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ORIGINAL RESEARCH

Diaphragmatic Dynamics Assessed by Bedside Ultrasound Predict Extubation in the Intensive Care Unit: A Prospective Observational Study

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Background: This study aims to evaluate the predictive value of bedside ultrasound evaluation of diaphragmatic dynamics in determining successful extubation outcomes for patients eligible for weaning.

Methods: This prospective observational study was conducted on patients who were mechanically ventilated and ready for weaning during the spontaneous breathing trial (SBT). The diaphragm contraction and motion-related parameters of patients such as end inspiratory diaphragm thickness (DT-insp), end respiratory diaphragm thickness (DT-exp), diaphragm thickening fraction (DTF), diaphragmatic thickening fraction rapid shallow breathing index (DTF-RSBI), diaphragmatic excursion (DE), diaphragmatic excursion rapid shallow breathing index (DE-RSBI) were recorded and the association with failure in ventilatory extubation was analyzed. A receiver operating characteristic (ROC) curve was conducted to analyze the prediction of successful weaning.

Results: Out of 95 patients, 14 (14.74%) died, and 68 (71.58%) were successfully extubated. There were significant differences between the two groups in all parameters except DT-exp. The results indicated that duration of mechanical ventilation (OR = 0.850, 95% CI: 0.770–0.938, P = 0.001), DTF (OR = 1.214, 95% CI: 1.108–1.330, P = 0.000), DTF-RSBI (OR = 0.917, 95% CI: 0.880–0.954, P = 0.000), DE (OR = 127.02, 95% CI: 15.004–1075.291, P = 0.000), DE-RSBI (OR = 0.752, 95% CI: 0.657–0.861, P = 0.000) had predictive value for weaning. DTF and DE had a high sensitivity of 91.18%, 100%, respectively. Whereas, duration of mechanical ventilation, DTF-RSBI, DE-RSBI showed a high specificity of 81.48,85.19%, 81.48%. Considering all the above factors, the sensitivity was 88.24% and the specificity was 88.89%.

Conclusion: Bedside ultrasound assessment of diaphragmatic parameters enables the detection of diaphragmatic dysfunction, thus proving valuable in predicting extubation success and facilitating a favorable weaning outcome.

Keywords: diaphragmatic dynamics, bedside ultrasound, extubation, intensive care unit

Introduction

Mechanical ventilation (MV) is a widely used therapeutic tool in intensive care units (ICU). However, the challenge of determining the optimal timing for extubation persists even after the patient recovers from their critical condition. Current guidelines[1] recommend the implementation of a SBT as a tool to predict weaning outcome. Nevertheless, there are still parts of mechanically ventilated patients fail their first attempt to wean following a successful SBT.[2]

The onset of diaphragmatic weakness occurs upon initiation of MV, posing challenges for around 20%–30% patients during extubation attempts.[3] Diaphragm atrophy and weakness are associated with longer duration of MV[4] and longer weaning.[5] Some preliminary data suggests that during MV, the better diaphragm function, the better oxygenation and lung aeration.[6] The assessment of the diaphragm by ultrasound is both feasible[7] and an important tool for respiratory evaluation in clinical settings.[8] Several studies have shown that ultrasound-derived indices could potentially serve as predictors for successful weaning from MV.[9–12]

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Nevertheless, the utilization of ultrasound-guided weaning parameters remains infrequent, potentially attributed to uncertainties in its effectiveness and cut-off values for predicting liberation from MV. Our main aim was to evaluate the predictive capability of diaphragmatic indices in successful extubation by comparing these measurements with the eventual outcome.

Methods

Subjects

This study was conducted in the ICU of Zhoupu Hospital in Pudong New Area, Shanghai, during the period from November 2021 to November 2023. The study is compliant with the Declaration of Helsinki and has been approved by the Ethics Committee of Zhoupu Hospital (2023-C-100-E01). Informed consent was obtained from all the patient relatives who was conducted on mechanically ventilated and weaning-ready.

The study participants were mechanically ventilated patients selected for weaning by the intensivist's team and who were considered fit for weaning. Selection of patients for SBT was based on this weaning criteria: (1) The primary diseases causing respiratory failure were under control; (2) Good oxygenation, fraction of inspired oxygen [FiO2] <0.5, positive end-expiratory pressure [PEEP] ≤8cmH2O, partial pressure of arterial oxygen [PaO2]/FiO2 >150); (3) Stable hemodynamic status (HR ≤ 120 beats/min, 90 mmHg < SBP < 160 mmHg, no use of vasoactive drugs or low-dose application); (4) Strong ability of spontaneous breathing and cough; (5) No high fever (T < 38°C); (6) No obvious respiratory acidosis; (7) Hemoglobin level not less than 8–10 g/dl; (8) Good mental status; (9) Stable metabolic status (no significant electrolyte disturbance, normal blood glucose level).

