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Original Research Article

Diagnostic Accuracy of Lung and Diaphragmatic Ultrasound Parameters in Predicting Successful Extubation among Adult Patients Receiving Invasive Mechanical Ventilation: A Prospective Cohort Study

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Abstract

Background: Prolonged mechanical ventilation can increase significantly both mortality and morbidity of patient. It is imperative to initiate weaning procedures at the earliest. Recent advancements in lung and diaphragmatic ultrasound techniques have shown promising avenues for evaluating lung aeration, diaphragmatic function and assessing suitability for extubation.

Objectives: To assess the ability and accuracy of diaphragmatic and lung ultrasound in predicting successful extubation among adult patients on invasive mechanical ventilation.

Methods: This is a hospital-based, prospective cohort study conducted among patients presenting to the Department of Critical Care Medicine between January 2023 to June 2024.

Results: Out of 40 patients studied, 92.5% were successfully extubated, while 7.5% experienced extubation failure. Patients who failed extubation had a significantly longer duration of ventilation (8.0 vs. 4.3 days, $p<0.05$), ICU stay (12.3 vs. 6.5 days, $p<0.05$), and total hospital stay (15.0 vs. 10.0 days, $p<0.05$). The Rapid Shallow Breathing Index (RSBI), Lung Aeration Score (LAS), diaphragm excursion (DE), and diaphragm thickening fraction (DTF) were significantly different between the successful and failed extubation groups. RSBI was higher (80.3 vs. 51.4, $p<0.05$), and DE was lower (1.4 vs. 1.6, $p<0.001$) in the failed extubation group and these parameters were useful predictors of weaning outcomes. RSBI, LAS, DE, and DTF all demonstrated statistically significant predictive value with AUCs ranging from 0.787 to 0.843. RSBI had a sensitivity of 66.7% and specificity of 88.9%, while the LAS, DE, and DTF also showed high positive predictive values, indicating their utility in predicting extubation success.

Conclusion: The findings highlight the potential use of lung and diaphragmatic ultrasound in guiding clinical decisions regarding weaning and extubation from mechanical ventilation.Thus, using lung and diaphragmatic ultrasound provides information to improve extubation success.

Keywords: Lung ultrasound, Diaphragmatic ultrasound, Extubation, Rapid Shallow Breathing Index, Lung Aeration Score, Diaphragm excursion, Diaphragm thickening fraction.

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Introduction

In the intensive care unit (ICU), mechanical ventilation undoubtedly plays a pivotal role in saving lives; however, its prolonged use can significantly elevate both mortality and morbidity rates. Therefore, it becomes imperative to initiate weaning procedures at the earliest feasible. Despite efforts, instances of unsuccessful extubation leading to the necessity of reintubation persist, a circumstance that is often linked with elevated risks of mortality and morbidity. [1] Various ventilatory indices have been devised to pinpoint the opportune moment for extubation; however, none have proven to be exceptionally accurate. Notably, even after the application of established weaning and extubation criteria, approximately 10% of patients experience extubation failure. [2] Among the indices frequently employed to gauge a patient's readiness to be liberated from the ventilator are, minute ventilation, maximum inspiratory pressure (MIP), maximum expiratory pressure (MEP), and rapid shallow breathing index (RSBI), calculated as the ratio of respiratory frequency to tidal volume.

Routine evaluations encompassing parameters such as respiratory rate, minute ventilation, and negative inspiratory force demonstrate limited efficacy in ensuring successful weaning. [3] Notably, of the various parameters examined, RSBI emerges as a valuable tool in determining the timing of extubation during spontaneous breathing trials (SBTs). [4]

