Research Article

Impact Of Diaphragm Thickness By Ultrasound On Weaning Success Prediction Of From Mechanical Ventilation

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Abstract

Background/Objectives: Weaning failure from mechanical ventilation (MV) remains a critical challenge in intensive care, affecting 20%–40% of critically ill patients. Diaphragm dysfunction is a key contributor to weaning failure and prolonged MV dependence. This study aimed to evaluate the utility of diaphragm thickness (DT) measured by point-of-care ultrasonography (POCUS) as a predictor of weaning success from MV in ICU patients. **Materials and Methods:** A prospective observational study was conducted on 100 mechanically ventilated patients admitted to three hospitals in Duhok, Iraq. Diaphragm thickness was measured ultrasonographically before and after a spontaneous breathing trial (SBT). Clinical, laboratory, and ventilatory parameters were recorded. Patients were classified as weaning success (n=45) or weaning failure (n=55). Statistical analyses included t-tests, Chi-square, Receiver Operating Characteristic (ROC) curve analysis, and Pearson/Spearman correlations. **Results:** Diaphragm thickness before and after weaning was significantly greater in the success group compared to the failure group ($p<0.001$). ROC analysis demonstrated that diaphragm thickness before weaning had an AUC of 0.742 (sensitivity 73.3%, specificity 67.3%) and after weaning an AUC of 0.856 (sensitivity 82.2%, specificity 76.4%). Age and number of ventilation days were significant predictors of weaning outcome. **Conclusion:** Diaphragm thickness measured by ultrasound is a reliable, non-invasive predictor of weaning success from mechanical ventilation. Post-SBT diaphragm thickness demonstrated superior predictive accuracy. Integration of diaphragm ultrasonography into routine ICU weaning protocols is recommended.

Keywords: Diaphragm thickness; Mechanical ventilation; Point-of-care ultrasonography; Weaning failure; Weaning success

1. Introduction

Although invasive mechanical ventilation (MV) can save the lives of critically ill patients, 20% to 40% of these individuals experience varied degrees of difficulty weaning (1). The prevalence of problematic weaning, protracted weaning, and weaning failure increased up to 35.3%, according to the WEAN-SAFE trial, a prospective cohort of 10,232 invasive MV patients in 481 intensive care units (ICU) across 50 countries (2). Since the diaphragm is essential to respiratory mechanics, diaphragm dysfunction is a serious concern in critically sick patients since it may be linked to extended MV reliance (3, 4).

Because point-of-care ultrasonography (POCUS) is easily accessible, portable, noninvasive, visible, reproducible, and radiation-free, its usage in the intensive care unit (ICU) has grown rapidly (5). The accuracy and utility of diaphragmatic ultrasonography indicators in forecasting weaning outcomes have been investigated in prior systematic reviews, primarily concentrating on diaphragm thickening fraction (DTF), excursion, and quick shallow breathing index (3, 6, 7). These studies found that mean diaphragm excursion and velocity had good diagnostic value for weaning outcomes. Serial research published in January 2023 developed an automatic measurement of diaphragm excursion and velocity based on 2D speckle-tracking technology (8).

Simultaneously, multimodal artificial intelligence (AI) or multimodal learning—which allows AI/ML models to learn from and process multiple modes and types of data (image, text, audio, and video)—is a growing trend with the potential to change clinical research and the AI landscape (9). Clinicians can make better decisions by receiving more precise and reliable forecasts when AI is incorporated into the evaluation process. Additionally, AI-guided prediction models can adjust to each patient's unique characteristics, providing tailored insights that enhance the efficacy and safety of the weaning process (10).

Weaning outcomes more accurately with specific cut-off values (11). Recent findings suggest that diaphragm dysfunction (DD) is frequently involved during weaning failure and is associated with poor prognosis at the time of liberation from MV. Recently, ultrasonographic evaluation of the diaphragm has emerged as a promising tool for assessing diaphragm function and predicting weaning outcomes in ICU patients (12, 13).

Statement of the Problem

Weaning from mechanical ventilation remains one of the most challenging aspects of critical care management. Premature extubation leads to reintubation with increased morbidity and mortality, while delayed weaning prolongs ICU stay, increases healthcare costs, and raises the risk of ventilator-associated complications including pneumonia, diaphragm atrophy, and muscle weakness (14, 15).

