Utilizing Point of Care Ultrasound for Ventilation Liberation: A State-of-the-Art Narrative Review

Haneen Mallah, MD[1]; Ahmad AL-Tanjy[2]; Muhannad M. Mahmoud[2]; Lina Alkhdour, MD[2]; Leen Amro[2], MD; Abdallah H. Alshurafa, MD[2]; Mu'taz Alshaikh Hasan[3]; Bashar Alzghoul, MD[1]

[1] Division of Pulmonary, Critical Care and Sleep Medicine, Department of Internal Medicine, University of Florida, Gainesville, Florida, USA

[2] University of Jordan, Amman, Jordan

[3] Al Bashir Hospital, MOH, Amman, Jordan

Financial support/ funding source: None-
Conflict of interest: No conflict of interest.

Corresponding Author:
Bashar Alzghoul M.D, FCCP
Assistant Professor of Medicine, Associate Program Director , Pulmonary, Critical Care and Sleep Medicine, Department of Medicine, University of Florida, Gainesville, Florida,USA

KEYWORDS - Lung ultrasound, Point of care ultrasound, ventilator liberation, weaning, extubation, positive end-expiratory pressure, recruitment, atelectasis, diaphragmatic thickening fraction, diaphragmatic excursion

INTRODUCTION

Caring for critically ill patients encompasses many crucial aspects, with mechanical ventilation (MV) being a fundamental component of intensive care in many cases. Mechanical ventilation provides life-sustaining support to patients experiencing acute respiratory failure or other conditions requiring respiratory assistance (1). Despite its life-saving benefits, prolonged MV can introduce a spectrum of complications that can impact patient outcomes and recovery. Complications like ventilator-associated pneumonia (VAP), ventilator-induced lung injury, diaphragmatic dysfunction, and extra diaphragmatic respiratory muscle weakness may arise, necessitating a careful and proactive approach to liberating patients from MV. Regardless of the underlying cause necessitating MV, the early liberation of patients from MV is paramount in improving outcomes and mitigating a wide range of potential complications (2).

Several studies to evaluate ultrasound (US) parameters have been conducted including the ABCDE approach in mechanical ventilator weaning failure: Aeration of the lung and the presence of pleural effusion, Below the diaphragm as ascites, Cardiac function, Diaphragm, and Extra diaphragmatic respiratory muscles (3).

Diaphragmatic dysfunction is a critical factor to consider during the weaning process. The diaphragm is the most important muscle that gets weakened and fatigued by prolonged MV, making it challenging for patients to initiate and sustain spontaneous breathing once liberated from MV (4). Early and appropriate weaning protocols, diaphragmatic function assessment, Positive end-expiratory pressure (PEEP) titration, lung aeration, and cardiac function assessment can all aid in identifying patients at risk for liberation failure and implementing interventions to optimize their liberation potential. (2) Point of Care Ultrasound (POCUS) emerges as an invaluable tool in this regard, providing real-time and bedside imaging capabilities to assess these parameters, thus complementing existing weaning protocols, and facilitating informed clinical decision-making during the ventilator liberation process (5).

This review explores POCUS's current practice and implementation in critical care settings. By examining the role of POCUS in assessing diaphragmatic function, lung aeration, cardiac function, and other relevant parameters, we aim to highlight its potential to complement existing weaning protocols and facilitate informed clinical decision-making during the ventilator liberation process. We comprehensively analyzed existing literature and relevant studies to provide valuable perspectives on how POCUS enhances point-of-care decision-making and ultimately contributes to better patient care in the context of ventilator liberation.

LUNG ULTRASOUND IN GUIDING WEANING AND SUCCESSFUL EXTUBATION

Successful weaning can be defined as the maintenance of extubation for over 48 hours after the removal of the endotracheal tube. Lung ultrasound has emerged as an important modality in guiding the weaning process and ensuring successful extubation among critically ill patients (5).

A. LUNG PATHOLOGIES BY LUNG ULTRASOUND (LUS)

In contrast to conventional methods, LUS provides real-time, noninvasive visualization of lung parenchyma and ventilation patterns. By objectively evaluating lung aeration and identifying lung congestion or atelectasis, clinicians can make evidence-based decisions during the weaning phase, customizing ventilator settings to suit individual patient requirements(5). This personalized approach may mitigate the risks associated with prolonged MV and expedite the overall weaning process. Additionally, lung ultrasound facilitates dynamic monitoring of lung recruitment, enabling timely recognition of potential weaning failure and facilitating timely interventions to avert extubation difficulties. The successful integration of lung ultrasound into weaning protocols holds substantial promise, augmenting patient care, elevating extubation success rates, and improving clinical outcomes in critically ill patients (5).