Post-extubation complications, including respiratory distress or need for reintubation, often stem from factors such as cardiac dysfunction, impaired gas exchange, or diaphragmatic dysfunction. To anticipate and assess the likelihood of successful extubation, it is advisable to adopt a standardized, integrated approach encompassing clinical, laboratory, and ultrasound assessments of lung, heart, and respiratory muscle function. Optimal assessment of weaning outcomes typically occurs both at the initiation and conclusion of SBTs. [5] The diaphragm assumes a pivotal role as a respiratory muscle, and difficulties in weaning may arise from impaired diaphragmatic function. An imbalance between the load and capacity of the respiratory system stands out as a significant contributor to SBT and extubation failures. While the role of diaphragmatic dysfunction in weaning remains a topic of debate, it is noteworthy that patients have been successfully weaned from ventilators despite such dysfunction. [6,7] Consequently, monitoring diaphragm function emerges as a potentially crucial aspect during weaning and extubation processes. [8] Methods employed to assess diaphragmatic function, such as fluoroscopy, phrenic nerve conduction, and transdiaphragmatic pressure measurements, exhibit several limitations and are not universally accessible in clinical practice. [9] Recent advancements in lung and diaphragmatic ultrasound techniques have presented promising avenues for evaluating lung aeration and diaphragmatic function (diaphragm thickness, diaphragm movement or excursion during spontaneous breathing and the thickening fraction of the diaphragm). [10] Against this background, the objective of the present study was to assess the ability and accuracy of diaphragmatic ultrasound (diaphragmatic excursion, thickening fraction of diaphragm) and lung ultrasound (lung aeration score) in predicting successful extubation among adult patients on invasive ventilation.

Materials and Methods

This was a single-center, hospital-based, prospective cohort study conducted in the Department of Critical Care Medicine of a tertiary care teaching hospital in India over a period of 18 months (January 2023–June 2024). The study was approved by the Institutional Human Ethics Committee (IHEC). The participants (and their attenders) were given the Participant Information Sheet (PIS) in their native language, and its contents were verbally explained to ensure their understanding and satisfaction. Enrolment into the study proceeded upon receipt of written informed consent. Patients were included if they were aged 18 years or above, had received invasive mechanical ventilation for at least two days, and were considered ready for extubation after successful weaning (Table 1). Patients were excluded if they were younger than 18 years, pregnant, had pneumothorax, pneumomediastinum, or an intercostal drainage tube in situ that could interfere with ultrasound assessment, had undergone pleurocentesis, had postoperative adhesions, had a do-not-reintubate status, had severe neurological injury, required prolonged ventilation for two weeks or more, or had a history of neuromuscular disease.

The sample size was calculated using Banerjee et al. (2018) that reported the correlation between lung ultrasound parameters and RSBI scores, ranging between 0.032 and 0.469. [2] Considering the correlation coefficient to be 0.469, type 1 error (alpha error) to be 5.0%, type 2 error (beta error) to be 20.0% (or 80.0% power), and 10.0% non-response rate the minimum estimated sample size was rounded off to 40 patients with 95% confidence. The patients were enrolled using nonprobability sampling technique – convenience sampling/complete enumeration. Once the weaning criteria had been met and the patients were scheduled for extubation (Table 1), [11] they were subjected to a spontaneous breathing trial using PSV. During this trial, the RSBI was calculated by determining the ratio of RR in breaths per minute to the tidal volume in liters: RSBI = RR/TV. After 30 minutes, lung ultrasound and diaphragmatic ultrasound were performed. [12]

In the diaphragmatic ultrasound, the patient was positioned in a semi-recumbent position, and a convex probe (2-5 MHz) was placed subcostally, parallel to the intercostal space, to measure the range of diaphragmatic movement. Using M-mode, the diaphragmatic excursion (displacement in centimeters) was measured. [13] Diaphragm thickness was measured using a linear probe (6-13 MHz) in B-mode. The probe was placed perpendicular to the chest wall in the 9^{th} intercostal space between the anterior and midaxillary lines, with the patient in a semi-recumbent position.

The costophrenic sinus was identified as the transition between the lung and liver (on the right side) or between the lung and spleen (on the left side), with the diaphragm located caudal to the costophrenic sinus. Two echogenic layers of the peritoneum and pleura, sandwiching a more hypoechoic layer of the diaphragm, were identified. M-mode was then used to measure the diaphragm thickness at the end of expiration and at the end of inspiration. [13] The diaphragmatic thickening fraction was calculated as, (Thickness at end-inspiration–Thickness at end-expiration)/ Thickness at end-expiration. Three consecutive readings were taken, and the average was calculated. In B-mode, the diaphragm appeared as a three-layer structure, while in M-mode, it was thinnest at end-expiration and thickest at end-inspiration.

In lung ultrasound, a convex probe (2-5 MHz) in B-mode was used to measure lung aeration. Each lung was divided into three zones, examined anteriorly and posteriorly using B-mode to assess the degree of lung aeration across a total of 12 zones (6 on each side). Four ventilation patterns (A, B1, B2, and C) were identified, with each zone being scored from 0 to 3.

