultrasound and the oxygenation index (OI), the recommended measure of oxygenation impairment in pediatric ARDS according to PALICC–2, has not been well defined. In addition, the prognostic performance of lung ultrasound in comparison with radiographic assessment remains incompletely understood. Therefore, we conducted a prospective observational study to evaluate the associations among lung ultrasound score, RALE score, and oxygenation index at two early time points after ARDS diagnosis in critically ill children, and to explore the comparative prognostic performance of ultrasound–based and radiograph–based models for ICU mortality.

Materials and Methods

This study was approved by the Ethics Committee of Children's Hospital 2, Ho Chi Minh City, Vietnam (Approval No. 725/GCN-BVNĐ2; September 5, 2024). Written informed consent for study participation was obtained from the parents or legal guardians of all enrolled children before data collection. The study was conducted in accordance with the principles of the Declaration of Helsinki and relevant local regulations governing research involving human participants. Given the observational nature of the study, no study–specific interventions were performed, and all clinical management decisions were made at the discretion of the treating physicians.

This prospective observational study was conducted in the Pediatric Intensive Care Unit (PICU) of Children's Hospital 2, Ho Chi Minh City, Vietnam, between September 2024 and May 2025. Children aged 2 months to 16 years who met the PALICC–2 criteria for ARDS were eligible for inclusion and were enrolled within 48 hours of ARDS diagnosis. Exclusion criteria included congenital chest wall malformations, subcutaneous emphysema that interfered with adequate lung ultrasound assessment, congenital heart disease, or chronic lung disease that could confound chest radiographic interpretation.

The primary variables of interest were the Lung Ultrasound Score (LUS), the Radiographic Assessment of Lung Edema (RALE) score, and the Oxygenation Index (OI). Comorbidity was defined as the presence of one or more pre-existing chronic medical conditions documented before PICU admission, including immunodeficiency, hematologic/oncologic disorders, neurologic diseases, gastrointestinal disorders, prematurity and/or low birth weight, and other chronic diseases. For statistical analyses, comorbidity was treated as a binary variable (yes/no). The primary outcome was to evaluate the associations of the Lung Ultrasound Score (LUS) and the Radiographic Assessment of Lung Edema (RALE) score with the oxygenation index (OI) in pediatric ARDS. The secondary outcome was to evaluate the early prognostic performance of LUS– and RALE–based models for predicting ICU mortality.

The study workflow is shown in Figure 1. Patients underwent assessment at two predefined time points: T1: within 48 hours after ARDS diagnosis, and T2: 48 hours after the first assessment (T1). At each time point, three evaluations were performed, including lung ultrasound (LUS), chest radiography for RALE scoring, and measurement of the OI.

For lung ultrasound, each hemithorax was divided into six regions (anterior, lateral, and posterior zones, each subdivided into superior and inferior areas), yielding a total of 12 regions assessed bilaterally [6]. Each region was scored from 0 to 3 based on the predominant sonographic pattern [7,8]: A score of 0 indicated normal lung aeration, with A–lines or fewer than three B–lines observed. A score of 1 indicated the presence of well–separated B–lines involving less than 50% of the pleural line. A score of 2 was assigned when coalescent B–lines covered more than 50% of the pleura, reflecting severe loss of aeration. A score of 3 denoted the presence of subpleural consolidation, representing complete loss of aeration. The total Lung Ultrasound Score (LUS_{TOT}) was calculated by summing the scores of all 12 lung regions, ranging from 0 to 36. Higher scores indicated more extensive and severe loss of lung aeration.