The exclusion criteria were as follows: (1) Age < 18 years old; (2) Pregnant women; (3) The trachea incision; (4) Pneumothorax or mediastinal emphysema, closed thoracic drainage; (5) Primary neuromuscular diseases, Chronic obstructive pulmonary disease, asthma; (6) Patients undergoing cardiac or thoracic or abdominal surgery; (7) Severe liver, kidney and other organ dysfunction or end-stage tumor patients.

Study Procedure

Ninety-seven ICU patients who met the inclusion criteria were enrolled, and sociodemographic data such as age, gender, body mass index (BMI) of all patients were recorded, clinical variables such as length of hospital stay, duration and reason for mechanical ventilation, and heart rate, respiratory rate, mean arterial pressure (MAP), ventilator-related parameters, acute physiology and chronic health evaluation II (APACHE-II), laboratory investigation of all patients before SBT were collected.

In our study, the patients' readiness to wean, as per the aforementioned criteria, was assessed on a daily basis through clinical evaluation conducted by the attending physician. SBT was required before weaning mechanically ventilated patients. SBT with low levels of pressure support ventilation (PSV), PSV mode with pressure support of 7cmH_2O and constant FiO_2 during the procedure. SBT was maintained for 30min, without PEEP followed by extubation with continuous suctioning. The competent physician evaluated whether to decannulate the trachea.

SBT was considered to have failed if any of the following occurred: (1) respiratory rate > 35 breaths/min or < 8 breaths/min; (2) SaO2 < 90%; (3) Heart rate > 140 beats/min or change > 20%, new onset arrhythmia; (4) Systolic blood pressure > 180 mmHg or < 90mmHg; (5) Difficulty breathing, irritability, sweating, or overt anxiety.

Patients were considered to be successfully extubated and maintained spontaneous breathing for more than 48 hours. Extubation failure was defined[13] weaning failure as the occurrence of any of these: (1) failed spontaneous breathing trial (SBT); (2) reintubation/resumption of ventilator support within 48h after extubation; or (3) re-intubation or non-invasive mechanical ventilation support was required within 48 hours after extubation. At the end of SBT, the respiratory rate, tidal volume, rapid shallow breathing index (RSBI) and oxygenation index were recorded and calculated.

Ultrasonic Diaphragmatic Examination (B-Mode, M-Mode)

Ultrasonic diaphragmatic examination in the patients with MV at 30 minutes of SBT, on the right side of diaphragm in the liver as the acoustic window, patients take prostrate or half supine position.

Resona 8 ultrasound system (Mindray Medical International), with convex array probe SC6-1, linear array probe L11-3U was used for data collection; all the ultrasound data were collected by the same sonographer with 10 years of experience in critical ultrasound.

Diaphragm Contraction Related Parameters

The 3–11 MHz linear array probe was placed in the 8–10 intercostal section of the right midaxillary line of the patient. The diaphragm is a hypoechoic tissue structure located between these two linear echoes and normally moves in the direction of the probe during inspiration. The diaphragm thickness (DT) was measured after two-dimensional ultrasound clearly showed the diaphragm, or the sampling line was perpendicular to two parallel lines, and DT-exp and DT-insp was measured by B-mode ultrasound mode (Figure 1), respectively. The DTF and DTF-RSBI was calculated (Respiratory rate was at the end of SBT).

$$\text{DTF} = (\text{DT-insp} - \text{DT-exp})/\text{DT-exp}\times 100\%.$$

$$\text{DTF-RSBI} = \text{Respiratory rate}/\text{DTF}.$$

Diaphragmatic Motion Related Parameters

The 1–6MHz convex array probe was held and placed at the intersection of the right midclavicular line or right anterior axillary line and the lower edge of the costal arch, and pointed to the medial, cephalic and dorsal sides. After the patient was asked to breathe calmly and smoothly, satisfactory two-dimensional images were obtained. The ultrasound beam was perpendicular to the posterior 1/3 of the diaphragm, and M-ultrasound was used to monitor the movement of the right diaphragm. DE and time (T) in a single breath was obtained by using the menu of measurement speed (Figure 2), which marked the trough and peak of the waves. DE-RSBI was calculated (Respiratory rate was at the end of SBT).

$$\text{DE-RSBI} = \text{Respiratory rate}/\text{DE}.$$

Contraction velocity was measured multiple times if the breathing rhythm was irregular. The above data were measured three times and averaged.

