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Original Article

Value of diaphragmatic ultrasound parameters in assessing weaning outcomes and survival in ventilator-dependent intensive care unit patients

Liuhua Pan*, Jing Zhao*, Xiaofang Wang, Lu Huang, Shiying Li, Shunnan Sun

*Department of Critical Care Medicine, Lishui People's Hospital, Lishui 323000, Zhejiang, China. *Equal contributors and co-first authors.*

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Abstract: Objective: To retrospectively evaluate the utility of diaphragmatic ultrasound parameters in assessing ventilator weaning outcomes and survival in ventilator-dependent intensive care unit (ICU) patients. Methods: A total of 105 ventilator-dependent ICU patients admitted to our hospital between October 2019 and February 2024 were included in this study. Depending on weaning outcomes, patients were divided into a successful group (n = 86) and a failure group (n = 19). Diaphragmatic ultrasound parameters, including diaphragm excursion (DE), diaphragmatic thickness at the end of expiration (DTee), diaphragmatic thickness at the end of inspiration (DTei), and diaphragmatic thickening fraction (DTF), were collected. Receiver operating characteristic (ROC) curves were plotted to assess the predictive value of these parameters for weaning success. Survival curves were analyzed to explore their relationships with survival. Logistic regression analysis was used to identify risk factors influencing survival in ventilator-dependent ICU patients. Results: Diaphragmatic ultrasound parameters were statistically higher in the successful group compared to the failure group. TFor ventilator-dependent ICU patients, the areas under the curve (AUCs) of DE, DTee, DTei, and DTF in predicting weaning outcomes were 0.757, 0.765, 0.770, and 0.677, respectively. However, when these four indicators were combined for prediction, the AUC could be elevated to 0.938. Logistic regression analysis identified that gender, age, body mass index, disease type, comorbidities, as well as DE, DTee, DTei, and DTF, were not risk factors influencing the survival of these ventilator-dependent ICU patients. Conclusions: Diaphragmatic ultrasound parameters are valuable tools for assessing the weaning outcomes and survival of ventilator-dependent ICU patients. These parameters provide auxiliary guidance for clinical decision-making and subsequent patient management.

Keywords: Diaphragmatic ultrasound parameters, ventilator-dependent ICU patients, weaning outcomes, survival

Introduction

Most patients admitted to intensive care units (ICUs) suffer from critical respiratory diseases such as acute exacerbations of chronic obstructive pulmonary disease (COPD), severe pneumonia, and acute respiratory distress syndrome (ARDS) [1]. Mechanical ventilation (MV), a commonly used respiratory support technique in ICUs, not only ensures airway patency but also prevents hypoxemia and carbon dioxide retention, which is conducive to surviving the critical period [2, 3]. The management of MV weaning is a key aspect of ICU care. Both premature weaning and prolonged dependence on MV increase the risk of complications and medical care costs for ICU patients [4]. Statistics indicate that 5-10% of ICU patients on MV require prolonged MV use (more than 21 days of use). The annual economic burden brought on by prolonged MV in the United States alone is as high as 25 billion, while only 50% of the patients with prolonged MV achieve successful weaning [5-7]. Nevertheless, research on predicting the ventilator weaning outcomes of ventilator-dependent ICU patients remains limited. This study seeks to address this gap by providing an in-depth analysis and contributing valuable insights to guide clinical decision-making.

The subjective accuracy of physicians in predicting successful ventilator weaning remains

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low [8]. Therefore, an objective assessment of the clinical condition of ventilator-dependent ICU patients is important for accurately predicting weaning outcomes [9]. Diaphragmatic dysfunction has been identified as a major factor associated with unsuccessful ventilator weaning and is strongly linked to adverse events during the weaning process [10, 11]. Traditional methods for assessing diaphragmatic function, such as X-rays, phrenic nerve conduction research, and transdiaphragmatic pressure measurements have limitations, including high technical complexity, limited applicability, and high cost [12, 13]. Ultrasound, on the other hand, offers a non-invasive, cost-effective, and widely applicable alternative. It allows for the evaluation of the relationship between diaphragm thickness and lung volume during inspiration, as well as the detection of diaphragm atrophy and paralysis with high accuracy [14]. A systematic review and meta-analysis highlighted the moderate to high specificity of diaphragmatic ultrasound parameters, such as diaphragm thickening fraction and diaphragmatic displacement, in predicting weaning outcomes; however, its sensitivity is relatively low, and the overall predictive accuracy requires further improvement [15].

This study focuses on analyzing the utility of diaphragmatic ultrasound parameters - diaphragm excursion (DE), diaphragmatic thickness at the end of expiration (DTee), diaphragmatic thickness at the end of inspiration (DTei) and diaphragmatic thickening fraction (DTF), in predicting ventilator weaning outcomes and evaluating survival of ventilator-dependent ICU patients. By doing so, it aims to enhance the prediction of weaning outcomes and survival assessment in this patient population.