Portable anteroposterior chest radiographs were obtained at the bedside at the same time points as the lung ultrasound examinations. The time interval between chest radiography and lung ultrasound assessments did not exceed 12 hours to ensure temporal comparability. Each lung was divided into four quadrants–upper and lower zones on both the right and left sides–using the vertebral column as the vertical midline and the first branch of the left main bronchus (approximately at the carina level) as the horizontal divider [1]. For each quadrant, two components were evaluated: (1) Extent of consolidation (Con)**:** scored from 0 to 4 according to the estimated percentage of alveolar opacities (0 = none, 1 = <25%, 2 = 25–50%, 3 = 50–75%, and 4 = >75%) and (2) Density of opacification (Den)**:** scored from 1 to 3 based on the radiographic appearance (1 = hazy, 2 = moderate, 3 = dense or white-out). The score for

each quadrant was calculated by multiplying the consolidation and density scores (Con × Den), and the total RALE score was obtained by summing all four quadrants, yielding a possible range from 0 to 48.

The Oxygenation Index was calculated using the standard equation:

$$OI = \frac{FiO_2 \times MAP \times 100}{PaO_2}$$

where FiO_2 is the fraction of inspired oxygen, MAP is the mean airway pressure (cmH_2O), and PaO_2 is the arterial partial pressure of oxygen (mmHg).

Image acquisition and scoring

Lung ultrasound examinations were independently performed and scored by the study investigator and a pediatric intensivist certified in point–of–care ultrasound (POCUS). Chest radiographs were independently scored by the study investigator and a board–certified pediatric radiologist. Both readers were blinded to patients' clinical data and outcomes at the time of image interpretation. Any discrepancies between readers were resolved by consensus discussion, and the final consensus scores were used for analysis.

Statistical analysis

All analyses were performed using SPSS version 26.0 (IBM Corp, Armonk, NY, USA). Continuous variables were assessed for normality using the Shapiro–Wilk test and summarized as mean ± standard deviation (SD) or median with interquartile range (IQR), as appropriate. Categorical variables were presented as frequencies and percentages. Correlations between LUS, RALE, and OI were evaluated using Spearman’s rank correlation. Survivors and non-survivors were compared using Fisher’s exact or Chi–square tests for categorical variables and the Mann–Whitney U test for continuous variables. A two–sided p–value < 0.05 was considered statistically significant.

To identify early predictors of ICU mortality using T1 data, we constructed parsimonious multivariable logistic regression models, limiting each model to a maximum of three predictors to minimize overfitting (19 deaths among 42 patients). Candidate predictors included age, sex, comorbidity, PALICC–2 severity (severe vs non–severe), OI (analyzed per 10-unit increase to facilitate interpretation of the adjusted odds ratios), LUS, and RALE at T1. Three prespecified models were examined: (1) LUS + OI/10 + comorbidity, (2) RALE + OI/10 + comorbidity, and (3) severity + OI/10 + comorbidity. For each model, adjusted odds ratios (aORs) with 95% confidence intervals (CIs) were reported, and discrimination was assessed using the area under the receiver operating characteristic curve (AUC).

Results

Cohort Characteristics

Forty–two children were included in the final analysis, with a total of 77 lung ultrasound examinations performed across two predefined points. The first assessment (T1) was conducted in all 42 patients at study entry, while the second assessment (T2) was performed 48 hours later in 35 patients. Seven children were not available for follow–up at T2 due to four deaths and three transfers to other wards after clinical stabilization.

The cohort had a median age of 11 months (IQR 5.6–54.8), and 64.3% of patients were male. According to the PALICC–2 severity classification, 54.8% presented severe ARDS, while 45.2% had moderate or mild disease. During the ICU stay, the median duration of invasive mechanical ventilation was 9 days (IQR 6–12), and the median length of ICU stay was 10 days (IQR 7–20.8). Overall ICU mortality was 45.2%. (see Table 1).

Correlation Between Imaging Scores and Oxygenation

At both time points, the total Lung Ultrasound Score (LUS_{TOT}) was positively correlated with the OI. At T1, LUS_{TOT} demonstrated a correlation coefficient of $r = 0.65$ ($p < 0.001$), which increased to $r = 0.74$ at T2 ($p < 0.001$). The RALE score was also correlated with OI, with correlation coefficients of $r = 0.41$ at T1 ($p = 0.007$) and $r = 0.65$ at T2 ($p < 0.001$). In addition, LUS_{TOT} and RALE scores were correlated with each other at both time points (T1: $r = 0.59$, $p < 0.001$; T2: $r = 0.72$, $p < 0.001$) (see Supplemental Table 1).