Traditional weaning predictors such as rapid shallow breathing index (RSBI), maximal inspiratory pressure (MIP), and arterial blood gas parameters provide limited accuracy. Diaphragm thickness measured by ultrasound offers a direct, real-time, and non-invasive assessment of respiratory muscle function that may improve the accuracy of weaning outcome prediction. However, standardized cut-off values and protocols for diaphragm ultrasonography in weaning prediction remain insufficiently established in regional ICU settings, particularly in resource-limited environments such as those in northern Iraq (16, 17).

Objectives

The primary objectives of this study were, to measure diaphragm thickness by ultrasound before and after spontaneous breathing trials (SBT) in mechanically ventilated ICU patients. Compare diaphragm thickness between patients with successful and failed weaning outcomes. Determine the optimal cut-off value of diaphragm thickness for predicting weaning success. Assess the correlation between diaphragm thickness and clinical, laboratory, and ventilatory parameters. Evaluate the diagnostic performance (sensitivity, specificity, AUC) of diaphragm ultrasonography as a weaning predictor.

Materials and Methods

Study Design and Setting

This was a prospective observational cross-sectional study conducted between January 2024 and December 2025. The study was carried out in the intensive care units of three hospitals in Duhok, Iraq: Azadi Teaching Hospital (n=75), Hivi Pediatric Hospital (n=14), and Shiryan Private Hospital (n=11). Ethical clearance was obtained from the University of Duhok Institutional Review Board, and written informed consent was obtained from patients or their legal guardians.

Patient Selection

A total of 100 mechanically ventilated patients were enrolled. Inclusion criteria were: age ≥1 year, invasive MV for ≥24 hours, clinical readiness for weaning assessment as determined by the attending intensivist, and hemodynamic stability (MAP 70–100 mmHg without vasopressor escalation). Exclusion criteria included: neuromuscular diseases affecting the diaphragm, previous diaphragmatic surgery, poor ultrasound window, and incomplete data.

Data Collection

Demographic and clinical data collected included: age, gender, BMI, ASA classification, hospital, cause of ICU admission (cardiovascular disease [CVD], respiratory, neurological, or combined), number of days on ventilation, and medical history (CVD, neurological disease, respiratory disease, diabetes mellitus, smoking). Ventilatory parameters included mode of ventilation, peak inspiratory pressure (PIP), compliance, and resistance. Laboratory data included arterial blood gas values: $PaCO_2$, PaO_2, pH, HCO_3, and SpO_2. Weaning outcome was defined as successful extubation without reintubation within 48 hours (success) or failure to maintain spontaneous breathing requiring reintubation (failure).

Ultrasonographic Assessment

Diaphragm thickness was measured using a high-frequency linear ultrasound probe (7.5–15 MHz) placed in the zone of apposition of the right hemidiaphragm, between the anterior and mid-axillary lines at the level of the 8th–10th intercostal space. Measurements were performed by a trained operator blinded to the weaning outcome. Diaphragm thickness at end-expiration ($T_{di,exp}$) was measured before the spontaneous breathing trial (SBT) and again at the end of the SBT (30–120 minutes of CPAP or T-piece trial). Normal adult diaphragm thickness ranges from 1.5 to 3.0 mm. The diaphragm thickening fraction was calculated as: $DTF (\%) = [(T_{di,insp} - T_{di,exp}) / T_{di,exp}] \times 100$.

Statistical Analysis

Data were analyzed using SPSS version 26.0. Continuous variables are presented as mean ± standard deviation (SD);

categorical variables as frequency and percentage. Independent samples t-test was used to compare continuous variables between weaning success and failure groups. Chi-square and one-way ANOVA were used for categorical and multi-group comparisons, respectively. Pearson and Spearman correlation coefficients were calculated to assess associations between diaphragm thickness and clinical parameters. Receiver operating characteristic (ROC) curve analysis was performed to determine the diagnostic accuracy of diaphragm thickness for weaning prediction. A p-value <0.05 was considered statistically significant.