Information and methodology

Patient selection

This retrospective study was approved by the Ethics Committee of Lishui People's Hospital. A total of 105 ICU patients with severe ventilator dependence admitted between October 2019 and February 2024 were selected as the study subjects. Patients were categorized into two groups based on their weaning outcomes: the successful group (n = 86) and the failure group (n = 19). No significant differences were observed in the general demographic or clinical characteristics between the two groups ($P > 0.05$), ensuring clinical comparability.

Inclusion criteria: 1) Patients who had undergone invasive MV for more than 48 hours; 2) Patients who met the criteria for ventilator withdrawal; 3) Patients with quantitative measurements of the ipsilateral diaphragm parameters; 4) Patients with intact medical records, normal cognitive function, and the ability to communicate effectively.

Exclusion criteria: 1) Conditions such as pneumothorax, intra-abdominal hypertension, severe pancreatitis, spinal cord injury, massive pleural effusion, neuromuscular disease, history of diaphragm paralysis, cervical spine injury, or contraindication to ultrasonography; 2) Pregnant women; 3) Patients unable to sustain spontaneous breathing.

Detection methods

The detection was carried out in accordance with a previously established method [16]. An ultrasonic diagnostic system and an electrocardiogram (ECG) monitor were used to for ventilator weaning screening once the patient's condition improved or related clinical symptoms subsided. Patients were placed in a supine position for the measurements. The ultrasound probe frequency was set to 3.5 MHz, and the range of diaphragm movement was calibrated in M mode to determine DE. After locating the diaphragm according to the thoracoperitoneum between the 8th and 9th ribs between the anterior axillary and midaxillary lines, the probe frequency was 13 Mhz to measure DTee and DTei in M mode. Measurements were conducted in M-mode over a single respiratory cycle, and the DTF was calculated using the formula: DTF = (DTei - DTee)/DTee. Representative diaphragmatic ultrasound images are shown in **Figure 1**.

Weaning outcomes

Following a successful spontaneous breathing trial and completion of diaphragmatic ultrasound, the machine was removed, and the patient was extubated within 24 hours. Successful weaning was defined as no need for re-intubation within 48 hours after extubation. Weaning failure refers to the following situations: failure to pass the spontaneous breath-