Multivariable Linear Regression for Oxygenation Impairment

In multivariable linear regression using T1 data, both LUS_{TOT} and RALE scores were independently associated with log-transformed OI. LUS_{TOT} was associated with higher log[OI] ($\beta = 0.062$, $p < 0.001$), as was the RALE score ($\beta = 0.017$, $p = 0.038$). The final model explained approximately 50% of the variance in oxygenation impairment (see Figure 2).

Prognostic performance of LUS– and RALE–Based Models at T1

LUS-based and RALE–based prognostic models at T1 showed similar apparent discrimination for ICU mortality. In multivariable logistic regression analysis (Table 2), comorbidity was the only consistent and independent predictor of ICU mortality across all models. In Model A (LUS + OI/10 + comorbidity), neither LUS_{TOT} nor OI was independently associated with mortality, whereas comorbidity showed a strong association (aOR 18.8; 95% CI 2.08–170.3; $p = 0.009$). Similar results were observed in Model B (RALE + OI/10 + comorbidity), with RALE and OI not reaching statistical significance, and comorbidity remained independently associated with mortality (aOR 16.2; 95% CI 1.9–142.7; $p = 0.012$). In Model C (severity + OI/10 + comorbidity), comorbidity was again identified as an independent risk factor (aOR 15.8; 95% CI 1.8–138.9; $p = 0.015$), while severe PARDS was not significantly associated with mortality. All three models demonstrated similar discriminative capacity, with AUC values ranging from 0.791 to 0.822.

ROC analysis

ROC analysis was performed to evaluate the discriminative ability of the LUS–based and RALE–based prognostic models for ICU mortality. The models demonstrated comparable performance for predicting ICU mortality, with AUC values of 0.817 and 0.822, respectively. The ROC curves showed substantial overlap, indicating that LUS and RALE showed similar apparent discrimination between survivors and non-survivors (Figure 3).

Discussion

To our knowledge, this study adds to the limited evidence on the associations among lung ultrasound score, the RALE score, and oxygenation index in pediatric ARDS. The main findings were as follows: (1) LUS was significantly associated with the OI at both assessment time points; (2) LUS and RALE were significantly correlated, and both imaging scores were independently associated with oxygenation impairment in multivariable regression; and (3) in exploratory prognostic analyses, the LUS–based and RALE–based models demonstrated similar apparent discrimination for ICU mortality (AUC ≈ 0.82).

Our cohort consisted predominantly of infants (median age, 11 months) and male patients (64.3%). These findings are consistent with previous pediatric ARDS studies that also reported a higher prevalence among younger children and boys [10,11]. The overall ICU mortality in our cohort was 45.2%, which exceeded the 17–35% reported in several previous pediatric ARDS studies [12–14]. Mortality occurred predominantly in children with severe ARDS, supporting the prognostic value of PALICC–2 severity classification. However, comparisons across studies should be interpreted cautiously because of differences in diagnostic criteria, inclusion thresholds, comorbidities, and the availability and quality of intensive care resources.

LUS scores showed a significant positive correlation with OI at both time points: within the first 48 hours after ARDS diagnosis (T1: $r = 0.65$, $p < 0.001$) and 48 hours later (T2: $r = 0.74$, $p < 0.001$). These findings indicate that more extensive lung injury detected by ultrasound is associated with greater oxygenation impairment in pediatric ARDS. Our findings are consistent with previous adult studies in which higher LUS scores correlated with worsening oxygenation measured by the PaO_2/FiO_2 ratio. For example, Todur et al. [5] reported a moderate negative correlation ($r \approx -0.49$, $p = 0.002$), while Lianhua et al. [6] described a stronger association ($r \approx -0.76$, $p < 0.001$). Although OI is used in pediatrics and PaO_2/FiO_2 in adults, both indices reflect oxygenation status. Taken together, these findings suggest that the association between increasing LUS scores and worsening hypoxemia is consistent across pediatric and adult ARDS.