The lung aeration score was calculated by adding the points from all 12 lung zones, yielding a total score ranging from 0 to 36. [14,15] Following the ultrasound measurements, the patient was extubated according to the decision of the treating team, who were blinded to the ultrasound results. Post-extubation, the patient was placed on NIV if needed. Extubation success was defined as not requiring reintubation within 48 hours of extubation.

Statistical Analysis: The data obtained was manually entered into Microsoft Excel and analysed using Statistical Package for Social Sciences (SPSS) v23. All the categorical variables were summarised using frequencies and percentages. Continuous variables were summarized using mean (standard deviation) and/or median (interquartile range) (based on the results of data normality, tested using Kolmogorov–Smirnov test and the Shapiro–Wilk test). To test for statistical significance, Chi square test or Fisher exact test (for categorical variables); and independent 't' test (for continuous outcomes) was used. Statistical significance was considered at p value less than 0.05. Sensitivity, specificity, positive and negative predictive values were computed for RSBI, DTF, and DE as weaning prediction indicators. Receiver operating characteristic (ROC) analysis was done and area under the curve (AUC) was noted with 95% confidence interval. The cut off points for RSBI, DTF, and DF were chosen as the point that maximised Youden's index because this provided the optimal trade-off between sensitivity and specificity.

Results

Among the 40 patients included in the present study, 37 patients (92.5%) had successful extubation, whereas 3 patients (7.5%) had failed extubation. The mean age was slightly higher among patients with failed extubation than among those with successful extubation, although this difference was not statistically significant (66.3±7.0 vs. 61.2±10.4 years, p=0.415).

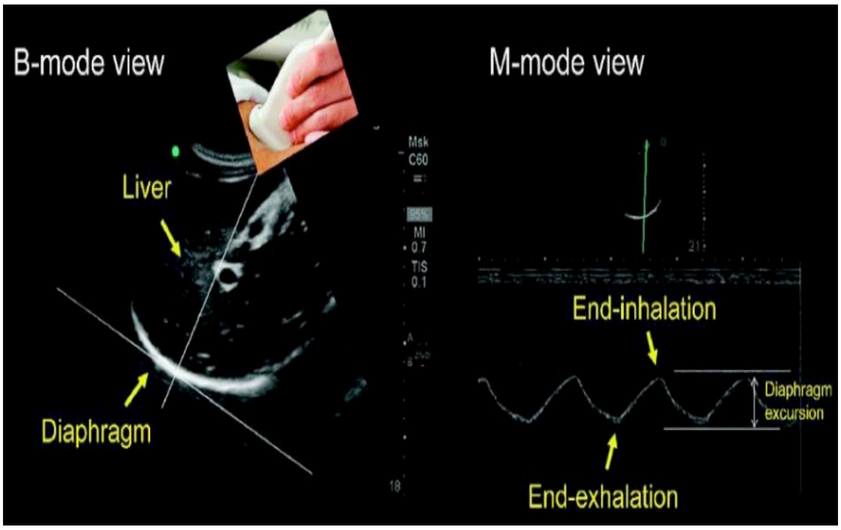
All patients in the failed extubation group were male. Patients with failed extubation had significantly longer duration of mechanical ventilation (8.0±5.3 vs. 4.3±1.7 days, p=0.005), longer ICCU stay (12.3±5.5 vs. 6.5±4.0 days, p=0.024), and longer total hospital stay (15.0±1.0 vs. 10.0±4.1 days, p<0.001). The failed extubation group also had a higher rapid shallow breathing index (80.3±5.4 vs. 51.4±3.8, p<0.001) and lung aeration score (14.7±1.2 vs. 8.7±4.4, p=0.025), along with lower diaphragm excursion (1.4±0.3 vs. 1.6±0.2, p<0.001) and lower diaphragm thickening fraction (26.1±4.2 vs. 43.7±5.2, p=0.004).

RSBI at a cut-off of <77.7 had a sensitivity of 66.7%, specificity of 88.9%, positive predictive value of 96.0%, and AUC of 0.787 (95% CI: 0.460–1.000; p=0.041). Lung aeration score at a cut-off of <8.2 showed a sensitivity of 66.7%, specificity of 83.3%, and AUC of 0.806 (95% CI: 0.555–1.000; p=0.039). Diaphragm excursion at a cut-off of >1.4 had an AUC of 0.843 (95% CI: 0.581–1.000; p=0.023), while diaphragm thickening fraction at a cut-off of >32.0 showed an AUC of 0.806 (95% CI: 0.506–1.000; p=0.038). These findings indicated that lung and diaphragmatic ultrasound parameters had clinically useful accuracy in predicting extubation outcome.