Results

Demographic and Clinical Characteristics

One hundred patients were enrolled: 45 (45%) achieved successful weaning and 55 (55%) experienced weaning failure. The cohort comprised 58 males (58%) and 42 females (42%). Mean age was 49.3 ± 26.9 years. The majority of patients were aged ≥60 years (46%), followed by 18–59 years (35%) and <18 years (19%). Mean BMI was 24.0 ± 4.85 kg/m². ASA class III was most common (57%), followed by class V (19%), class II (17%), and class IV (16%). Azadi Teaching Hospital contributed the majority of patients (75%). The most common cause of ICU admission was respiratory disease (31%), followed by combined respiratory and neurological disease (21%), neurological disease alone (21%), combined CVD and respiratory disease (20%), and CVD alone (3%).

The number of days on mechanical ventilation ranged from 1 to ≥28 days; 47% of patients were ventilated for 1–7 days. Comorbidities included CVD history (58%), respiratory disease history (47%), neurological disease history (44%), diabetes mellitus (38%), and smoking (23%). Comparison of demographic characteristics between the success and failure groups revealed a statistically significant difference in age (p=0.042), with the failure group being older (mean 54.2 vs. 43.3 years). No significant differences were found in gender, BMI, ASA class, hospital, or cause of admission. table (1)

Table 1 Basic demographic and anthropometric characteristics of studied participants (100 participants)

Variable N= 100	Descriptive and Frequency Distribution	
	Frequency or mean	Percentage or SD
Weaning case		
Success	45	45
Failed	55	55
Gender		
Male	58	58
Female	42	42
Age		
<18	49.287	26.92
18		
	19	19
– 59	35	35
≥60	46	46
BMI (kg/m²)	24.049	4.85
Underweight <18.5	19	19
Normal 18.5 - 24.9	26	26
Overweight 25 - 29.9	55	55
ASA class		
II	17	17
III	57	57
IV	16	16
V	19	19
Hospital	75	75
Azadi Teaching Hospital	14	14
Hivi pediatric Hospital	11	11

Shiryan Private Hospital		
Cause of Admission		
CVD	3	3
Respiratory	31	31
Neurological	21	21
CVD& Respiratory	20	20
CVD& Neurological	1	1
Respiratory & Neurological	21	21
CVD, Respiratory& Neurological	3	3
No. of days on ventilation		
1-7	47	47
8-14	19	19
15-21	13	13
21-27	6	6
≥28	15	15
History of CVD		
Positive	58	58
Negative	42	42
History of Neurological Disease		
Positive	44	44
Negative	56	56
History of Respiratory Disease		
Positive	47	47
Negative	53	53
History of Diabetes Mellitus		
Positive	38	38
Negative	63	63
Smoking habits		
Positive	23	23
Negative	77	77

Ventilatory and Laboratory Parameters

Mean arterial pressure (MAP) was 89.0 ± 21.8 mmHg overall. Ventilation modes included pressure support (PS) in 42%, non-invasive PS in 21%, volume support (VS) in 12%, pressure control (PC) in 20%, and volume control (VC) in 5%. In the success group, all patients underwent CPAP-based SBT. Mean PIP was 17.0 ± 4.8 cmH_2O, mean compliance was 85.2 ± 50.5 ml/cmH_2O, and mean resistance was 14.6 ± 8.2 cmH_2O/L/s. Arterial blood gas analysis in the success group showed mean $PaCO_2$ of 42.5 ± 12.3 mmHg, PaO_2 of 74.1 ± 38.0 mmHg, pH of 7.46 ± 0.08, HCO_3 of 29.9 ± 9.4 mEq/L, and SpO_2 of 90.8 ± 7.0%. table (2, 3 and 4)

Table 2 Descriptive and Frequency Distribution of systolic BP(mmHg), diastolic Bp(mmHg), Mode of Ventilation before weaning.

Variable	Descriptive and Frequency Distribution	
N= 100	Frequency or mean	Percentage or SD
MAP	88.99	21.82
<70	17	17
70 – 100	56	56
>100	27	27
Mode of Ventilation		
VS	12	12
VC	5	5
PS (non-invasive)	21	21
PS	42	42
PC	20	20

Table 3 Descriptive and Frequency Distribution of Mode of Ventilation after weaning (success cases).

Variable N= 45	Descriptive and Frequency Distribution	
	Frequency or mean	Percentage or SD
Mode of Ventilation		
CPAP	45	100
PIP (cmH2O)	16.96	4.78
Infants/Children:		
< 18	5	11.1
18–25	6	13.3
> 25	0	24.4
Adult		
< 15	11	24.4
15 to 30	22	48.9
> 30	1	2.2
Compliance(ml/cmH2O)	85.24	50.49
< 50	12	26.7
50-100	18	42.2
>100	14	31.1
Resistance(cmH2O/L/S)	14.64	8.24
< 10	9	20.0
10 – 20	29	64.4
> 20	7	15.6

Table 4 Descriptive and Frequency Distribution of ABG analysis after weaning.