In contrast, RALE scores also showed significant correlations with OI in our cohort. At T1, the correlation was moderate ($r = 0.41$, $p < 0.05$), and was stronger at T2 ($r = 0.65$, $p < 0.001$). These findings suggest that increasing radiographic edema was associated with worsening oxygenation impairment in pediatric ARDS. Similar findings have been reported in adult ARDS: Todur et al [5] found a moderate correlation between RALE and PaO_2/FiO_2 ($r = -0.42$, $p = 0.009$), while Zimatore et al [7] noted only a weak association ($r = 0.21$) despite RALE's good diagnostic accuracy. In pediatrics, Han et al. [8] also reported

modest correlations of RALE with both PaO_2/FiO_2 and OI (r = –0.34 and –0.40, respectively). We also found significant positive correlations between LUS and RALE at both assessment time points (T1: r = 0.59; T2: r = 0.72). These findings are consistent with adult data. Specifically, Hien et al. [9] reported a strong correlation (r = 0.74), and Zhang et al. [10] demonstrated positive associations at 48 and 72 hours after ICU admission (r = 0.55 and r = 0.57).

In the multivariable linear regression model, both LUS and RALE were independently associated with oxygenation impairment after log–transformation of OI, with variance inflation factor values < 2, indicating no significant multicollinearity. The regression coefficients were β = 0.062 for LUS ($p < 0.001$) and β = 0.017 for RALE ($p = 0.038$). The model explained approximately 50% of the variance in OI ($R^2 \approx 0.50$). In addition to the correlations observed between imaging scores and oxygenation, our exploratory prognostic analysis identified comorbidity as the only independent predictor of ICU mortality. Neither LUS nor RALE remained statistically significant after adjustment for OI and comorbidity. However, the LUS-based model (LUS + OI + comorbidity) and the RALE–based model (RALE + OI + comorbidity) showed similar apparent discrimination for ICU mortality in exploratory analyses (AUC ≈ 0.82). These findings suggest that prognostic models incorporating lung ultrasound may perform comparably to those incorporating chest radiography, supporting the role of lung ultrasound as a practical bedside adjunct while avoiding ionizing radiation.

These findings may have important clinical implications in contemporary pediatric intensive care practice, where dynamic bedside assessment of respiratory status is essential. In many PICUs, chest radiographs remain a routine component of monitoring during the acute phase of respiratory failure [11]. However, repeated radiographic imaging may result in considerable cumulative ionizing radiation exposure, particularly in infants and young children requiring prolonged ICU care [12,13]. As ARDS can evolve rapidly, timely reassessment of lung injury is often required. Bedside lung ultrasound may help address these challenges by providing rapid, repeatable assessment of lung aeration without ionizing radiation [4,14]. Our results support the clinical utility of lung ultrasound as a bedside adjunct for the evaluation and monitoring of pediatric ARDS. This is consistent with the expanding role of point–of–care ultrasound in pediatric critical care worldwide [15].

This study has several limitations. The sample size was relatively small, particularly for the prognostic analyses, which limited statistical power and may reduce the generalizability of the findings. Its single–center design may also limit the applicability of the results to other patient populations and healthcare settings. Additionally, assessing patients at only two predefined time points might not fully capture the dynamic progression of lung injury during ARDS. Although LUS and RALE scores were independently assessed by two readers and discrepancies were resolved by consensus, interobserver agreement was not formally quantified, which may limit the reproducibility of the imaging assessments**.** Despite these limitations, our findings suggest that structured lung ultrasound may serve as a useful bedside adjunct in the evaluation and follow–up of pediatric ARDS, particularly in situations requiring repeated assessment while minimizing cumulative ionizing radiation exposure.