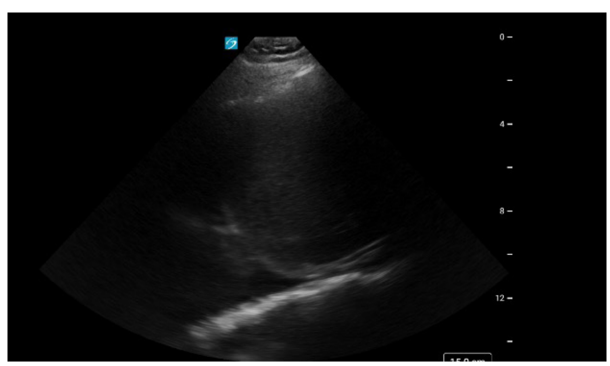
LUS has shown to be superior to chest X-ray and non-inferior to chest CT in diagnosing various lung and pleural pathologies including pleural effusion or hemothorax, pneumothorax, atelectasis, reduced lung aeration (as in pulmonary edema, pneumonia, ARDS, pulmonary fibrosis, or lung contusion). The BLUE-plus protocol has been suggested as a systematic approach to diagnosing several lung and pleural pathologies (6).

Based on a prospective observational study that was done at an ICU of a tertiary hospital involving 102 mechanically ventilated patients for longer than 24 hours aged above 18 years, LUS was a significant predictor of a successful spontaneous breathing trial (SBT) at the beginning and 30 minutes of SBT (5). In another study, researchers accurately evaluated lung reaeration using bedside LUS in 30 critically ill VAP patients. (7).

B. ASSESSMENT OF THE PLEURA

Assessing pleural effusion helps evaluate the need for pleural fluid drainage. It could also predict the degree of atelectasis (6). Although no consistent data is available about the significance of pleural fluid removal on the likelihood of successful extubation, many factors affect the likelihood of a beneficial pleural fluid drainage. One prospective study concluded there was no significant correlation between the presence or absence of pleural effusion at the time of extubation and weaning outcomes(8). Conversely, a prospective multicenter observational study concluded that the presence of a moderate-to-large pleural effusion (Figure 1) (defined as a maximal intrapleural distance o of ≥ 15 mm) at weaning initiation was associated with more failures of the first SBT, more weaning failures, less ventilator-free days at day 28 and higher mortality at day 28 (9).

Figure 1. Pleural effusion



C.LUNG ULTRASOUND SCORE PREDICTION IN THE ASSESSMENT OF WEANING AND LIBERATION:

Bouhemad et al. were the first to introduce LUS as an attempt to generate quantifiable measures of changes in lung aeration in patients with VAP (7). The score was later studied further and used to predict ventilator weaning and liberation outcomes. Several studies have demonstrated LUS as a reliable index of quantifying respiratory function and its potential to predict weaning failure independently. (10-12)

The LUS score ranges from 0 – 36, assessing all 12 lung regions, which is the total value after adding in each lung region's score running from 0 – 3; a higher score indicates a more severe loss of aeration. Given the need for a dynamic score that measures changes in lung aeration over time and assessment of successful treatment, the LUS dynamic reaeration score was established. It can be calculated by adding 1, 3, or 5 points respectively, in case of slight, moderate, or substantial improvement in lung aeration and subtracting the same values if loss of aeration is observed as illustrated in the table below (13).