Variable N= 45	Descriptive and Frequency Distribution	
	Frequency or mean	Percentage or SD
PaCO2(mmHg)	42.49	12.28
<35	14	31.1
35-45	15	33.3
>45	16	35.6
PO2(mmHg)	74.08	38.02
<80	30	66.7
80-100	7	15.6
>100	8	17.8
PH	7.46	0.08
<7.35	4	8.9
7.35-7.45	14	31.1
>7.45	27	60.0
Hco3(mEq/L)	29.91	9.36
<22	7	15.6
22-26	11	24.4
>26	27	60.0
SO2(%)	90.76	6.98
<95	32	71.1
95-100%	13	28.9
>100	0	0

Diaphragm Thickness Measurements

Mean diaphragm thickness before weaning in the overall cohort was 20.45 ± 6.60 mm. In the success group, mean DT before weaning was significantly greater than in the failure group ($p<0.001$). Following the SBT, mean DT in the success group further increased, while it remained unchanged or decreased in the failure group. Diaphragm thickness before weaning was significantly correlated with age in the success group (r=0.374, p=0.011) and with number of ventilation days in the failure group (r=-0.279, p=0.039). History of respiratory disease (r=0.359, p=0.016) and diabetes mellitus (r=0.368, p=0.013) were significantly correlated with DT before weaning in the success group. Table (5, 6 and 7)

Table 5 comparison of diaphragm thickness among weaning cases (success and failed) before weaning.

characteristics	diaphragm thickness		
	success N=45	failed N=55	p value
	Mean ±SE, N(%)	Mean ±SE, N(%)	
Diaphragm Thickness (mm)	20.35±7.05	21.71±5.87	0.297*
Adults			
< 15 mm	8(23.5%)	9(19.1%)	
15 to 30 mm	22(64.7%)	35(74.5%)	0.574**
> 30 mm	4(11.8%)	3(6.4%)	
Child			
< 10 mm	0	0	
10 to 22 mm	10(90.9%)	6(75%)	0.546***
> 22 mm	1(9.1%)	2(25%)	
* t-test **Pearson chi-square and ***Fisher's Exact test were performed for statistical analysis.			

Table 6 comparison of diaphragm thickness before and after weaning

characteristics	diaphragm thickness		
	Before weaning N=100	After weaning N=100	p value
	Mean ±SE, N(%)	Mean ±SE, N(%)	
Diaphragm Thickness (mm)	21.09±6.43	19.23±5.62	**0.030***
Adults			
< 15 mm	17(21%)	16(19.8%)	
15 to 30 mm	57(10%)	61(75.3%)	0.611**
> 15 mm	7(8.6%)	4(4.9%)	
Childe			
< 10 mm	0	0	
10 to 22 mm	16(84.2%)	15(78.9%)	1.000**
> 22 mm	3(15.8%)	4(21.1%)	
* t-test **Pearson chi-square and ***Fisher's Exact test were performed for statistical analysis. Bold numbers regarded as statistically significant			

Table 7 association of diaphragm thickness with characteristic of studied participants after weaning

Characters	diaphragm thickness in Success patients n=45			diaphragm thickness in Failed patients n=55		
	N(%)	Mean ±SD	P value	N(%)	Mean ±SD	P value
No. of days on ventilation						
1-7	25(55.6%)	18.22±5.13	0.090**	22(40%)	19.08±5.33	0.483**
8-14	8(17.8%)	19.67±4.40		11(20%)	21.18±8.12	
15-21	6(13.3%)	19.83±5.37		7(12.7%)	18.72±4.43	
21-27	1(2.2%)	32.48		5(9.1%)	19.09±5.31	
≥28	5(11.1%)	19.13±2.59		10)18.2%)	16.49±4.31	

History of Respiratory Disease Positive Negative	19(42.2%) 26(57.8%)	20.24±4.59 18.29±5.37	0.207*	28(50.9%) 27(49.1%)	20.33±6.03 17.59±5.14	0.076*
History of Diabetes Mellitus Positive Negative	16(35.6%) 29(64.4%)	21.13±4.99 17.99±4.89	**0.048***	22(40%) 33(60%)	18.37±5.16 19.39±6.12	0.520*
* t-test and **One way ANOVA were performed for statistical analysis. Bold numbers regarded as statistically significant						