Conclusion

In this prospective observational study of children with ARDS receiving mechanical ventilation, lung ultrasound was significantly correlated with both oxygenation impairment and chest radiography–based RALE scores. Structured lung ultrasound may serve as a useful radiation–free bedside adjunct for the evaluation and follow–up of pediatric ARDS, particularly when repeated assessment is required. Although comorbidity emerged as the only independent predictor of ICU mortality in our study, exploratory analyses showed that models incorporating either LUS or RALE together with oxygenation status and comorbidity had similar apparent discrimination for ICU mortality. These findings support the complementary role of lung ultrasound in the bedside evaluation and follow–up of pediatric ARDS.

Abbreviations

ARDS
Acute respiratory distress syndrome
AUC
Area under the receiver operating characteristic curve
CI
Confidence interval
CXR
Chest radiography
FiO_2
Fraction of inspired oxygen
ICU
Intensive care unit
IQR
Interquartile range
LUS
Lung ultrasound score
MAP
Mean airway pressure
OI
Oxygenation index
OR
Odds ratio
PALICC-2
Pediatric Acute Lung Injury Consensus Conference-2
PARDS
Pediatric acute respiratory distress syndrome
PICU
Pediatric intensive care unit

POCUS
Point-of-care ultrasound
RALE
Radiographic Assessment of Lung Edema
SD
Standard deviation

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Duong Thi Minh Diem: Conceptualization, data curation, investigation, formal analysis, visualization, and writing – original draft. Bui Thanh Liem: Conceptualization, methodology, validation, supervision, investigation, technical support for lung ultrasound, and writing – review and editing. Huynh Nguyen Anh Thu: Data curation, investigation, and writing – review and editing. Tran Nam Hung: Resources, validation, imaging analysis, and visualization. Nguyen Phuoc Long: Methodology, formal analysis, analytical supervision, and writing – review and editing. Nguyen Huy Luan: Conceptualization, methodology, supervision, project administration, and writing – review and editing. All authors read and approved the final manuscript.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Children's Hospital 2, Ho Chi Minh City, Vietnam (Approval No. 725/GCN-BVNĐ2; September 5, 2024).

Consent to participate

Written informed consent was obtained from the parents or legal guardians of all children included in the study.

Consent for publication

Not applicable. This manuscript does not contain identifiable individual patient data, images, or videos.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Tables

Table 1
Baseline demographic and clinical characteristics of the study population

Variable		**Baseline characteristics (n = 42)**
Age, months		11 (5.6–54.8)[b]
Sex, n (%)	Male	27 (64.3)
	Female	15 (35.7)
Pre-existing comorbidity, n (%)		29 (69.0)
ARDS severity[a], n (%)	Severe	23 (54.8)
	Mild/moderate	19 (45.2)
Duration of IMV[c], days		9 (6–12)[b]
Length of ICU stay, days		10 (7–20.8)[b]
ICU outcome, n (%)	Survival	23 (54.8)
	Death	19 (45.2)
a ARDS severity was classified according to the PALICC–2 criteria.		
b Data are presented as median (interquartile range [IQR]) or n (%).		
c IMV, invasive mechanical ventilation; ICU, intensive care unit.		

Table 2

Exploratory multivariable logistic regression models for ICU mortality using T1 data

Model	Predictors	Adjusted OR[a] (95% CI)	p-value	Apparent AUC[b]
Model A (LUS + OI/10 + Comorbidity)	LUS_{TOT} (per point)	1.05 (0.88–1.25)	0.63	0.817
	OI (per 10-point increase)	1.59 (0.47–5.36)	0.45	
	Comorbidity	18.8 (2.08–170.3)	0.009	
Model B (RALE + OI/10 + Comorbidity)	RALE (per point)	1.06 (0.91–1.23)	0.44	0.822
	OI (per 10-point increase)	1.41 (0.41–4.81)	0.58	
	Comorbidity	16.2 (1.9–142.7)	0.012	
Model C (Severity + OI/10 + Comorbidity)	Severe PARDS	4.37 (0.72–26.5)	0.11	0.791
	OI (per 10-point increase)	1.46 (0.43–4.93)	0.54	
	Comorbidity	15.8 (1.8–138.9)	0.015	

a OR, odds ratio; CI, confidence interval.

b AUC, area under the receiver operating characteristic curve.