Table 1: Weaning criteria

Arterial blood gas	Respiratory rate	Other mechanics
PaO_2 >60 mmHg	<35 breaths/min	Tidal volume >5 ml/Kg
$PaCO_2$ <50 mmHg		Vital capacity >10 ml/Kg
FiO_2 <0.5		Minute ventilation 4 to 10 L/min
PaO_2/FiO_2 >150 mmHg		Afebrile
PEEP <5 cm of H_2O		No electrolyte/metabolic abnormality

Diaphragm Excursion



Thickening fraction of diaphragm

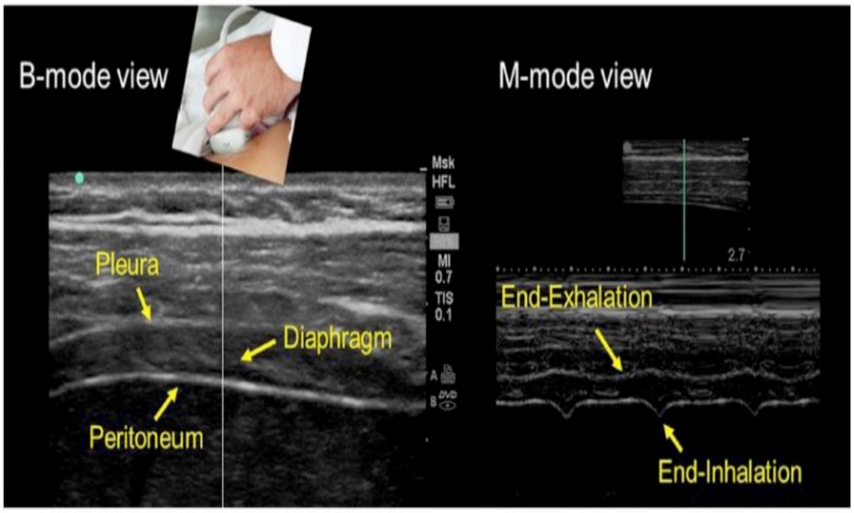


Figure 1: Diaphragmatic ultrasound

Table 2: Lung Aeration Score

Point for each lung zone	Degree of lung aeration	Pattern	Profile
0 point	Normal	B lines	A
1 point	Moderate loss	Multiple B lines – Regular/irregular	B1
2 point	Severe loss	Multiple coalescent B lines	B2
3 point	Complete loss	Lung consolidation	C

Table 3: Factors associated with failed extubation

		Successful extubation N = 37	Failed extubation N = 3	P value
		Mean (SD)	Mean (SD)	
Age (in years)		61.2 (10.4)	66.3 (7.0)	0.415
Gender, n (%)	Female	9 (24.3)	0 (0.0)	0.332
	Male	28 (75.7)	3 (100)	
Ventilation days		4.3 (1.7)	8.0 (5.3)	0.005*
ICCU days		6.5 (4.0)	12.3 (5.5)	0.024*
Total duration of hospital stay (in days)		10.0 (4.1)	15.0 (1.0)	<0.001*
Rapid shallow breathing index		51.4 (3.8)	80.3 (5.4)	<0.001*
Lung Aeration Score		8.7 (4.4)	14.7 (1.2)	0.025*
Diaphragm Excursion		1.6 (0.2)	1.4 (0.3)	<0.001*
Thickening Fraction of the Diaphragm		43.7 (5.2)	26.1 (4.2)	0.004*
SD, Standard deviation, *Statistically significant at p<0.05				

Table 4: Diagnostic accuracy of lung and diaphragmatic ultrasound parameters to predict successful extubation

	Cut off	Sensitivity	Specificity	PPV	NPV	Youden Index	AUC (95% CI)	P value
RSBI	<77.7	66.7	88.9	96.0	58.5	0.32	0.787 (0.460 to 1.000)	0.041*
Lung Aeration Score	<8.2	66.7	83.3	96.0	39.9	0.57	0.806 (0.555 to 1.000)	0.039*
Diaphragm Excursion	>1.4	66.7	72.2	92.3	42.6	0.49	0.843 (0.581 to 1.000)	0.023*
Thickening Fraction of the Diaphragm	>32.0	66.7	77.8	96.0	54.6	0.66	0.806 (0.506 to 1.000)	0.038*
AUC, Area under the curve; CI, Confidence interval, *Statistically significant at p<0.05								