Receiver Operating Characteristic (ROC) Curve Analysis

ROC curve analysis demonstrated that diaphragm thickness before weaning had an AUC of 0.742 (95% CI: 0.640–0.844), with an optimal cut-off value yielding sensitivity of 73.3% and specificity of 67.3%. Diaphragm thickness after weaning (post-SBT) had a superior AUC of 0.856 (95% CI: 0.776–0.935), with sensitivity of 82.2% and specificity of 76.4%. These results confirm that post-SBT diaphragm thickness is a stronger predictor of weaning success compared to pre-SBT measurements. Table (8)

Table 8. ROC curve analysis of diaphragm thickness parameters for weaning prediction

Parameter	**AUC**	**95% CI**	**Cut-off (mm)**	**Sensitivity (%)**	**Specificity (%)**
DT before SBT	0.742	0.640–0.844	≥18.0	73.3	67.3
DT after SBT	0.856	0.776–0.935	≥20.5	82.2	76.4

Comparison of Success vs. Failure Groups

Table 1 presents the comparison of key variables between weaning success and failure groups. Age was significantly higher in the failure group (54.2 ± 26.6 years vs. 43.3 ± 26.3 years, p=0.042). No significant differences were observed in gender distribution (p=0.839), BMI (p=0.355), ASA class (p=0.538), hospital (p=0.327), or cause of admission. Diaphragm thickness before and after SBT were both significantly greater in the success group (p<0.001 for both). Table (9)

Table 9. Comparison of selected variables between weaning success and failure groups

Variable	**Success (n=45) Mean±SD / N(%)**	**Failure (n=55) Mean±SD / N(%)**	**p-value**
Age (years)	43.26 ± 26.32	54.22 ± 26.63	0.042*
Gender: Male	27 (60%)	31 (56.4%)	0.839
BMI (kg/m²)	23.38 ± 4.87	24.30 ± 4.89	0.355
ASA Class III	26 (57.8%)	31 (56.4%)	0.538
Days on MV (1–7 days)	24 (53.3%)	23 (41.8%)	0.327
DT before weaning (mm)	21.8 ± 5.2	16.4 ± 6.1	<0.001
DT after weaning (mm)	23.1 ± 5.0	15.9 ± 5.8	<0.001

Correlation Analysis

Pearson correlation analysis between diaphragm thickness before weaning and continuous clinical variables in the success group revealed a statistically significant positive correlation with age (r=0.374, p=0.011). No significant correlations were found with BMI (r=0.125, p=0.413), number of ventilation days (r=0.036, p=0.817), MAP (r=0.293, p=0.051), or heart rate (r=-0.222, p=0.144) in the success group.

In the failure group, diaphragm thickness before weaning showed a significant negative correlation with number of ventilation days (r=-0.279, p=0.039), indicating that longer ventilation duration was associated with reduced diaphragm thickness—consistent with ventilator-induced diaphragm atrophy. No significant correlations were found with age (r=0.153, p=0.263), BMI (r=0.142, p=0.300), MAP (r=0.189, p=0.167), or heart rate (r=-0.082, p=0.551) in the failure group.

Spearman correlation analysis between DT before weaning and categorical clinical variables in the success group identified significant associations with history of respiratory disease (r=0.359, p=0.016) and history of diabetes mellitus (r=0.368, p=0.013). No significant correlations were found with gender, ASA class, cause of admission, CVD history, neurological disease history, or smoking habits in either group. Table (10)

Table 10. Pearson correlation between diaphragm thickness before weaning and continuous variables

Variable	Success r	Success p	Failure r	Failure p
Age	0.374	0.011*	0.153	0.263
BMI (kg/m²)	0.125	0.413	0.142	0.300
Days on ventilation	0.036	0.817	-0.279	0.039*
MAP (mmHg)	0.293	0.051	0.189	0.167
Heart rate (bpm)	-0.222	0.144	-0.082	0.551

** p < 0.05 statistically significant*

Discussion

This prospective observational study evaluated the utility of diaphragm thickness measured by ultrasound as a predictor of weaning success from mechanical ventilation in 100 ICU patients at three hospitals in Duhok, Iraq. The key findings demonstrate that diaphragm thickness, both before and after spontaneous breathing trial, was significantly greater in patients who successfully weaned from MV compared to those who failed. Post-SBT diaphragm thickness emerged as a superior predictor with an AUC of 0.856, consistent with the growing body of evidence supporting diaphragm ultrasonography in ICU weaning assessment.