Figure 2. Lung ultrasound score 3

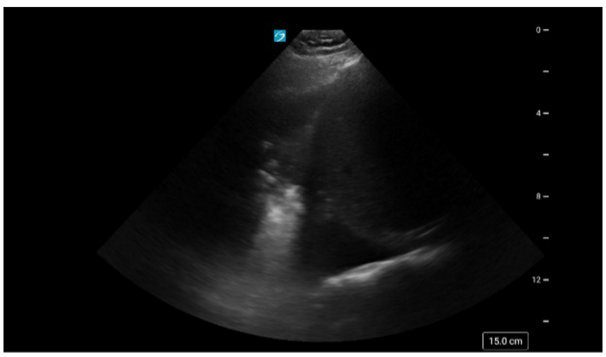


Figure 3. Lung ultrasound score 2

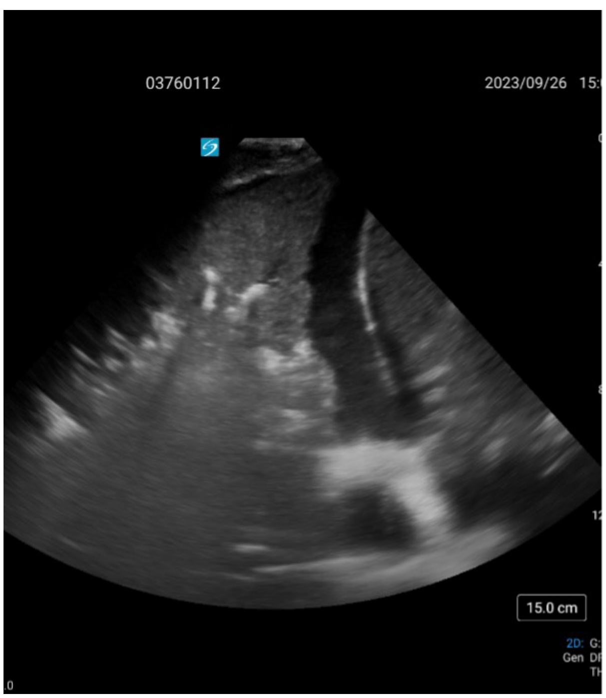


Figure 4. Lung ultrasound score 1

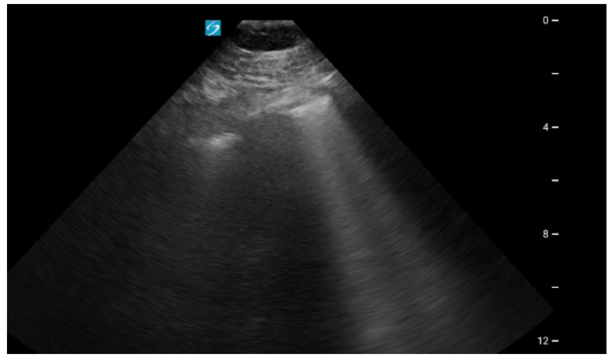


Figure 5. Lung ultrasound score zero

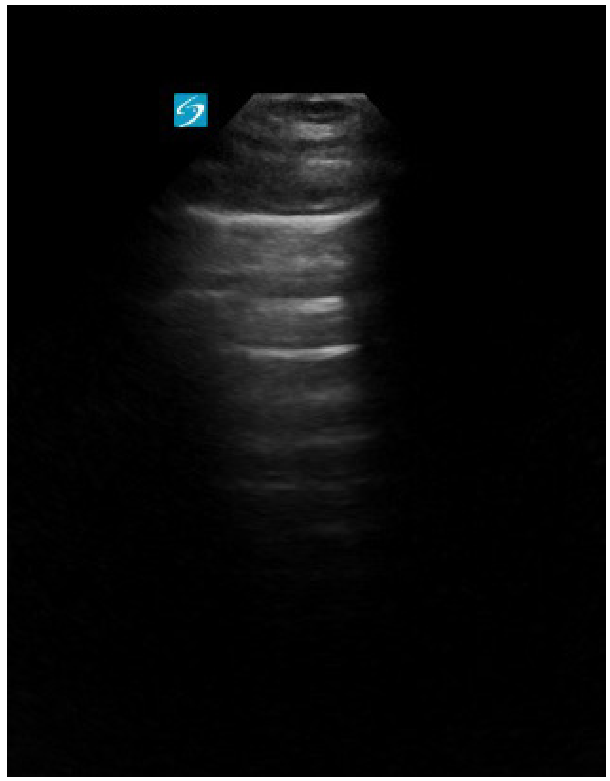


Figure 6. Diaphragmatic excursion

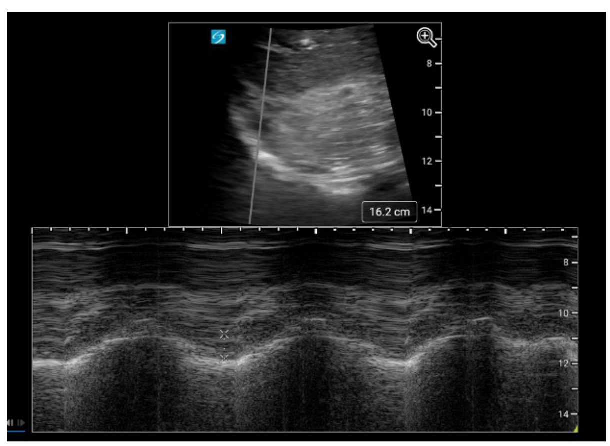


Figure 7. Diaphragmatic thickening fraction

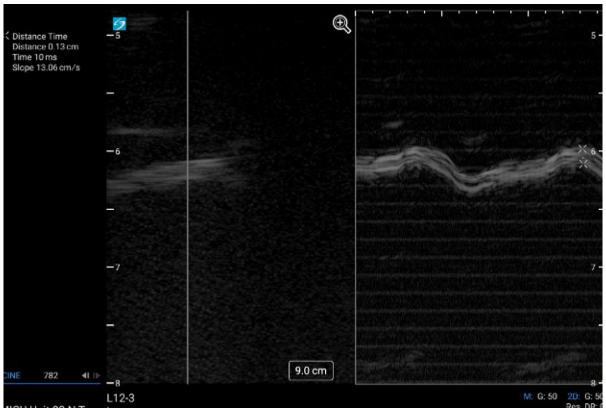


Table 1. Degree of lung aeration on LUS

Degree of Lung Aeration on LUS	Points
Complete aeration loss (Consolidation) (C)	3 (Figure 2)
Severe aeration loss (B2)	2 (Figure 3)
Moderate aeration loss (B1)	1 (Figure 4)
Normal aeration (N)	0 (Figure 5)