Statistical Analysis

Statistical analyses were performed using SPSS (version 23.0) and MedCalc (version 20.104). Measurement data were expressed as (x ± s), and comparison between the two groups was analyzed using the group *t* test. The count data were

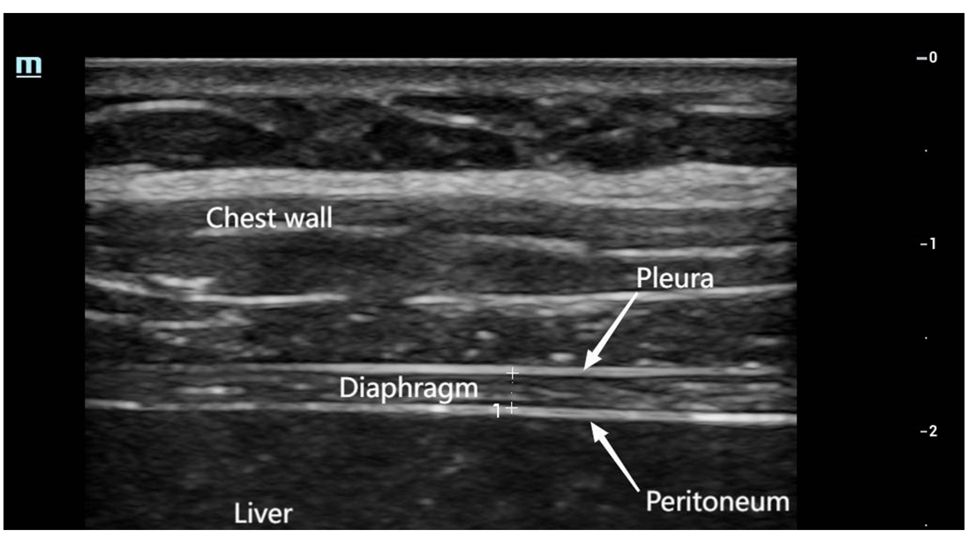

Figure 1 Measurement of diaphragm thickness in B mode.

