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REVIEW

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Diaphragmatic ultrasound: A clinical perspective on diaphragm function in the ICU

Nonpisit Tangkitkiatkul[1], Taweevat Assavapokee[2]

[1]Division of Critical Care Medicine, Department of Medicine, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand, 10400;
[2]Division of Geriatric Medicine, Department of Medicine, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand, 10400

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Corresponding author:
Taweevat Assavapokee
Division of Geriatric Medicine, Department of Medicine, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand, 10400
Tel: (+66) 2-201-1301
Fex: (+66) 2-201-1715
E-mail: drgames061@gmail.com

ABSTRACT:

Mechanical ventilation (MV) is a critical component in managing respiratory failure in critically ill patients. While lifesaving, prolonged MV can induce ventilator-induced diaphragmatic dysfunction (VIDD), characterized by decreased diaphragmatic function, atrophy, and loss of contractility. These complications exacerbate weaning challenges, extend ICU stays, and escalate mortality rates. Diaphragmatic ultrasound (DUS) offers a non-invasive, real-time evaluation tool that has revolutionized the monitoring and management of diaphragm function. This review delves into the pathophysiology of VIDD, evaluates its clinical impacts, and the integral role of DUS in implementing protective ventilation strategies to optimize outcomes for both lung and diaphragm health.

Keywords: Diaphragmatic ultrasound; Ventilator-induced diaphragmatic dysfunction; Weaning; Diaphragmatic excursion; Diaphragm monitoring; Diaphragmatic protective ventilation

INTRODUCTION

Mechanical ventilation is integral in the management of respiratory failure, providing life-saving support in a range of conditions such as acute respiratory distress syndrome (ARDS), pneumonia, and exacerbations of chronic obstructive pulmonary disease (COPD). The diaphragm, a thin, dome-like muscle, is anatomically divided into costal and crural segments, with a central tendon that does not contract. When the muscle fibers are activated, they cause the diaphragm to shorten and thicken, particularly in the zone of apposition, leading to a downward movement of the muscle dome. This muscle has a substantial capacity for generating contraction and pressure, which are essential for its primary muscle of respiration, and is particularly vulnerable to the effects of MV. Prolonged ventilatory support leads to VIDD, a condition resulting from muscle disuse, inflammation, and oxidative stress [1, 2]. This phenomenon is compounded by patient-ventilator asynchrony and inappropriate ventilatory settings, which can lead to further injury.

Diaphragm weakness tends to develop early during the ICU stay of critically ill patients. The pathophysiological underpinnings of this condition, including muscle disuse and inflammation [3].

MECHANISMS OF DIAPHRAGMATIC DYSFUNCTION IN MECHANICAL VENTILATION [14, 15]

1. Over-Assistive Myotrauma: Excessive ventilatory support leads to disuse atrophy, characterized by a reduction in diaphragmatic thickness and a shift from fatigue-resistant Type I fibers to less efficient Type II fibers.
2. Under-Assistive Myotrauma: Insufficient support increases the workload on the diaphragm, causing muscle strain and injury, exacerbated by oxidative stress and inflammatory cytokine release.
3. Asynchronous Myotrauma: Patient-Ventilator Asynchrony (PVA) results in uncoordinated diaphragmatic contractions, increasing energy expenditure and contributing to muscle microtrauma.
4. Expiratory Myotrauma: High PEEP settings alter the diaphragm's length-tension relationship, leading to suboptimal muscle function and longitudinal atrophy.

The presence of significant diaphragmatic weakness can complicate the process of weaning patients from mechanical ventilation and adversely affect their clinical outcomes [4].

In recent years, attention has shifted toward diaphragm-protective strategies, emphasizing the need to maintain adequate diaphragmatic activity during MV. DUS has emerged as a valuable tool in this context, enabling clinicians to monitor diaphragmatic performance, detect dysfunction early, and tailor ventilation strategies to prevent further injury. Thus, accurate assessment and continual evaluation of diaphragmatic function are crucial in the ICU setting. Utilizing ultrasound technology allows for the non-invasive visualization and monitoring of diaphragmatic function and activity, providing valuable insights at the bedside [10].