Table 2. Lung Ultrasound dynamic reaeration score as suggested by Bouhemad et al. (7)

Quantification of reaeration			Quantification of loss of aeration		
1 point	3 points	5 points	-5 points	-3 points	-1 point
Bl→N	B2→N	C→N	N→C	N→B2	N→Bl
B2→Bl	C→Bl			Bl→C	B1→B2
C→B2					B2→C

D.PEEP TITRATION AND ALVEOLAR RECRUITMENT BY BEDSIDE LUNG ULTRASOUND

Atelectasis is a very common complication in mechanically ill ventilated patients. Bedside lung ultrasound (LUS) has proven to be an essential tool in evaluating lung recruitment and optimizing PEEP levels in severe acute respiratory distress syndrome (ARDS) patients as it detects increased interstitial and alveolar fluids using B lines. B lines indicate lung pathology and correlate well with ultrasound interstitial syndrome. By assessing lung recruitment and evaluating the response to interventions, LUS provides real-time information to guide PEEP titration and alveolar recruitment strategies (7).

There is a four-step algorithm using US to guide clinical recruitment maneuvers (RMs): two for assessment before the maneuver and two for confirmation of results post-recruitment. The first step is determining if the patient requires an RM, as pulmonary impairment may have diverse causes beyond lung collapse. To accomplish that, an operator conducts a comprehensive LUS scan using the standard three-region examination in each hemithorax to diagnose a patient's lung condition. Ultrasound effectively detects lung collapse, primarily in dependent areas, indicated by the presence of coalescent B lines and consolidations with a high aeration score, signaling the potential need for an RM (14).

The second step involves assessing the patient's clinical condition to tolerate RMs, considering factors like sedation, ventilator adaptation, and hemodynamic stability. Ultrasound aids in diagnosing the patient's hemodynamic status using somewhat simple measurements like the inferior vena cava collapsibility index measured from the subcostal view and the papillary muscle kiss sign calculated using parasternal short axis views as well as left ventricular contractility. More advanced measurements can also be obtained such as diastolic function. If atelectasis is confirmed and an appropriate hemodynamic status is ensured, RMs can be initiated which is the third step in the algorithm (15). It is noteworthy to keep in mind that the decision to utilize RMs needs to be personalized on a case-by-case basis.

Ultrasound allows identification of the lung's opening and closing pressures during the PEEP titration trial, facilitating personalized implementation of an open lung strategy (15). During the third step, standard LUS is performed, and the probe is placed in the most dependent zone of the atelectatic lung during the recruitment maneuver. Sequential lung reaeration patterns are observed, and the identified pressures are used to set the PEEP level for ongoing ventilation. Step 4 confirms the effect of the recruitment maneuver on lung aeration and hemodynamics, guiding further hemodynamics treatment adjustment to maintain improved cardiopulmonary condition.

THE UTILITY OF DIAPHRAGMATIC US IN WEANING AND LIBERATION FROM THE MV

Mechanical ventilation leads to diaphragmatic atrophy, exhibiting an inverse correlation between diaphragm thickness and MV duration. Subsequently, the development of diaphragmatic atrophy is linked to prolonged MV, hence increased intensive care unit (ICU) length of stay, and a higher rate of complications (16). Notably, a subset of mechanically ventilated patients has shown increased thickness, which has also been linked to diaphragmatic dysfunction (17). Therefore, as MV support is gradually withdrawn, assessing diaphragmatic function becomes crucial in determining a patient's readiness for extubation. In this context, diaphragmatic US, encompassing measurements of excursion and thickening fraction, presents a valuable objective and noninvasive approach. The diaphragmatic excursion (DE) refers to the movement of the diaphragm during respiration (Figure 6), This parameter is measured using US to assess the distance the diaphragm moves during inspiration and expiration. The diaphragmatic thickening fraction (DTF) is another ultrasound parameter used to evaluate diaphragmatic function. It measures the change in diaphragm thickness during respiration, indicating its contractility (Figure 7). This was illustrated in the metanalysis that included 19 studies with over 1200 patients with the conclusion that measuring DE and DTF had satisfactory prediction of successful extubation (4). Measurement of DE and DTF has been shown to be feasible, reproducible, and a relatively easy skill to perform. Image acquisition in multiple views has been detailed with images and a video by Kilaru et al. (18)

A recent systematic review and meta-analysis has shown that DE and DTF have satisfactory diagnostic accuracy in predicting successful weaning from MV, echoing the findings of previously published studies (4, 19-21). The meta-analysis, which included 1204 patients from 19 studies, revealed a sensitivity of 80% and specificity of 80% for DE, while DTF exhibited a sensitivity of 85% and specificity of 75% (4). A noteworthy observation was the presence of significant heterogeneity among the included studies, which was attributed primarily to inconsistencies in the patient's position during the test and in the cut-off values used for each measurement. In particular, excluding studies with atypical thresholds led to improved sensitivity and specificity values for DTF and sensitivity for DE (4). There is an apparent demand for more standardized studies to address this concern.