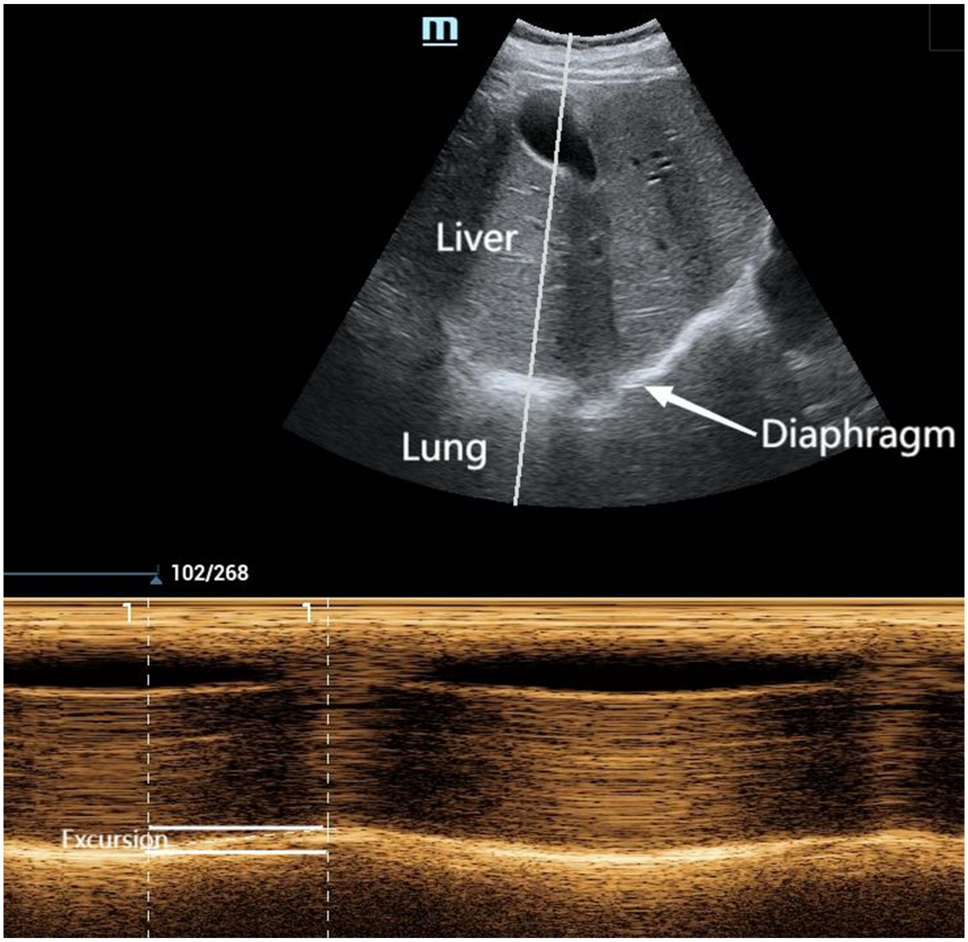

Figure 2 Measurement of diaphragm mobility in M mode.

expressed as relative numbers, and the comparison between the two groups was analyzed by chi-square test. Logistic regression model was used to analyze the parameters affecting the weaning outcome of critically ill patients with mechanical ventilation. The predictive power of each parameter for extubation was evaluated based on the AUC. The cut-off value was used as the diagnostic reference. $P < 0.05$ was considered statistically significant.

Results

General Conditions

Because two patients could not be measured the diaphragm excursion due to the falling lung shielding the diaphragm during inspiration, 95 patients (60 males and 35 females) completed all data collection, the flowchart of the subject process is shown in Figure 3.

Among the 95 mechanically ventilated weaning-ready patients, 14 (14.74%) were died, 68 (71.58%) were successfully extubated. Duration of mechanical ventilation were significantly higher in the extubation failure group than in the extubation success group, but the tidal volume and Albumin is lower in the extubation failure group than in the extubation success group ($P < 0.05$) (Table 1). There were significant differences between the two groups in all parameters except DT-exp (Table 2).

Variables Associated with Extubation Success

With weaning outcome as the dependent variable (failure = 0, success = 1), Logistic regression analysis was performed with duration of mechanical ventilation, V_T, Albumin, DTF, DTF-RSBI, DE, and DE-RSBI. The results showed that duration of mechanical ventilation (OR = 0.850, 95% CI: 0.770–0.938, P = 0.001), DTF (OR = 1.214, 95% CI: 1.108–1.330, P = 0.000),

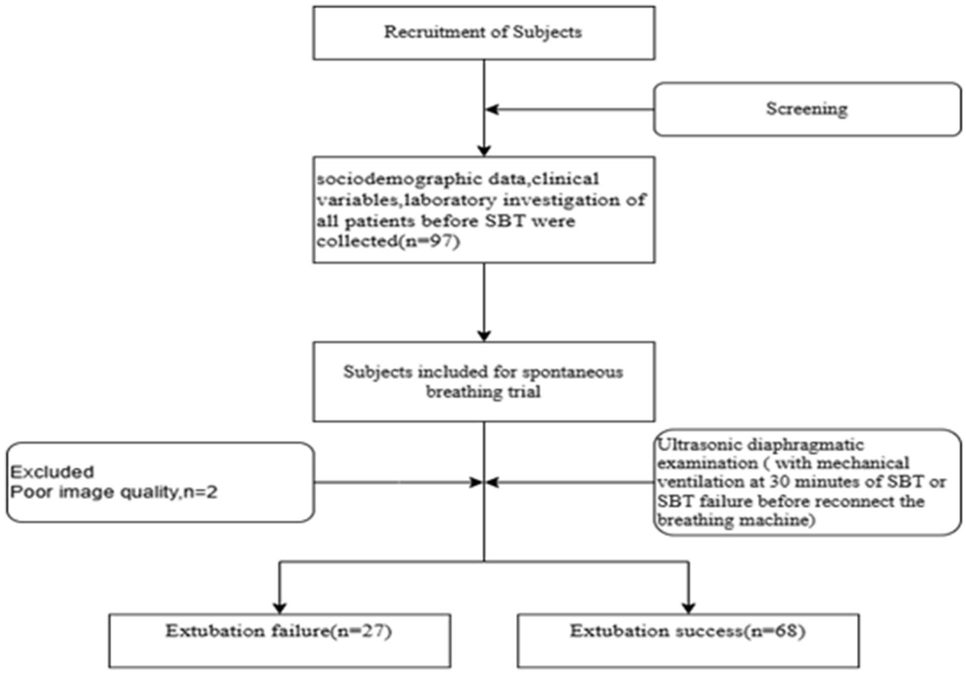

Figure 3 Study flow chart.