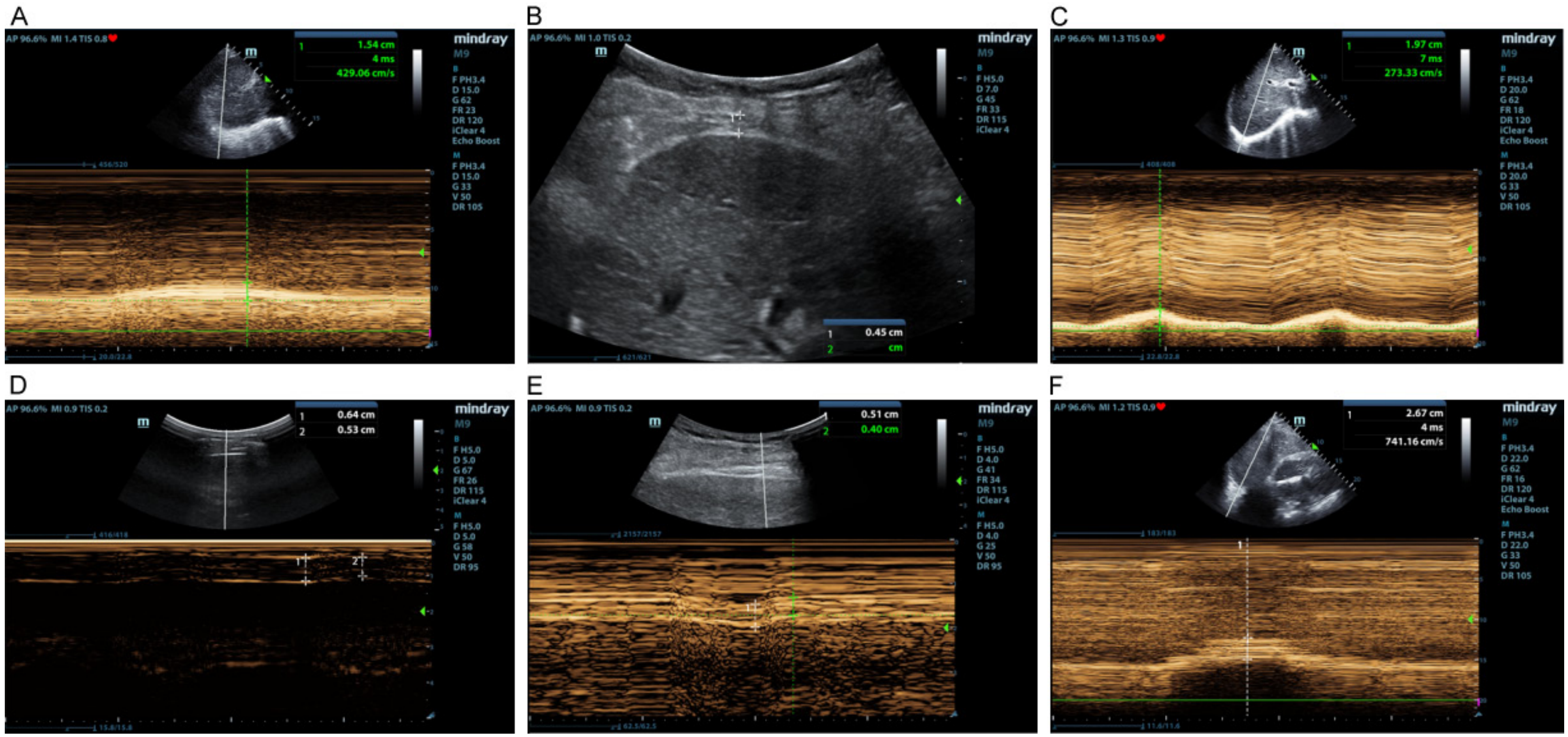

Figure 1. Diaphragmatic ultrasound images. A-F. Diaphragmatic ultrasound images of 6 patients.

Table 1. Comparison of general information between the success and failure groups

Indicators	Failure group (n = 19)	Success group (n = 86)	χ^2/t	P
Sex			0.129	0.720
Male	12 (63.16)	58 (67.44)		
Female	7 (36.84)	28 (32.56)		
Age (years old)	64.47±3.99	66.07±7.21	0.934	0.353
Body mass index (kg/m^2)	19.21±2.27	20.16±3.14		
Disease type			0.514	0.773
Chronic obstructive pulmonary disease	8 (42.11)	32 (37.21)		
Pneumonia	6 (31.58)	24 (27.91)		
Acute respiratory distress syndrome	5 (26.32)	30 (34.88)		
Comorbidities				
Coronary heart disease	2 (10.53)	8 (9.30)	0.027	0.869
Hypertension	6 (31.58)	14 (16.28)	2.362	0.124
Diabetes mellitus	4 (21.05)	13 (15.12)	0.404	0.525

ing trial; re-intubation for invasive MV 48 hours after weaning, with re-intubation criteria including heart rate ≤ 50 beats/min, cardiac arrest, uncoordinated respiratory movement of the chest and abdomen, massive aspiration, and hemodynamic instability; death after 48 hours of extubation.

Sample size

In this research, we hypothesized a weaning success rate of 60%. Given that the diaphragmatic ultrasound parameters have a medium-sized effect (effect size = 0.05) on weaning outcome, and with a statistical power (1 - β) set at 80% and the α level set at 0.05, the binomial proportion-based sample size calculation formula suggested a minimum sample size of 75 cases. Considering the possible 10% loss-to-follow-up rate, the minimum sample size was adjusted to 84 cases. The actual sample size included in this study was 105 cases, which sufficiently meets the minimum sample size requirements.

Statistical methods

Statistical analyses were performed using SPSS 22.0. For data comparisons, independent sample t-tests were used for quantitative data ($\bar{x}\pm s$), and χ^2 tests were employed for enumeration data (n [%]). Receiver operating characteristic (ROC) curve and areas under the curve (AUC) were used to determine the predictive efficiency of each index. Kaplan-Meyer (K-M) curves were drawn to analyze the survival outcomes. Binary logistic regression analysis was used to identify factors influencing survival in ventilator-dependent ICU patients. Statistical significance was set at $P < 0.05$ for all analyses.

Results

Comparison of general data between the two groups

There were no significant differences between the failure and successful groups in terms of gender, age, body mass index (BMI), disease types, or comorbidities (all $P > 0.05$, **Table 1**).

Comparison of diaphragmatic ultrasound parameters between the two groups

The diaphragmatic ultrasound parameters, including DE, DTee, DTei, and DTF, were assessed in both groups. The data showed significantly higher levels of these parameters in the successful group compared to the failure group (all $P < 0.01$, **Figure 2**).

Predictive value of diaphragmatic ultrasound parameters for weaning outcomes in ventilator-dependent ICU patients

The predictive value of diaphragmatic ultrasound parameters for weaning outcomes in ventilator-dependent ICU patients was analyzed using ROC curves. The AUC for DE was 0.757 (95% CI: 0.662-0.852), with an optimal cut-off of 12.50, specificity of 84.21%, and sen-