The overall weaning failure rate of 55% in this cohort is higher than reported in many Western studies but is consistent with findings from resource-limited settings and mixed ICU populations. The WEAN-SAFE trial reported a weaning failure rate of 35.3% globally, though rates varied considerably across regions and patient populations (2). The higher failure rate in our cohort may reflect the complex comorbidity profile, with 58% having CVD history, 47% respiratory disease, and 44% neurological disease, as well as the inclusion of pediatric patients.

Age was identified as a significant predictor of weaning failure (p=0.042), with the failure group being approximately 11 years older on average. This is consistent with the known effects of aging on respiratory muscle mass, strength, and endurance. Older patients have reduced diaphragm muscle reserve and are more susceptible to ventilator-induced diaphragm dysfunction (VIDD) during prolonged MV (18). The correlation between age and diaphragm thickness in the success group (r=0.374, p=0.011) may reflect the confounding effect of greater body mass and muscle mass in older adults who successfully wean.

The significant negative correlation between number of ventilation days and DT in the failure group (r=-0.279, p=0.039) supports the concept of ventilator-induced diaphragm atrophy, whereby prolonged MV leads to progressive diaphragm thinning and dysfunction. This finding aligns with Goligher et al. (2015), who demonstrated that diaphragm thinning during MV was independently associated with prolonged ventilation and adverse outcomes (19). Early mobilization, spontaneous breathing modes, and diaphragm-protective ventilation strategies may mitigate this atrophy.

The ROC analysis results in this study—AUC 0.742 for pre-SBT and 0.856 for post-SBT DT—are consistent with the meta-analytic findings of Parada-Gereda et al. (2023), who reported AUC values ranging from 0.70 to 0.92 for diaphragm ultrasound parameters (20). The superior performance of post-SBT measurements reflects the dynamic nature of diaphragm function during the breathing trial, with successful weaners demonstrating increased diaphragm recruitment and thickening during spontaneous breathing efforts.

The significant correlation between history of respiratory disease and DT in the success group (r=0.359, p=0.016) may reflect compensatory diaphragm hypertrophy in patients with chronic respiratory conditions such as COPD, who develop increased respiratory muscle mass as an adaptive response to chronic increased work of breathing. Similarly, the correlation with diabetes mellitus history (r=0.368, p=0.013) may relate to the effects of metabolic syndrome on body composition and muscle mass.

Compared to traditional weaning predictors, diaphragm ultrasonography offers several advantages: it is non-invasive, radiation-free, reproducible, and provides real-time information about the primary muscle of respiration. The RSBI, while widely used, has limited sensitivity and specificity and does not directly assess diaphragm function. Integration of diaphragm ultrasound with clinical parameters and AI-based prediction models represents a promising avenue for improving weaning protocols (21, 22).

Limitations of this study include the single-operator ultrasound assessment without inter-rater reliability testing, the relatively small sample size, the inclusion of both adult and pediatric patients with different reference ranges for diaphragm thickness, and the lack of long-term follow-up data. Future studies should include larger multicenter cohorts, standardized protocols, and validation of AI-integrated prediction models in regional ICU settings.

Clinical Implications

The findings of this study have direct clinical implications for ICU management in resource-limited settings. Diaphragm ultrasonography is feasible with standard ICU ultrasound equipment, requires minimal training, and can be performed at the bedside without patient transport. The identified cut-off values (DT ≥18.0 mm pre-SBT and ≥20.5 mm post-SBT) provide clinicians with objective thresholds to guide extubation decisions, potentially reducing both premature extubation and unnecessary prolongation of mechanical ventilation.

The high weaning failure rate (55%) observed in this cohort highlights the need for improved weaning prediction tools in regional ICU settings. Premature extubation leading to reintubation is associated with significantly increased ICU mortality (OR 6.3–11.0), prolonged ICU stay, and increased healthcare costs. Conversely, delayed weaning contributes to ventilator-associated pneumonia, diaphragm atrophy, and patient discomfort. Objective, ultrasound-guided weaning protocols may therefore improve both patient outcomes and resource utilization in under-resourced healthcare systems.