All predictors were measured at T1.

AUC values represent apparent discrimination and were not externally validated.

Figures

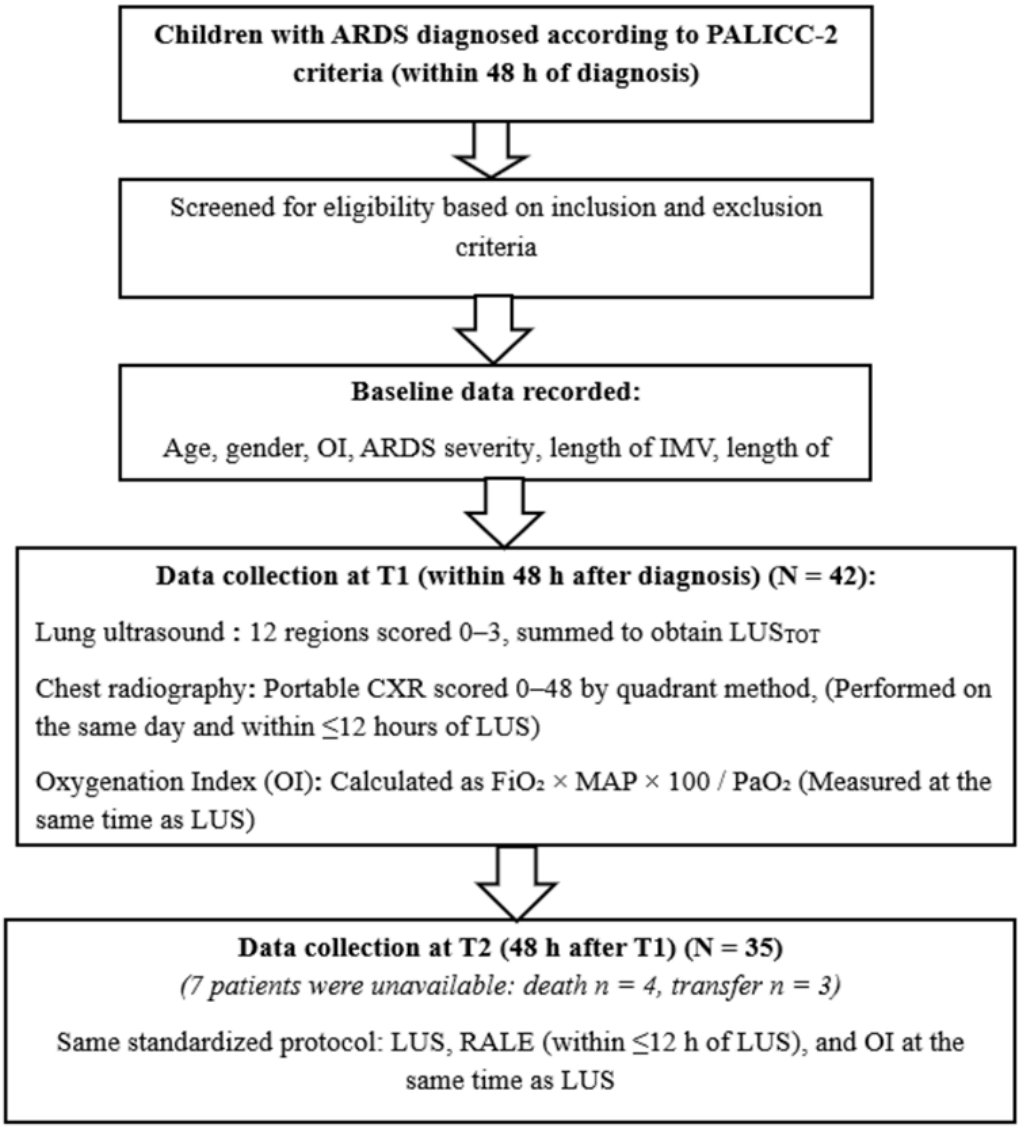


Figure 1

Study flow and methodology.