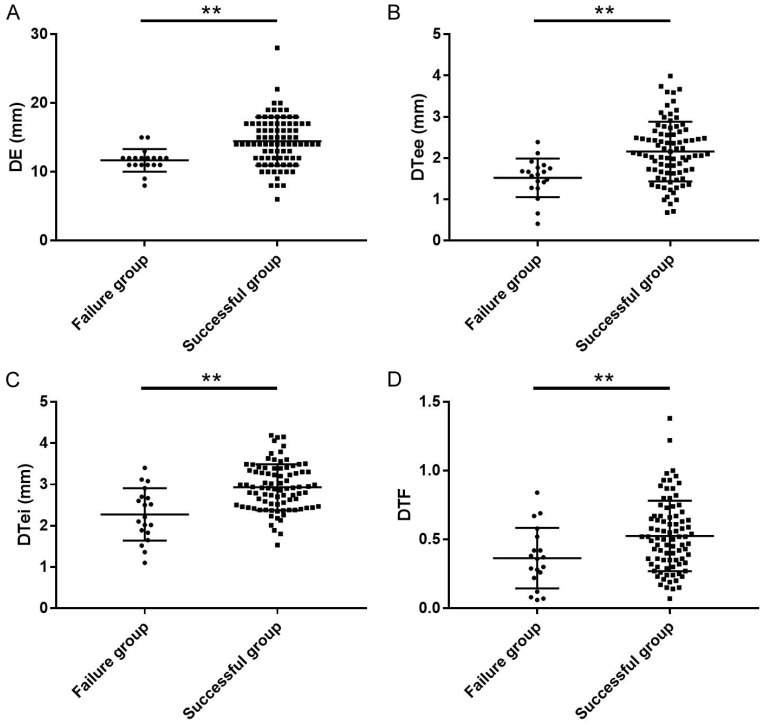

Figure 2. Comparison of diaphragmatic ultrasound parameters between success and failure groups. A. Inter-group comparison of DE. B. Inter-group comparison of DTee. C. Inter-group comparison of DTei. D. Inter-group comparison of DTF. Note: **P < 0.01; DE, diaphragm excursion; DTee, diaphragmatic thickness at the end of expiration; DTei, diaphragmatic thickness at the end of inspiration; DTF, diaphragmatic thickening fraction.

sitivity of 69.77%. The AUC for DTee was 0.765 (95% CI: 0.669-0.861), with an optimal cutoff, specificity, and sensitivity of 1.93, 89.47%, and 63.95%, respectively. DTei had an AUC of 0.770 (95% CI: 0.649-0.890), an optimal cut-off of 2.22, a specificity of 52.63%, and a sensitivity of 93.02%. The AUC of DTF was 0.677 (95% CI: 0.543-0.810), the optimal cutoff was 0.43, and the specificity and sensitivity were 73.68% and 61.63%, respectively. The AUC of the combined model (DE + DTee + DTei + DTF) was 0.938 (95%CI: 0.889-0.986), with an optimal cutoff value of 0.85, specificity and sensitivity of 94.74% and 83.72%, respectively. See **Figure 3** and **Table 2** for details.

Correlation of diaphragmatic ultrasound parameters with survival in ICU patients with ventilator dependence

Survival curves were drawn to analyze the correlation of diaphragmatic ultrasound parameters with survival in ICU patients with ventilator dependence. The optimal cut-off value of each diaphragmatic ultrasound parameter was used to categorize patients into high and low expression groups. The results demonstrated that higher levels of DE, DTee, DTei, and DTF were closely associated with better survival (all P < 0.05). See **Figure 4** for details.

Risk factors affecting survival in ventilator-dependent ICU patients

An in-depth binary logistic regression analysis was performed to identify the risk factors affecting survival in ventilator-dependent ICU patients. The results indicated that sex, age, BMI, disease type, comorbidities, DE, DTee, DTei, and DTF were not risk factors for survival in such patients (P > 0.05, **Table 3**).

Discussion

Delayed MV weaning increases the risk of death in ICU patients and can lead to serious complications, such as ventilator-associated pneumonia, diaphragmatic atrophy, and pulmonary edema [17, 18]. This is related to the complexity of the transition from complete ventilation support to autonomous respiration, which imposes significant stress on multiple organs [19]. Therefore, accurately evaluating the weaning outcomes and survival in ventilator-dependent ICU patients holds important clinical value in improving their survival outcomes.

Diaphragmatic ultrasound, as a bedside imaging technology, offers significant advantages in the clinical management of ICU patients, including non-invasiveness, low radiation exposure, and simple operation [20]. This technique enables real-time dynamic observation of diaphragm changes and provides guidance for weaning ICU patients from MV by measuring changes in diaphragmatic ultrasound parameters such as DE, DTee, DTei, and DTF [21]. Among these parameters, DE reflects diaphragm functionality, and lower levels indicate diaphragm dysfunction and a higher risk of