In certain studies, DTF and DE were assessed for their predictability either individually, in comparison with standard parameters, or in combination with them. The commonly used weaning parameter, rapid shallow breathing index (RSBI), calculated by dividing respiratory rate (RR) by tidal volume (TV), demonstrated lower predictability than DE or DTF. In addition, combining RSBI with DE and DTF (RSBI-DE and RSBI-DTF) yielded better predictability than using RSBI alone, which was consistent with the findings of another study (22, 23). Song et al. found similar results, presenting two weaning parameters obtained by dividing RR by either DE or DTF, both of which showed greater accuracy in predicting weaning outcomes compared to the conventional RSBI (RR/VT) (24). The RR/DTF ratio application exhibited greater reliability in predicting extubation success when compared to using either RSBI or DTF alone (25). In a separate study, the earlier observations of enhanced predictability achieved by combining traditional indices with diaphragmatic parameters could not be reproduced. Specifically, the RSBI/DE ratio did not demonstrate success in predicting weaning outcomes (26).

Some studies contest the reliability of DTF and DE in predicting weaning failure, with certain studies reporting conflicting outcomes on their relative superiority. A multicenter study found no correlation between DTF values and weaning outcomes in critically ill COVID-19 patients (27). Another study found DTF to be a dependable indicator of diaphragm contractile activity, whereas DE did not show similar reliability (28). Conversely, Saravanan et al. reported higher sensitivity and specificity values for DE than DTF (22).

Therefore, diaphragmatic ultrasound should be used in conjunction with other clinical criteria, such as RSBI, to enhance its effectiveness and ensure safe and successful liberation from mechanical ventilation.

RESPIRATORY MUSCLES (EXTRA DIAPHRAGMATIC RESPIRATORY MUSCLES) ULTRASOUND IN THE WEANING PROCESS

The diaphragm is not the only respiratory muscle involved in ventilation, especially when it is damaged or weakened. When the load inflicted on the diaphragm increases, the accessory inspiratory muscles (parasternal, external intercostal, scalene, and sternocleidomastoid muscles) are recruited. As the load increases, the expiratory muscles contract to aid in expiration (29). These include the transversus abdominis muscle and the internal and external oblique muscles.

It has been shown that extubation outcomes cannot be predicted using isolated ultrasound observations of the diaphragm (30). Monitoring respiratory muscles' function is, therefore, very useful during the weaning process (31). Several studies have proposed systematic ultrasound-based evaluation of the respiratory muscles including the diaphragm as well as the extra diaphragmatic muscles (3, 32).

In a sub-study that involved 54 patients, it was found that those who failed the SBT had higher parasternal intercostal muscle thickening and a lower parasternal intercostal muscle to DTF ratio measurement (33). It also confirmed that parasternal intercostal muscle thickening is responsive to respiratory load. Additionally, the combination of parasternal intercostal muscle thickening and DTF yielded similar information to parasternal intercostal muscle thickening alone.

ASSESSMENT OF CARDIAC FUNCTION AND ITS ROLE IN VENTILATOR LIBERATION

Cardiovascular problems are one of the most common causes of ventilation weaning failure. The assessment of cardiac function plays a crucial part in managing patients on MV, especially during ventilator liberation or weaning. This could be accomplished by using echocardiography, as it allows a noninvasive cardiac function assessment (34).

Based on the assessment findings, clinicians can adjust ventilator settings, manage fluid balance, and address cardiac issues before attempting the weaning process (34). Micael R. Pinsky has compared the cardiovascular response to weaning from MV to exercise, in which occult cardiovascular insufficiency may be the primary cause of weaning failures in many patients. (35). In addition, MV weaning in patients with coronary artery diseases may increase myocardial stress, which may lead to cardiac ischemia (36).

To enhance the management of weaning and extubation, strategies for identifying patients who are at high risk for extubation failure are crucial. In a prospective descriptive study published by Vincent Caille and colleagues, transthoracic echocardiography (TTE) was evaluated for its ability to determine how SBT affects central hemodynamics and possibly find indicators that could aid in predicting weaning failure from cardiac origin. (34) TTE was performed on patients just before and at the end of a 30-minute SBT. Several parameters were measured, including E wave and A wave (maximal flow velocity during early diastole and atrial systole, respectively), DTE (deceleration time of E wave), maximal velocity of lateral E' wave (tissue Doppler at the lateral mitral annulus) and left ventricular (LV) stroke volume. A decreased LV ejection fraction, a shortened mitral E wave deceleration time, and an elevated E/e' ratio were among the TTE findings that could predict weaning failure (34).