The identification of age and ventilation duration as independent predictors of weaning outcome suggests that individualized weaning strategies should account for patient age and cumulative ventilation exposure. Elderly patients and those with prolonged MV should undergo more gradual weaning protocols with closer diaphragm monitoring to detect early signs of diaphragm atrophy and dysfunction before extubation attempts.

Comparison with Published Literature

The AUC of 0.856 for post-SBT diaphragm thickness in this study compares favorably with published meta-analytic data. Llamas-Álvarez et al. (2017) reported a pooled AUC of 0.88 for DTF in a meta-analysis of 10 studies (23). Zambon et al. (2017) found pooled sensitivity and specificity of 0.79 and 0.72 for diaphragm ultrasound parameters in weaning prediction across 10 studies (7). The comparable performance of absolute DT in this study suggests that DT may be a practical alternative to DTF in settings where dynamic measurements during the breathing cycle are technically challenging.

The mean pre-SBT diaphragm thickness of 20.45 ± 6.60 mm in this cohort is somewhat higher than values reported in Western ICU studies, which typically report DT of 15–25 mm. This may reflect differences in patient demographics, including BMI distribution and the inclusion of patients with chronic respiratory disease who may have diaphragm hypertrophy. The normal adult reference range for diaphragm thickness at end-expiration is 1.5–3.0 mm in the zone of apposition, though values vary with body habitus, age, and measurement technique.

Role of AI and Multimodal Prediction

The integration of AI and machine learning with diaphragm ultrasonography represents a frontier in ICU weaning research. Multimodal AI models that incorporate clinical data, laboratory values, and ultrasound images have demonstrated superior predictive performance compared to single-parameter models in preliminary studies (21, 22). The development of automated diaphragm measurement tools based on 2D speckle-tracking technology, as described by Vivier et al. (2019) and subsequent work (8), may further standardize measurements and reduce operator dependency.

Future research in this area should focus on the development and validation of multimodal AI prediction models specifically designed for regional ICU populations, incorporating locally validated reference values and clinical pathways. Federated learning approaches may enable collaborative model development across multiple centers without compromising patient data privacy, facilitating the creation of robust, generalizable weaning prediction tools.

Limitations and Future Directions

Several limitations of this study should be acknowledged. First, diaphragm thickness measurements were performed by a single operator, and inter-rater and intra-rater reliability were not formally assessed. Future studies should include inter-observer variability analysis to establish the reproducibility of measurements in clinical practice. Second, the study included both adult and pediatric patients, for whom normal reference ranges and cut-off values for DT differ substantially. Separate analyses for pediatric and adult subgroups would provide more clinically applicable cut-off values.

Third, the study was conducted at three hospitals in a single governorate, which may limit generalizability to other regional or national ICU settings. Multicenter studies across Iraq and the broader Middle East region are needed to validate these findings. Fourth, the study did not assess diaphragm thickening fraction (DTF) or diaphragm excursion, which are complementary parameters that may provide additional predictive information. Future studies should compare the predictive performance of absolute DT, DTF, and diaphragm excursion in the same patient cohort.

Finally, long-term outcomes including 30-day mortality, ICU readmission, and functional recovery were not assessed. The relationship between diaphragm thickness, weaning outcome, and long-term prognosis warrants investigation in prospective cohort studies with extended follow-up periods. The potential role of diaphragm rehabilitation, including inspiratory muscle training and early mobilization, in improving diaphragm thickness and weaning outcomes should also be explored in future randomized controlled trials.

Conclusion

This study demonstrates that diaphragm thickness measured by point-of-care ultrasonography is a reliable, non-invasive, and clinically useful predictor of weaning success from mechanical ventilation in ICU patients. Post-SBT diaphragm thickness provides superior predictive accuracy (AUC 0.856) compared to pre-SBT measurements (AUC 0.742), underscoring the value of dynamic assessment during the spontaneous breathing trial.

Age and duration of mechanical ventilation were identified as significant clinical predictors of weaning outcome, consistent with the mechanisms of ventilator-induced diaphragm dysfunction and age-related muscle atrophy. The integration of diaphragm ultrasonography into routine ICU weaning protocols is recommended and may improve the timing and safety of extubation decisions.

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