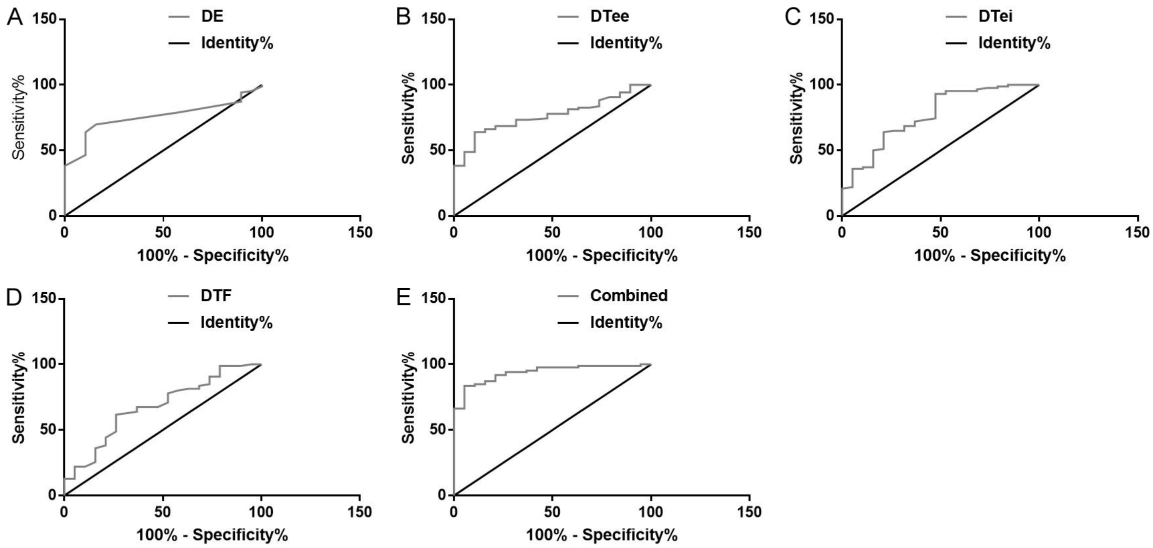

Figure 3. The predictive value of diaphragmatic ultrasound parameters for ventilator weaning outcomes in ICU patients with ventilator dependence. A. The ROC curve of DE for predicting weaning outcomes in ventilator-dependent ICU patients. B. The ROC curve of DTee for predicting weaning outcomes in ventilator-dependent ICU patients. C. The ROC curve of DTei for predicting weaning outcomes in ventilator-dependent ICU patients. D. The ROC curve of DTF for predicting weaning outcomes in ventilator-dependent ICU patients. E. The ROC curve of joint measurement for predicting weaning outcomes in ventilator-dependent ICU patients by joint detection. Note: ICU, intensive care unit; AUC, area under the curve; DE, diaphragm excursion; DTee, diaphragmatic thickness at the end of expiration; DTei, diaphragmatic thickness at the end of inspiration; DTF, diaphragmatic thickening fraction.

Table 2. Predictive value of diaphragmatic ultrasound parameters for weaning outcomes in ventilator-dependent ICU patients

Indicators	AUC	95% CI	P	Optimal cutoff	Specificity	Sensitivity
DE	0.757	0.662-0.852	< 0.001	12.50	84.21%	69.77%
DTee	0.765	0.669-0.861	< 0.001	1.93	89.47%	63.95%
DTei	0.770	0.649-0.890	< 0.001	2.22	52.63%	93.02%
DTF	0.677	0.543-0.810	0.016	0.43	73.68%	61.63%
Joint detection	0.938	0.889-0.986	< 0.001	0.85	94.74%	83.72%

Note: ICU, intensive care unit; DE, diaphragm excursion; DTee, diaphragmatic thickness at the end of expiration; DTei, diaphragmatic thickness at the end of inspiration; DTF, diaphragmatic thickening fraction.

weaning failure [22]. Reduced DE levels are commonly observed in patients with spontaneous dyspnea and contribute to worsening diaphragmatic dysfunction, thereby decreasing the likelihood of successful weaning [23]. While DTee and DTei are essential for assessing changes in diaphragm thickness, their clinical utility may be affected by individual specificity, such as body and weight [24]. In contrast, DTF reflects the active diaphragm contraction during MV and less impacted by individual specificity, making it a more reliable predictor of diaphragm function [25].

In this study, we evaluated DE, DTee, DTei, and DTF, finding that all these parameters were significantly higher in the successful group compared to the failure group. This suggests that failed weaning is associated with an imbalance between the mechanical and functional loads on the diaphragm, leading to diaphragmatic fatigue. Elevated levels of DE, DTee, DTei, and DTF are indicative of successful weaning. In the research by Xu Q et al. [26], the DE and DTF of the successful group were significantly higher than those of the failure group, consistent with our research results. Gok F et al. [27] also pointed out that DE ($r = 0.532$, $P \leq 0.001$) and DTF ($r = 0.499$, $P \leq 0.001$) were closely related to extubation success, also consistent with our observations.