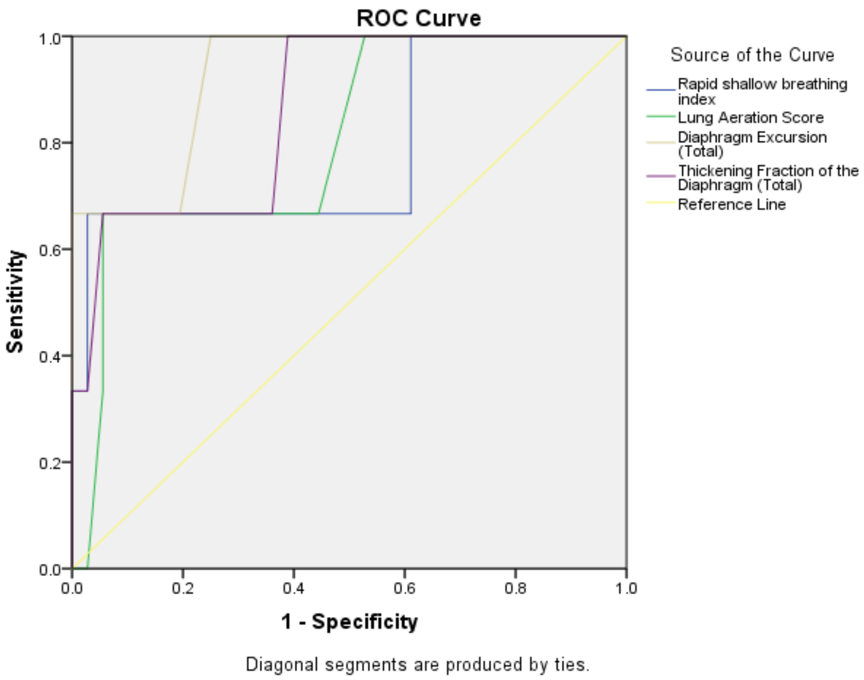


Figure 2: ROC analysis showing AUC for lung and diaphragmatic ultrasound parameters to predict successful extubation

Discussion

Weaning from mechanical ventilation is a multifaceted process, including the assessment of readiness to wean, conducting a spontaneous breathing trial (SBT), and proceeding with extubation. The failure to successfully wean from mechanical ventilation is underpinned by complex and multifactorial pathophysiology, which may involve dysfunctions in pulmonary, neurological, cardiac, endocrine, and respiratory muscle systems. [16] Critically ill patients often present with a combination of clinical conditions, including pulmonary and cardiovascular complications, alterations in chest wall mechanics, peripheral muscle weakness, diminished respiratory drive, and neurological impairments, all of which can complicate the weaning process and reduce its likelihood of success. The prevalence of extubation failure is approximately 10-20%, even after a successful SBT. [17] In high-risk patients, failure rates and subsequent reintubation can exceed 20%. [18] In our study, the lower prevalence of extubation failure (7.5%) can likely be attributed to the use of prophylactic noninvasive ventilation (NIV) in 69.0% of cases. Specifically, 72.5% of patients in our study were placed on NIV post-extubation, and 7.5% required reintubation. Similarly, in a study by Carrie et al. [19] in France, 19 out of 47 patients (40%) who were extubated received prophylactic NIV, which aligns with our findings.

Several bedside indices have been developed to predict successful weaning and extubation; however, none of these indices has proven to be optimal in consistently predicting weaning success. Prior to the advent of ultrasonography, the RSBI was the standard tool for assessing weaning readiness. In our study, with a cutoff value of 77.7, we found that the sensitivity and specificity were 66.7% and 88.9%, respectively, with an AUROC of 0.787 (95% CI: 0.460 to 1.000). Lower predictive values for RSBI have been reported, with differences in patient populations and methodologies contributing to the wide range of results. Sarvanan et al. [20] found that using an RSBI cutoff value of 82 resulted in a sensitivity of 94% and a specificity of 31%, with an AUROC of 0.422. In contrast, the study by Banerjee et al. [2] reported that RSBI outperformed other parameters, with a sensitivity and specificity of 100% and an AUROC of 0.996, while all other parameters had AUROCs of less than 0.8. Additionally, Gok et al. [21] identified a cutoff value of 64 for RSBI.