ROLE OF DIAPHRAGMATIC ULTRASOUND IN CRITICAL CARE

- Excursion and thickness fraction measurement: Assessing diaphragmatic excursion and thickness fraction during tidal breathing and adequate efforts to gauge diaphragm functionality.
- Monitoring atrophy recovery: Serial measurements of diaphragmatic thickness help monitor muscle wasting and recovery.
- Guiding protective ventilation: DUS findings help optimize ventilatory support to balance lung and diaphragm protection, crucial in diaphragm-protective ventilation strategies.

TECHNICAL CONSIDERATIONS FOR BILATERAL DIAPHRAGMATIC ULTRASOUND IN CLINICAL PRACTICE

Performing a diaphragmatic ultrasound bilaterally is technically feasible; however, a right-sided approach often suffices and is generally easier to execute, except in cases where unilateral diaphragmatic dysfunction is suspected.

KEY MESSAGES:

- Ventilator-Induced Diaphragmatic Dysfunction (VIDD): Prolonged mechanical ventilation leads to VIDD, characterized by diaphragmatic atrophy, loss of contractility, and reduced functionality, significantly complicating the weaning process.
- Clinical Impact of VIDD: VIDD contributes to extended ICU stays, higher weaning failure rates, and increased mortality, emphasizing the need for early recognition and intervention.
- Role of Diaphragmatic Ultrasound (DUS): DUS provides a non-invasive, bedside, and real-time tool for evaluating diaphragmatic structure and function, making it essential in diagnosing VIDD and guiding clinical decisions.
- Protective Ventilation Strategies: Integrating DUS into clinical practice supports diaphragm-protective ventilation approaches, aimed at minimizing VIDD and optimizing both lung and diaphragm health.
- Future Directions: Continued research on standardizing DUS protocols, validating diagnostic thresholds, and refining protective ventilation strategies will further improve outcomes in critically ill patients on mechanical ventilation.

The examination is typically conducted with the patient in a semi-recumbent position, utilizing dual approaches to achieve optimal visualization of the diaphragm [5, 6].

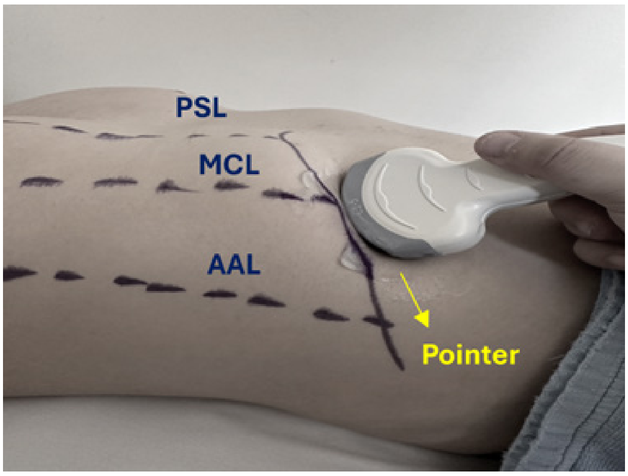
1. Subcostal ultrasound technique for measurement of diaphragmatic excursion