In another study, E/e' measured 10 minutes after starting the SBT showed that the cut-off value of 14.5 predicted weaning failure with a specificity of 95.8% and sensitivity of 75% (37).

Furthermore, a systematic review and a meta-analysis published in 2016 (38) aimed to determine whether diastolic dysfunction in critically ill patients receiving MV is a reliable indicator of weaning failure. The results showed that a higher E/e' ratio is significantly associated with weaning failure. Additional conclusions linking diastolic dysfunction and weaning insufficiency were limited due to the high heterogeneity of criteria for diastolic dysfunction and different clinical scenarios.

LIMITATIONS FOR THE USE OF POINT-OF-CARE ULTRASOUND IN WEANING AND LIBERATION

Despite its advantages, POCUS application is operator-dependent and requires proper training and practice to obtain reliable outcomes. It also needs adequate equipment, time, and resources, which might not be readily available in all clinical settings (39).

Additionally, patient-related factors, such as obesity, thoracic dressings, subcutaneous emphysema, or pleural calcifications, may interfere with the accuracy of POCUS during the weaning process (40). Compared to other imaging modalities like computed tomography (CT), US provides real-time imaging but with limited visualization. Therefore, an inadequate view of the respiratory system alters the findings detected during the weaning process (41).

Moreover, lung mechanics, such as compliance and resistance, which are important in determining the readiness for weaning, cannot be measured by ultrasound (42). For example, Lung US even though as explained above is able to identify atelectasis and help in RMs, is unable to detect hyperinflation in nondependent lung areas (43). Finally, the lack of standardized protocols and criteria for weaning based on POCUS findings leads to inconsistent practices among different institutions. Therefore, establishing uniform guidelines is necessary to enhance the reliability of POCUS-based weaning decisions.

It is imperative to also recognize that successful liberation from mechanical ventilation is more complicated and may be impacted by various additional factors, including but not limited to nutritional status, and psychological well-being.

CONCLUSION

Lung ultrasound is an effective, safe, and relatively easy to use method to guide the ventilation liberation process. It can aid in the evaluation of lung and pleural pathologies, cardiovascular function, diaphragmatic and extra diaphragmatic respiratory muscle assessment as well as the recruitment processes. Multiple limitations exist mainly the lack of standardized protocols and the need for training and resources to be able to utilize this technique on a wide scale. However, with the availability of US and its utilization, the importance of a standardized protocol is emerging.

Currently, diaphragm ultrasound is primarily used for the differential diagnosis of patients facing challenging weaning from MV by enabling the bedside detection of diaphragmatic weakness. Nonetheless, its capacity to predict the success of spontaneous breathing trials and extubation necessitates further investigation and cannot be universally endorsed at this point. Hence, there is a need for high-quality studies with rigorous methodologies to assess the role of diaphragmatic ultrasound as a predictor of weaning success in specific subgroups of intensive care unit patients which will help in establishing a standardized protocol for LUS-guided MV weaning.

AUTHORS' CONTRIBUTION

Bashar Alzghoul MD: Study conception and design, supervisor, critical review of the manuscript. Haneen Mallah, MD: Study outline, conclusion, abstract, construction of the manuscript, and critical review of the initial draft and the final manuscript .Ahmad AL-Tanjy: manuscript writing and review.Mu'taz Alshaikh Hasan: manuscript writing and review.Muhannad M. Mahmoud: manuscript writing and review.Lina Alkhdour: manuscript writing and review.Leen Amro: manuscript writing and review. Abdallah H. Alshurafa: manuscript writing and review.

DISCLAIMER

This article was made possible by the support of the American people through the United States Agency for International Development (USAID). The contents are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

REFERENCES

1 Schmidt GA, Girard TD, Kress JP, Morris PE, Ouellette DR, Alhazzani W, et al. Official Executive Summary of an American Thoracic Society/American College of Chest Physicians Clinical Practice Guideline: Liberation from Mechanical Ventilation in Critically Ill Adults. Am J Respir Crit Care Med. 2017;195(1):115-9.

2 Vahedian-Azimi A, Bashar FR, Jafarabadi MA, Stahl J, Miller AC, Collaborative M. Protocolized ventilator weaning verses usual care: A randomized controlled trial. Int J Crit Illn Inj Sci. 2020;10(4):206-12.

3 Tuinman PR, Jonkman AH, Dres M, Shi ZH, Goligher EC, Goffi A, et al. Respiratory muscle ultrasonography: methodology, basic and advanced principles and clinical applications in ICU and ED patients-a narrative review. Intensive Care Med. 2020;46(4):594-605.