Lung ultrasonography assesses the air-to-fluid ratio within the lung parenchyma. In areas where air is absent, such as in cases of lung consolidation, LUS offers accurate imaging that may indicate the presence of underlying disease. Reduced lung aeration can result from factors such as air loss, leading to atelectasis, or the accumulation of fluid within the interstitial or alveolar spaces. The global LUS score correlates directly with both extravascular lung water, as measured by transpulmonary thermodilution, and overall lung tissue density, as assessed by quantitative CT imaging. In the present study, the lung aeration score, using a cutoff of <8.2, showed a sensitivity of 66.7% and a specificity of 83.3%, with a PPV of 96.0% and an NPV of 39.9%. In a study by Soummer et al., [14] the lung ultrasound score was found to be both sensitive and specific in predicting weaning outcomes. Similarly, a study by Faris et al. [22] demonstrated that the LUS could predict weaning outcomes (post-extubation distress), with a sensitivity of 90% and a specificity of 75% using a cutoff value of 15.5. Osman et al. [23] also found that a lung aeration score below 12 was associated with a high probability of extubation success, while a score above 17 was linked to a high likelihood of extubation failure. In their study, a cutoff value of 12 showed 100% sensitivity and 96% specificity. Another study by Al-Husinat et al. [24] found that patients who successfully weaned exhibited significantly lower baseline LUS aeration scores compared to those who failed to wean. Scores greater than or equal to 18 had good predictive value for weaning failure, while a score of 11 or less was predictive of weaning success. A low LUS score (<10) demonstrated high accuracy in excluding weaning failure, with a negative predictive value (NPV) of 100%, and no patients with a score below 10 required reintubation.

In the present study, DE with a cutoff of >1.4, the sensitivity was 66.7% and specificity was 72.2%, yielding a PPV of 92.3% and an NPV of 42.6%. The TF of the diaphragm with a cutoff of >32.0 showed a sensitivity of 66.7% and specificity of 77.8%, with a PPV of 96.0% and an NPV of 54.6%. Diaphragmatic excursion cutoff values between 10 mm and 13 mm, and diaphragmatic thickening fraction values between 20% and 30%, are reliable predictors of successful extubation. [25,26] The 29% to 30% cutoff for DTF is the most commonly reported and is used to define diaphragm dysfunction. [27] There is no universally accepted cutoff for diaphragm dysfunction using DE, although values between 1 cm and 1.2 cm are frequently cited in studies predicting weaning outcomes. The variability in DTF cutoff values across studies (ranging from 20% to 36%) may be attributed to methodological differences. DiNino et al. [28] demonstrated that DTF predicts extubation success equally well in both settings. Shamil et al. [29] found that DE had a larger AUROC compared to RSBI (0.92 vs 0.58). Another Indian study by Sarvanan et al. [20] found that DE measured by ultrasound was a reliable and dynamic predictor of weaning success, with an AUROC of 0.81 and a cutoff value of 1.21 cm. The cutoff value for DTF was 37%, with a sensitivity of 79.5% and specificity of 51.7%. The combination of RSBI and DE was better than RSBI alone but not superior to DE as a standalone weaning indicator. Ferrari et al. [8] reported a DTF cutoff value of 36%, with a sensitivity of 82% and specificity of 88%, and an AUROC of 0.95 in a study of 46 patients. In a study by Gok et al. [21] of 62 patients the cutoff values for DTF (27.5%), DE (1.3 cm), and LUS (6.5) all had PPVs over 90%. A strong correlation between extubation success and RSBI ($r = 0.774$, $p \leq 0.001$) was observed, with moderate correlations for DE ($r = 0.532$, $p \leq 0.001$), DTF ($r = 0.499$, $p \leq 0.001$), and LUS score ($r = 0.396$, $p \leq 0.05$). In a Chinese study by Shigang et al., [30] successful weaning was also associated with a higher DTF (1.64 cm vs 0.78 cm, p=0.001) compared to weaning failure (49% vs. 27%, p = 0.001). The best cutoff values for predicting successful weaning were DTF ≥ 30%, DE ≥ 1.3 cm, LUS ≤ 11, and RSBI ≤ 102. DTF had the highest specificity (84%) compared to RSBI (53%), LUS (55%), and DE (62%) in predicting weaning outcomes, with DTF also showing the highest sensitivity (94%) compared to RSBI (85%), LUS (71%), and DE (65%). The combination of RSBI, LUS, DE, and DTF produced the highest AUROC (0.919), with a sensitivity of 96% and a specificity of 89%. In a study from Egypt, Eltrabili et al. [31] reported that a DTF greater than 30.7% and a DE greater than 10.4 mm during SBT in septic patients had sensitivities of 100% and 94.1%, and specificities of 94% and 85%, respectively, for predicting successful liberation from mechanical ventilation. The high predictive values in this study may be related to the population studied, as sepsis is known to be associated with diaphragmatic dysfunction. The