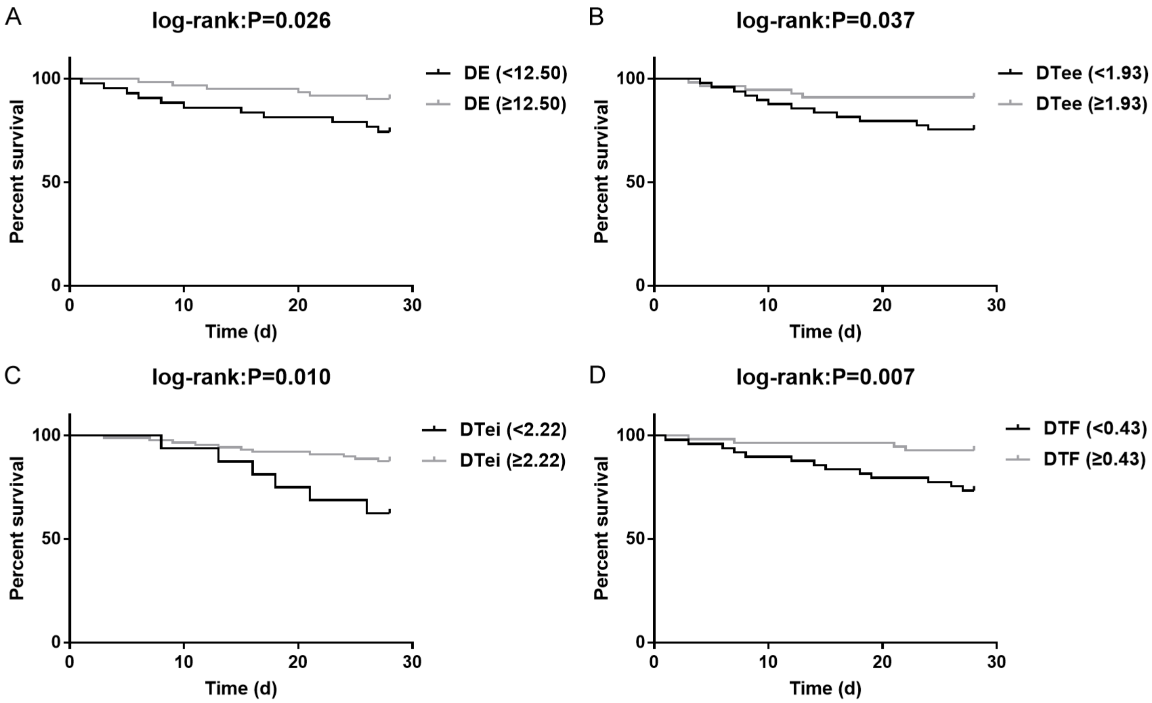

Figure 4. Correlation of diaphragmatic ultrasound parameters with survival in ventilator-dependent ICU patients. A. The association between DE and survival in ventilator-dependent ICU patients. B. The association between DTee and survival in ventilator-dependent ICU patients. C. The association between DTei and survival in ventilator-dependent ICU patients. D. The association between DTF and survival in ventilator-dependent ICU patients. Note: ICU, intensive care unit; DE, diaphragm excursion; DTee, diaphragmatic thickness at the end of expiration; DTei, diaphragmatic thickness at the end of inspiration; DTF, diaphragmatic thickening fraction.

Table 3. Multivariate analysis of risk factors affecting survival in ventilator-dependent ICU patients

Indicators	β	SE	Wald	P	Exp (β)	95% CI
Sex	1.360	0.832	2.670	0.102	3.897	0.762-19.915
Age (years old)	-0.027	0.047	0.333	0.564	0.973	0.888-1.067
Body mass index (kg/m^2)	-0.105	0.096	1.199	0.273	0.901	0.746-1.086
Disease type	-0.407	0.353	1.333	0.248	0.665	0.333-1.329
Comorbidities	-0.101	0.260	0.150	0.699	0.904	0.543-1.506
DE (mm)	0.025	0.090	0.075	0.784	1.025	0.860-1.221
DTee (mm)	-0.082	0.433	0.036	0.850	0.922	0.395-2.152
DTei (mm)	0.539	0.522	1.066	0.302	1.714	0.616-4.766
DTF	1.812	1.048	2.990	0.084	6.120	0.785-47.693

Note: ICU, intensive care unit; DE, diaphragm excursion; DTee, diaphragmatic thickness at the end of expiration; DTei, diaphragmatic thickness at the end of inspiration; DTF, diaphragmatic thickening fraction.

ROC analysis data in this study showed that the AUC for DE, DTee, and DTei in predicting weaning outcomes exceeded 0.750, with DTei achieving the highest AUC (0.770) and DTF the lowest AUC (0.677). These findings are consistent with Yao Y et al. [28], who reported AUCs of approximately 0.700 for DE, DTei, and DTF in predicting weaning outcomes in pediatric ICU patients, emphasizing that their combination improves predictive accuracy. Additionally, Saravanan R et al. [29] demonstrated high predictive value of diaphragmatic ultrasound for successful weaning in mechanically ventilated patients, with AUCs of 0.654 and 0.809 for DTF and DE, respectively, which are similar to our results. Among the four diaphragmatic ultrasound parameters, DE and DTee exhibited the highest specificity, with DE at 84.21% and DTee at

89.47%. Meanwhile, DTei had the highest sensitivity at 93.02%. When these parameters were combined, the AUC for predicting weaning outcomes in ICU patients with ventilator dependence reached 0.938, with a high specificity of 94.74% and sensitivity of 83.72%. This aligns with findings from Li S et al. [30], who reported that the combination of DE, DTF, lung ultrasound score (LUS), and rapid shallow breathing index (RSBI) maximized predictive value for successful weaning in elderly ICU patients, with an AUC reaching 0.919 and the sensitivity and specificity up to 96% and 89% respectively, similar to our research results.

Survival curve analysis revealed that low levels of DE, DTee, DTei, and DTF were all significantly related to lower survival, while improving their levels helps to extend survival to some extent. This indicates that diaphragmatic ultrasound parameters are valuable not only for predicting weaning outcomes but also for assessing disease progression and survival status in ventilator-dependent ICU patients. Finally, binary logistic regression analysis found that none of the examined factors - sex, age, BMI, disease type, comorbidities, DE, DTee, DTei, or DTF - were statistically significant risk factors for survival in this patient population. This suggests that while diaphragmatic ultrasound parameters provide important prognostic information, other unexamined factors may play a role in influencing long-term survival.