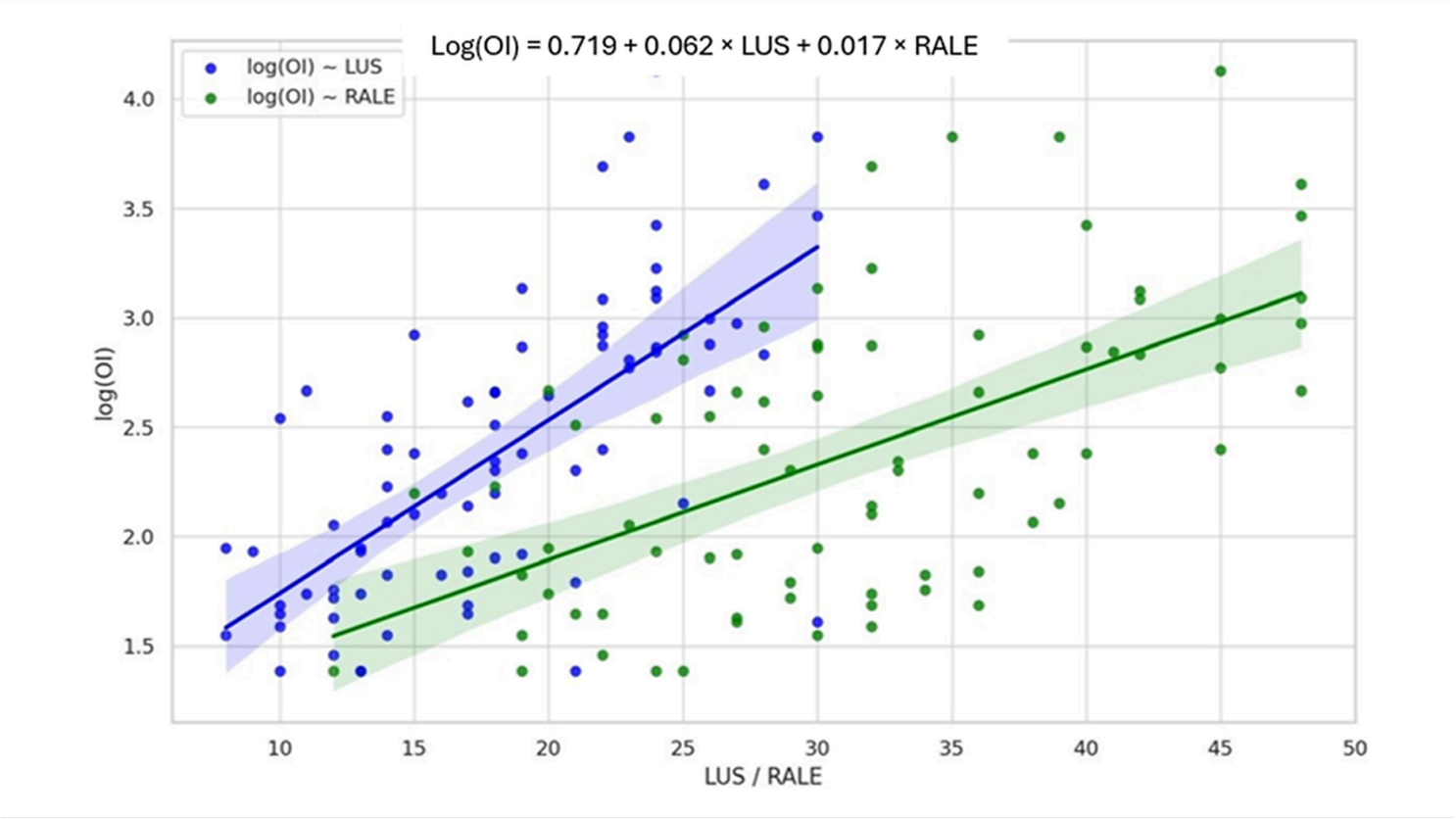


Figure 2

Linear regression model of log-transformed Oxygenation Index (log[OI]) with Lung Ultrasound Score (LUSTOT) and RALE score. Scatterplots with fitted regression lines and 95% confidence intervals are shown. The final multivariable model was: log[OI] = 0.719 + 0.062 × LUSTOT + 0.017 × RALE, with an R^2 of 0.495 ($p < 0.001$).