DTF-RSBI (OR = 0.917, 95% CI: 0.880–0.954, P = 0.000), DE (OR = 127.02, 95% CI: 15.004–1075.291, P = 0.000), DE-RSBI (OR = 0.752, 95% CI: 0.657–0.861, P = 0.000) had predictive value for weaning.

Parameters Predictor of Extubation Success

Accuracy of the different cut-off values with sensitivity, specificity to predict extubation success/failure were calculated (Table 3). DTF and DE had a high sensitivity of 91.18%,100% respectively. Whereas, duration of mechanical ventilation,

Table 1 Sociodemographic, Clinical, and Laboratory Characteristics of the Study Population

Variable	Extubation failure (27)	Extubation success (68)	P
Age (years)	75.19 ±10.85	64.66 ±17.53	0.005
Body mass index (kg/m^2)	23.10 ±3.63	22.88 ±5.76	0.856
Sex [% (n)]			0.064
Female	14.7(14)	22.1(21)	
Male	13.7(13)	49.5 (47)	
Principal diagnosis [% (n)]			0.034
ARDS	16.8 (16)	26.3 (25)	
Heart failure	2.3 (5)	11.6 (11)	
Surgery	4.2 (4)	25.3 (24)	
Others	2.1 (2)	8.4 (8)	
Duration of ventilation(d)	9.02± 7.83	4.23±3.78	0.000
APACHE-II	22.52±6.98	21.48±6.42	0.494
HR(bpm)	77.81±15.81	82.59±14.76	0.167
MAP(mmHg)	85.48±12.41	90.88±16.24	0.123
EF(%)	55.63±10.72	58.03±7.81	0.232
RR(breaths/min)	17.37±2.94	17.32±3.24	0.948
V_T (mL)	0.44±0.04	0.47±0.08	0.044
RSBI (beat/min ·L)	39.48±6.94	37.56±9.78	0.356
PaO_2(mmHg)	113.30±24.35	119.46±28.81	0.330

(*Continued*)

Table 1 (Continued).

Variable	Extubation failure (27)	Extubation success (68)	P
PaO_2/FiO_2(mmHg)	277.52±64.44	304.35±73.88	0.101
SCr(μ mol/L)	78.78±37.55	114.28±109.03	0.103
Albumin(g/L)	30.56±3.62	32.75±4.25	0.021
WBC (10^9/L)	9.62±3.23	11.17±3.80	0.064
Na(mmol/L)	141.78±5.99	138.74±17.19	0.373
K(mmol/L)	3.59±0.46	3.70±0.47	0.329
Cl(mmol/L)	104.89±6.77	104.90±4.96	0.995
Ca(mmol/L)	1.12±0.06	1.13±0.08	0.523

Note: Data are shown as mean ±standard deviation unless otherwise stated.
Abbrevations: BMI, body mass index; ARDS, Acute respiratory distress syndrome; APACHE II, Acute physiology and chronic health evaluation II; HR, Heart rate; MAP, Mean arterial pressure; EF, Ejection fraction; RR, Respiratory rate; VT, Tidal volume; RSBI, Rapid shallow breathing index; PaO2, partial pressure of oxygen in arterial blood; PaO2/FiO2, Partial pressure of arterial oxygen / fraction of inspired oxygen; SCr, Serum creatinine; WBC, White blood cell.

Table 2 Comparison of Extubation Success and Failure Groups According to Ultrasound Measurements

Parameters	Extubation failure (27)	Extubation success (68)	P
B-mode _Thickness (cm)			
DT-exp	0.15±0.04	0.16±0.05	0.105
DT-insp	0.19±0.05	0.24±0.05	0.000
DTF(%)	28.84±8.30	47.97±16.29	0.000
DTF-RSBI (beat/min ·%)	65.12±24.18	40.07 ±15.27	0.000
M-mode_Excursion			
DE (cm)	1.04±4.84	1.65±0.42	0.000
DE-RSBI (beat/min ·cm)	19.78±9.28	11.16±3.56	0.000

Note: Data expressed as mean±standard deviation.
Abbrevations: DT-exp, Diaphragm at the end of tidal expiration; DT-insp, Diaphragm at the end of tidal inspiration; DTF, Diaphragm thickening fraction; DTF-RSBI, diaphragmatic thickening fraction rapid shallow breathing index; DE, Diaphragmatic excursion; DE-RSBI, diaphragmatic excursion rapid shallow breathing index.