This study still has several limitations. First, the sample was restricted to severely ill ICU patients who were ventilator-dependent, which may limit the generalizability of the research results to other patient groups with difficulty in ventilator weaning. Second, long-term follow-up was not carried out in this study, which would have provided valuable insights into the prolonged survival of patients. Third, as a retrospective analysis, there is an inherent challenge to identify all possible confounding factors that might influence ventilator weaning outcomes. In future studies, a prospective design and more comprehensive data collection could help identify additional factors contributing to weaning outcomes.

In summary, the combination of diaphragmatic ultrasound parameters holds significant predictive value for weaning outcomes in ICU patients with ventilator dependence. The four key parameters (DE, DTee, DTei, and DTF) demonstrated potential in evaluating patients' ventilator weaning outcomes, which can not only provide a reliable reference for predicting the weaning outcomes of such patients but also offer scientific evidence for subsequent treatments and prognosis improvement.

Disclosure of conflict of interest

None.

Address correspondence to: Shunnan Sun, Department of Critical Care Medicine, Lishui People's Hospital, Lishui 323000, Zhejiang, China. Tel: +86-18957095176; E-mail: 18957095176@163.com

References

[1] Akbas T and Gunes H. Characteristics and outcomes of patients with chronic obstructive pulmonary disease admitted to the intensive care unit due to acute hypercapnic respiratory failure. Acute Crit Care 2023; 38: 49-56.

[2] Battaglini D, Siwicka Gieroba D, Brunetti I, Patroniti N, Bonatti G, Rocco PRM, Pelosi P and Robba C. Mechanical ventilation in neurocritical care setting: a clinical approach. Best Pract Res Clin Anaesthesiol 2021; 35: 207-220.

[3] Nielsen MB, Klitgaard TL, Weinreich UM, Nielsen FM, Perner A, Schjorring OL and Rasmussen BS. Effects of a lower versus a higher oxygenation target in intensive care unit patients with chronic obstructive pulmonary disease and acute hypoxaemic respiratory failure: a subgroup analysis of a randomised clinical trial. BJA Open 2024; 10: 100281.

[4] Jia Y, Kaul C, Lawton T, Murray-Smith R and Habli I. Prediction of weaning from mechanical ventilation using Convolutional Neural Networks. Artif Intell Med 2021; 117: 102087.

[5] Hassen KA, Nemera MA, Aniley AW, Olani AB and Bedane SG. Knowledge regarding mechanical ventilation and practice of ventilatory care among nurses working in intensive care units in selected governmental hospitals in Addis Ababa, Ethiopia: a descriptive cross-sectional study. Crit Care Res Pract 2023; 2023: 4977612.

[6] Shih CY, Hung MC, Lu HM, Chen L, Huang SJ and Wang JD. Incidence, life expectancy and prognostic factors in cancer patients under prolonged mechanical ventilation: a nationwide analysis of 5,138 cases during 1998-2007. Crit Care 2013; 17: R144.

[7] Damuth E, Mitchell JA, Bartock JL, Roberts BW and Trzeciak S. Long-term survival of critically ill patients treated with prolonged mechanical

ventilation: a systematic review and meta-analysis. Lancet Respir Med 2015; 3: 544-553.

[8] Liu CF, Hung CM, Ko SC, Cheng KC, Chao CM, Sung MI, Hsing SC, Wang JJ, Chen CJ, Lai CC, Chen CM and Chiu CC. An artificial intelligence system to predict the optimal timing for mechanical ventilation weaning for intensive care unit patients: a two-stage prediction approach. Front Med (Lausanne) 2022; 9: 935366.

[9] Wang Y, Lei L, Yang H, He S, Hao J, Liu T, Chen X, Huang Y, Zhou J, Lin Z, Zheng H, Lin X, Huang W, Liu X, Li Y, Huang L, Qiu W, Ru H, Wang D, Wu J, Zheng H, Zuo L, Zeng P, Zhong J, Rong Y, Fan M, Li J, Cai S, Kou Q, Liu E, Lin Z, Cai J, Yang H, Li F, Wang Y, Lin X, Chen W, Gao Y, Huang S, Sang L, Xu Y and Zhang K. Weaning critically ill patients from mechanical ventilation: a protocol from a multicenter retrospective cohort study. J Thorac Dis 2022; 14: 199-206.

[10] Boscolo A, Sella N, Pettenuzzo T, Pistollato E, Calabrese F, Gregori D, Cammarota G, Dres M, Rea F and Navalesi P; Padua-Lung Transplant Group. Diaphragm dysfunction predicts weaning outcome after bilateral lung transplant. Anesthesiology 2024; 140: 126-136.

[11] Dres M, Rozenberg E, Morawiec E, Mayaux J, Delemazure J, Similowski T and Demoule A. Diaphragm dysfunction, lung aeration loss and weaning-induced pulmonary oedema in difficult-to-wean patients. Ann Intensive Care 2021; 11: 99.

[12] Hu J, Guo R, Li H, Wen H and Wang Y. Perioperative diaphragm dysfunction. J Clin Med 2024; 13: 519.