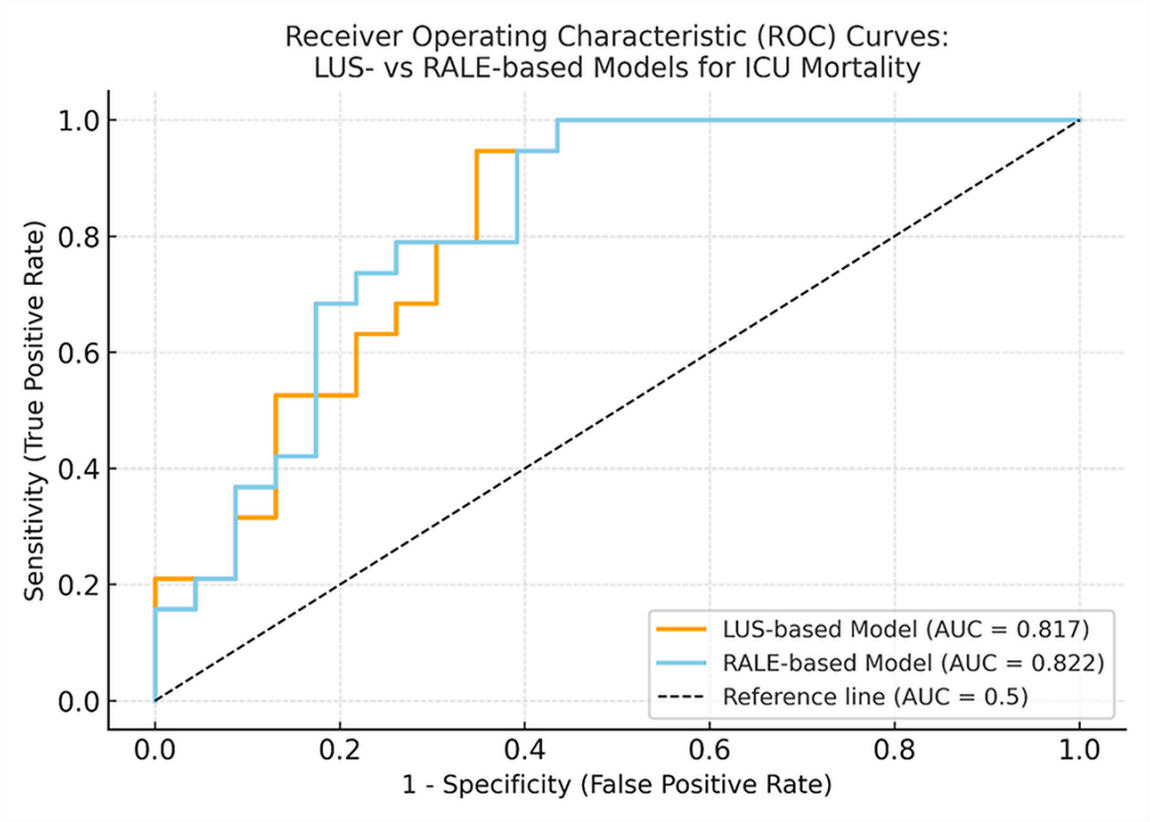


Figure 3

Receiver operating characteristic curves comparing the LUS-based and RALE-based logistic regression models for ICU mortality. The LUS-based and RALE-based models showed similar apparent discrimination, with AUC values of 0.817 and 0.822, respectively. The dashed line represents the reference line.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementalTable1.docx.docx