AUROC was higher for DTF compared to DE (0.98 vs. 0.85). Umbrello et al. [32] Observed that DTF is a more reliable indicator of respiratory effort compared to DE, as DE may underestimate diaphragmatic function in patients who have undergone abdominal surgery.

Vivier studied 191 patients, of whom 33 (17%) experienced extubation failure. [33] They proposed that the accuracy of detecting diaphragmatic dysfunction by ultrasound may be limited, or that diaphragmatic weakness is not a decisive factor in determining extubation failure. The primary outcome of their study was extubation failure, defined as reintubation or death within seven days post-extubation, contrasting with our study, where reintubation within 48 hours was the outcome measure. Additionally, 77% of patients in their study had chronic heart disease, which may explain the observed differences in diaphragm ultrasound diagnostic accuracy compared to our study. Li et al. [30] in a meta-analysis demonstrated satisfactory diagnostic accuracy in predicting extubation outcomes. Llamas Alvarez concluded that DTF alone is a modest predictor of weaning outcomes,(34) while Santana et al. [35] found that ultrasound-detected diaphragmatic dysfunction is associated with an increased risk of extubation failure. A more recent meta-analysis by Parada-Gerada et al., [36] which included 19 studies (five of which were new) and a total of 1205 patients (between 2016 and 2022), reported a combined sensitivity, specificity, and AUC for DE of 0.85, 0.75, and 0.87, respectively, and for DTF of 0.80, 0.80, and 0.87, indicating satisfactory diagnostic accuracy for predicting extubation success. The high sensitivity values suggest that patients with DTF above 29% and DE greater than 1 cm have a high probability of successful extubation. A large systematic review and meta-analysis compared the accuracy of multiple bedside respiratory muscle assessments for predicting weaning outcomes in critically ill patients. Most studies used cutoff values for DE between 10–15 mm and for DTF between 22–32%. The sensitivity for predicting weaning success was 75% for DE and 77% for DTF. [37] The accuracy of DE and DTF in predicting weaning success was significantly higher compared to PImax. Sensitivity analysis showed that DTF had significantly higher accuracy in predicting weaning success than DE ($p < 0.01$). The superiority of DTF over DE may be due to the influence of ventilatory support, patient positioning, and variations in thoracic and abdominal pressures on DE interpretation.

The present study had certain limitations. As it was conducted at a single centre using convenience sampling, the findings may have limited generalizability and may be subject to selection bias. The study population predominantly comprised elderly patients with multiple comorbidities, which may restrict the applicability of the results to younger or more diverse critically ill populations. In addition, the study primarily assessed short-term extubation outcomes within 48 hours and did not evaluate long-term outcomes such as delayed reintubation, mortality, or functional recovery. Potential confounding factors, including sedation practices, ventilator settings, and concurrent medications, were also not fully controlled.

Conclusion

The present study demonstrated that lung and diaphragmatic ultrasound parameters were useful predictors of successful extubation among adult patients receiving invasive mechanical ventilation. Patients who experienced extubation failure had significantly longer duration of mechanical ventilation, ICU stay, and total hospital stay, along with higher RSBI and lung aeration scores and lower diaphragm excursion and diaphragm thickening fraction. RSBI, lung aeration score, diaphragm excursion, and diaphragm thickening fraction showed statistically significant diagnostic accuracy in predicting extubation outcomes. These findings suggest that bedside ultrasound assessment of lung aeration and diaphragmatic function can serve as a valuable, non-invasive adjunct to conventional weaning parameters and may help guide clinical decision-making during ventilator liberation.

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