[13] Laghi FA Jr, Saad M and Shaikh H. Ultrasound and non-ultrasound imaging techniques in the assessment of diaphragmatic dysfunction. BMC Pulm Med 2021; 21: 85.

[14] Antenora F, Fantini R, Iattoni A, Castaniere I, Sdanganelli A, Livrieri F, Tonelli R, Zona S, Monelli M, Clini EM and Marchioni A. Prevalence and outcomes of diaphragmatic dysfunction assessed by ultrasound technology during acute exacerbation of COPD: a pilot study. Respirology 2017; 22: 338-344.

[15] Le Neindre A, Philippart F, Luperto M, Wormser J, Morel-Sapene J, Aho SL, Mongodi S, Mojoli F and Bouhemad B. Diagnostic accuracy of diaphragm ultrasound to predict weaning outcome: a systematic review and meta-analysis. Int J Nurs Stud 2021; 117: 103890.

[16] Bao Q, Chen L, Chen X, Li T, Xie C, Zou Z, Huang C, Zhi Y and He Z. The effects of external diaphragmatic pacing on diaphragm function and weaning outcomes of critically ill patients with mechanical ventilation: a prospective randomized study. Ann Transl Med 2022; 10: 1100.

[17] da Silva RB, Neves VR, Montarroyos UR, Silveira MS and Sobral Filho DC. Heart rate variability as a predictor of mechanical ventilation weaning outcomes. Heart Lung 2023; 59: 33-36.

[18] Dong Z, Liu Y, Gai Y, Meng P, Lin H, Zhao Y and Xing J. Early rehabilitation relieves diaphragm dysfunction induced by prolonged mechanical ventilation: a randomised control study. BMC Pulm Med 2021; 21: 106.

[19] Santangelo E, Mongodi S, Bouhemad B and Mojoli F. The weaning from mechanical ventilation: a comprehensive ultrasound approach. Curr Opin Crit Care 2022; 28: 322-330.

[20] Kheir M, Dong V, Roselli V and Mina B. The role of ultrasound in predicting non-invasive ventilation outcomes: a systematic review. Front Med (Lausanne) 2023; 10: 1233518.

[21] Lin H, Yao M, Qin Z, Fu S and Wang H. Predictive values of ultrasonic diaphragm thickening fraction combined with integrative weaning index in weaning patients with mechanical ventilation: a retrospective study. J Cardiothorac Surg 2024; 19: 66.

[22] Clement A, Zieleskiewicz L, Bonnec JM, Occean BV, Bastide S, Muller L, de La Coussaye JE, Boussuges A, Claret PG and Bobbia X. Diaphragmatic excursion measurement in emergency department patients with acute dyspnea to predict mechanical ventilation use. Am J Emerg Med 2020; 38: 2081-2087.

[23] Parada-Gereda HM, Tibaduiza AL, Rico-Mendoza A, Molano-Franco D, Nieto VH, Arias-Ortiz WA, Perez-Teran P and Masclans JR. Effectiveness of diaphragmatic ultrasound as a predictor of successful weaning from mechanical ventilation: a systematic review and meta-analysis. Crit Care 2023; 27: 174.

[24] Sun Q, Shan F, Dong H, Jiang Y, Sun Y and Sun Y. Predictive value of ultrasonic diaphragm thickening fraction on successful weaning for patients with myasthenia gravis crisis. Zhonghua Wei Zhong Bing Ji Jiu Yi Xue 2017; 29: 619-623.

[25] Vetrugno L, Orso D, Corradi F, Zani G, Spadaro S, Meroi F, D'Andrea N, Bove T, Cammarota G, De Robertis E, Ferrari S, Guarnieri M, Ajuti M, Fusari M, Grieco DL, Deana C, Boero E, Franchi F, Scolletta S, Maggiore SM and Forfori F. Diaphragm ultrasound evaluation during weaning from mechanical ventilation in COVID-19 patients: a pragmatic, cross-section, multicenter study. Respir Res 2022; 23: 210.

[26] Xu Q, Yang X, Qian Y, Hu C, Lu W, Cai S, Hu B and Li J. Comparison of assessment of diaphragm function using speckle tracking between patients with successful and failed weaning: a multicentre, observational, pilot study. BMC Pulm Med 2022; 22: 459.

[27] Gok F, Mercan A, Kilicaslan A, Sarkilar G and Yosunkaya A. Diaphragm and lung ultrasonography during weaning from mechanical ventilation in critically ill patients. Cureus 2021; 13: e15057.

[28] Yao Y, He L, Chen W, Zhou H, Lu G, Tao J and Wang S. Predictive value of diaphragmatic ultrasonography for the weaning outcome in mechanically ventilated children aged 1-3 years. Front Pediatr 2022; 10: 840444.

[29] Saravanan R, Nivedita K, Karthik K and Venkatraman R. Role of diaphragm ultrasound in weaning mechanically ventilated patients: a prospective observational study. Indian J Anaesth 2022; 66: 591-598.

[30] Li S, Chen Z and Yan W. Application of bedside ultrasound in predicting the outcome of weaning from mechanical ventilation in elderly patients. BMC Pulm Med 2021; 21: 217.