4 Parada-Gereda HM TA, Rico-Mendoza A, Molano-Franco D, Nieto VH, Arias-Ortiz WA, et al. Effectiveness of diaphragmatic ultrasound as a predictor of successful weaning from mechanical ventilation: a systematic review and meta-analysis. Crit Care. 2023;27(1):174.

5 Rajbanshi LK, Bajracharya A, Devkota D. Prediction of Successful Spontaneous Breathing Trial and Extubation of Trachea by Lung Ultrasound in Mechanically Ventilated Patients in Intensive Care Unit. Indian J Crit Care Med. 2023;27(7):482-7.

6 Saraogi A. Lung ultrasound: Present and future. Lung India. 2015;32(3):250-7.

7 Bouhemad B, Liu ZH, Arbelot C, Zhang M, Ferarri F, Le-Guen M, et al. Ultrasound assessment of antibiotic-induced pulmonary reaeration in ventilator-associated pneumonia. Crit Care Med. 2010;38(1):84-92.

8 Dres M, Roux D, Pham T, Beurton A, Ricard JD, Fartoukh M, et al. Prevalence and Impact on Weaning of Pleural Effusion at the Time of Liberation from Mechanical Ventilation: A Multicenter Prospective Observational Study. Anesthesiology. 2017;126(6):1107-15.

9 Razazi K, Boissier F, Neuville M, Jochmans S, Tchir M, May F, et al. Pleural effusion during weaning from mechanical ventilation: a prospective observational multicenter study. Ann Intensive Care. 2018;8(1):103.

10 Chiumello D, Mongodi S, Algieri I, Vergani GL, Orlando A, Via G, et al. Assessment of Lung Aeration and Recruitment by CT Scan and Ultrasound in Acute Respiratory Distress Syndrome Patients. Crit Care Med. 2018;46(11):1761-8.

11 Soummer A, Perbet S, Brisson H, Arbelot C, Constantin JM, Lu Q, et al. Ultrasound assessment of lung aeration loss during a successful weaning trial predicts postextubation distress*. Crit Care Med. 2012;40(7):2064-72.

Osman AM HR. Diaphragmatic and lung ultrasound application as new predictive indices for the weaning process in ICU patients. Egypt J Radiol Nucl Med. 2017(48):61–6.

12 Mayo P, Volpicelli G, Lerolle N, Schreiber A, Doelken P, Vieillard-Baron A. Ultrasonography evaluation during the weaning process: the heart, the diaphragm, the pleura and the lung. Intensive Care Med. 2016;42(7):1107-17.

13 Tusman G, Acosta CM, Costantini M. Ultrasonography for the assessment of lung recruitment maneuvers. Crit Ultrasound J. 2016;8(1):8.

14 Tusman G, Bohm SH. Prevention and reversal of lung collapse during the intra-operative period. Best Pract Res Clin Anaesthesiol. 2010;24(2):183-97.

15 Glau CL, Conlon TW, Himebauch AS, Yehya N, Weiss SL, Berg RA, et al. Progressive Diaphragm Atrophy in Pediatric Acute Respiratory Failure. Pediatr Crit Care Med. 2018;19(5):406-11.

16 Goligher EC, Fan E, Herridge MS, Murray A, Vorona S, Brace D, et al. Evolution of Diaphragm Thickness during Mechanical Ventilation. Impact of Inspiratory Effort. Am J Respir Crit Care Med. 2015;192(9):1080-8.

17 Kilaru D, Panebianco N, Baston C. Diaphragm Ultrasound in Weaning From Mechanical Ventilation. Chest. 2021;159(3):1166-72.

18 García-Sánchez A BE, Pintado B, et al. Disfunción diafragmática evaluada por ecografía como predictora del fracaso de la extubación: Revisión sistemática y metanálisis. Open Respir Arch. 2020;2(4):267-77.

19 Le Neindre A, Philippart F, Luperto M, Wormser J, Morel-Sapene J, Aho SL, et al. Diagnostic accuracy of diaphragm ultrasound to predict weaning outcome: A systematic review and meta-analysis. Int J Nurs Stud. 2021;117:103890.

20 Llamas-Alvarez AM, Tenza-Lozano EM, Latour-Perez J. Diaphragm and Lung Ultrasound to Predict Weaning Outcome: Systematic Review and Meta-Analysis. Chest. 2017;152(6):1140-50.

21 Saravanan R, Nivedita K, Karthik K, Venkatraman R. Role of diaphragm ultrasound in weaning mechanically ventilated patients: A prospective observational study. Indian J Anaesth. 2022;66(8):591-8.

22 Pirompanich P, Romsaiyut S. Use of diaphragm thickening fraction combined with rapid shallow breathing index for predicting success of weaning from mechanical ventilator in medical patients. J Intensive Care. 2018;6:6.