Table 3 The Value of Ultrasound Measurements for Predicting Extubation

Parameters	AUC	95% CI	Cut-off values	Sensitivity(%)	Specificity(%)	P
Duration of ventilation(d)	0.748	0.648–0.831	≤4	69.12	81.48	<0.0001
DTF(%)	0.888	0.807–0.943	>31.11	91.18	70.37	<0.0001
DTF-RSBI (beat/min ·%)	0.858	0.771–0.921	≤51	79.51	85.19	<0.0001
DE (cm)	0.856	0.769–0.919	>1.06	100.00	70.37	<0.0001
DE-RSBI (beat/min ·cm)	0.624	0.753–0.909	≤13.76	80.88	81.48	<0.001
Combined	0.942	0.875–0.980	—	88.24	88.89	<0.0001

Abbrevations: AUC, area under the curve; CI, confidence interval; DTF, Diaphragm thickening fraction; DTF-RSBI, diaphragmatic thickening fraction rapid shallow breathing index; DE, Diaphragmatic excursion; DMS, Diaphragmatic movement speed; DE-Ti, Diaphragm excursion-time index; DE-RSBI, diaphragmatic excursion rapid shallow breathing index.

DTF-RSBI, DE-RSBI showed a high specificity of 81.48,85.19%, 81.48%. Considering all the above factors, the sensitivity was 88.24% and the specificity was 88.89%.

Discussion

Diaphragmatic ultrasound can be used to predict weaning,[14–16] and it is reliable, valid, and responsive in ICU patients.[15] Most commonly measured was diaphragm thickness (DT) or DTF in B-mode, or DE in M-mode. But the sensitivity and specificity of these indices are highly variable,[10] so our study was planned to assess the diaphragm contraction, motion-related parameters using bedside ultrasound in selected weaning-eligible patients and only the right hemidiaphragm values were considered for analysis.

DTF can serve as an important indicator to assess diaphragmatic muscle function by reflecting variations in diaphragm thickness.[17] Previous study[18] has demonstrated that a DTF value of 0.3 or higher exhibits high predictive ability for ventilator outcomes. In our study, DT-insp and DTF is lower in the extubation failure group than in the extubation success group. The cut-off values of DTF is 31.11%, had a high sensitivity of 91.18%. Our study also combined approach of RSBI and DTF in the pre-extubation time, DTF-RSBI was associated with successful extubation with a sensitivity of 79.51% and a specificity of 85.19%.

The DT is associated with muscle strength and commonly used parameters to predict successful extubation.[14,19] Many studies[18,20,21] suggested that DE cut-off values of 10 mm to 13 mm. We observed that the patients with successful extubation had significantly higher DE than the extubation failure group. While the cut-off values of DE is 1.06cm with a sensitivity of 100% and a specificity of 70.37%. Whereas, DE-RSBI showed 80.88% sensitivity and 81.48% specificity.

Numerous other clinical indicators play a role in influencing the safe withdrawal process, including the potential impact of prolonged ventilation on diaphragmatic function. Previous studies[22] have indicated that mechanical ventilation exceeding 7 days is indicative of extraction failure. In this study, a specificity of 81.48% was observed for predicting successful extubation when the duration of ventilation was less than 4 days. Therefore, combining the duration of mechanical ventilation with ultrasound parameters can enhance clinicians'ability to achieve higher sensitivity and specificity.

The limitation of this study lies in the inadequate sample size and the inability to conduct a comprehensive investigation. In order to gain deeper insights into the diaphragmatic ultrasound parameters associated with successful weaning and their significance, we intend to carry out a multi-center study with a larger sample size.

In conclusion, the utilization of diaphragmatic ultrasound in MV weaning can prove particularly advantageous for healthcare professionals by facilitating smoother transitions. However, it is important to acknowledge certain limitations of this study. First, the inclusion of patients with various etiologies simultaneously prevents us from extrapolating these results to specific subgroups. Second, the study fails to explore the potential impact of other clinical variables such as duration of ventilation and age on extubation failure.

Conclusion

Clinicians can used diaphragmatic ultrasound to detect patients at risk of experiencing difficult weaning and to predict weaning outcome and successful extubation. The traditional parameters DTF and DE had a high sensitivity, whereas duration of mechanical ventilation, DTF-RSBI, DE-RSBI showed a high specificity. Considering all the above factors can improve prediction efficiency.

Data Sharing Statement

The validation dataset used and/or analyzed during the current study is available from the corresponding author upon reasonable request.

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Disclosure

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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