23 Song J, Qian Z, Zhang H, Wang M, Yu Y, Ye C, et al. Diaphragmatic ultrasonography-based rapid shallow breathing index for predicting weaning outcome during a pressure support ventilation spontaneous breathing trial. BMC Pulm Med. 2022;22(1):337.

24 Eksombatchai D, Sukkratok C, Sutherasan Y, Junhasavasdikul D, Theerawit P. The ratio of respiratory rate to diaphragm thickening fraction for predicting extubation success. BMC Pulm Med. 2023;23(1):109.

25 Fossat G, Daillet B, Desmalles E, Boulain T. Does diaphragm ultrasound improve the rapid shallow breathing index accuracy for predicting the success of weaning from mechanical ventilation? Aust Crit Care. 2022;35(3):233-40.

26 Vetrugno L, Orso D, Corradi F, Zani G, Spadaro S, Meroi F, et al. Diaphragm ultrasound evaluation during weaning from mechanical ventilation in COVID-19 patients: a pragmatic, cross-section, multicenter study. Respir Res. 2022;23(1):210.

27 Umbrello M, Formenti P, Longhi D, Galimberti A, Piva I, Pezzi A, et al. Diaphragm ultrasound as indicator of respiratory effort in critically ill patients undergoing assisted mechanical ventilation: a pilot clinical study. Crit Care. 2015;19(1):161.

28 Shi ZH, Jonkman A, de Vries H, Jansen D, Ottenheijm C, Girbes A, et al. Expiratory muscle dysfunction in critically ill patients: towards improved understanding. Intensive Care Med. 2019;45(8):1061-71.

29 Vivier E, Muller M, Putegnat JB, Steyer J, Barrau S, Boissier F, et al. Inability of Diaphragm Ultrasound to Predict Extubation Failure: A Multicenter Study. Chest. 2019;155(6):1131-9.

30 Doorduin J, van Hees HW, van der Hoeven JG, Heunks LM. Monitoring of the respiratory muscles in the critically ill. Am J Respir Crit Care Med. 2013;187(1):20-7.

31 Dres M, Demoule A. Monitoring diaphragm function in the ICU. Curr Opin Crit Care. 2020;26(1):18-25.

32 Dres M, Dube BP, Goligher E, Vorona S, Demiri S, Morawiec E, et al. Usefulness of Parasternal Intercostal Muscle Ultrasound during Weaning from Mechanical Ventilation. Anesthesiology. 2020;132(5):1114-25.

33 Caille V, Amiel JB, Charron C, Belliard G, Vieillard-Baron A, Vignon P. Echocardiography: a help in the weaning process. Crit Care. 2010;14(3):R120.

34 Pinsky MR. Breathing as exercise: the cardiovascular response to weaning from mechanical ventilation. Intensive Care Med. 2000;26(9):1164-6.

35 Lemaire F, Teboul JL, Cinotti L, Giotto G, Abrouk F, Steg G, et al. Acute left ventricular dysfunction during unsuccessful weaning from mechanical ventilation. Anesthesiology. 1988;69(2):171-9.

36 Moschietto S, Doyen D, Grech L, Dellamonica J, Hyvernat H, Bernardin G. Transthoracic Echocardiography with Doppler Tissue Imaging predicts weaning failure from mechanical ventilation: evolution of the left ventricle relaxation rate during a spontaneous breathing trial is the key factor in weaning outcome. Crit Care. 2012;16(3):R81.

37 de Meirelles Almeida CA, Nedel WL, Morais VD, Boniatti MM, de Almeida-Filho OC. Diastolic dysfunction as a predictor of weaning failure: A systematic review and meta-analysis. J Crit Care. 2016;34:135-41.

38 Islam M, Levitus M, Eisen L, Shiloh AL, Fein D. Lung Ultrasound for the Diagnosis and Management of Acute Respiratory Failure. Lung. 2020;198(1):1-11.

39 Lee J. Lung ultrasound in critically ill patients. Korean Journal of Critical Care Medicine. 2016; 31(1):4.

40 Colombi D, Petrini M, Maffi G, Villani GD, Bodini FC, Morelli N, et al. Comparison of admission chest computed tomography and lung ultrasound performance for diagnosis of COVID-19 pneumonia in populations with different disease prevalence. Eur J Radiol. 2020;133:109344.

41 Okabe Y, Asaga T, Bekku S, Suzuki H, Kanda K, Yoda T, et al. Lung-thorax compliance measured during a spontaneous breathing trial is a good index of extubation failure in the surgical intensive care unit: a retrospective cohort study. J Intensive Care. 2018;6:44.

42 Rouby JJ, Lu Q, Goldstein I. Selecting the right level of positive end-expiratory pressure in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med. 2002;165(8):1182-6.