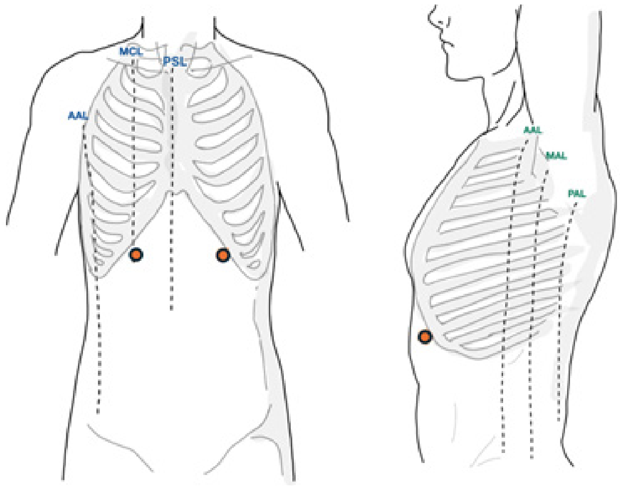
In the subcostal approach, a low-frequency ultrasound probe (2–5 MHz, curvilinear or phased array) is positioned along the mid-clavicular line, just below the costal margin. The probe is angled cranially and aligned perpendicular to the curvature of the diaphragm dome with the probe marker pointed at 9 o'clock (Table 1). This configuration enables visualization of the diaphragm in B-mode as a distinct bright line overlaying the liver or spleen, which moves toward the probe during inspiration. Diaphragmatic excursion (DE), reflecting the diaphragm's movement during normal breathing, is assessed in M-mode. The measurement line (M-line) is carefully oriented perpendicular to the diaphragm's motion to ensure precision. It is essential to distinguish passive ventilator-induced movements from active diaphragmatic contractions. For an accurate evaluation of diaphragmatic function, DE measurements should ideally be performed with minimal or no ventilatory support.

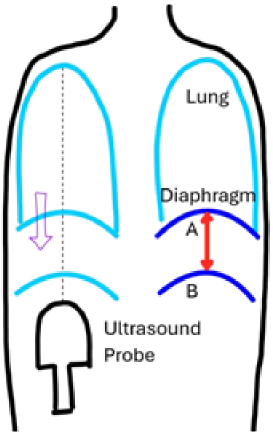
A significantly diminished DE, especially when observed alongside an adequate respiratory drive, suggests diaphragmatic weakness. In contrast, an abnormal upward movement of the diaphragm during inspiration indicates the presence of diaphragmatic paralysis.

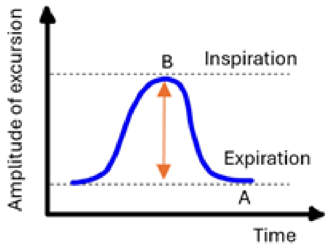
Table 1. Subcostal approach of ultrasound technique for diaphragmatic evaluation.

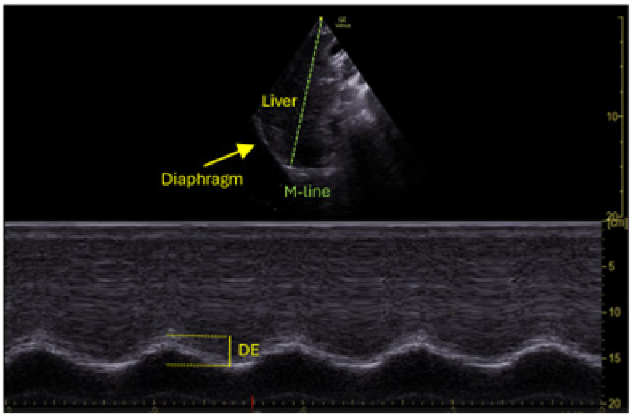
Preparation
Patient position – Adjust the patient in a semi-recumbent position (30-45°)
Ventilator setting – Adequate respiratory drive (e.g., $P_{0.1}$ > 2 cmH_2O, minimized sedation), Minimal ventilator support or Spontaneous breathing trial

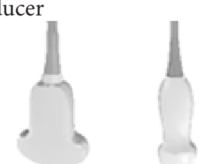










Probe	Position and imaging	Measurements
- 2-5 MHz, Curvilinear and Echo transducer  - * positioned along the mid-clavicular line, just below the costal margin. The probe is angled cranially and aligned perpendicular to the curvature of the diaphragm dome with the probe marker pointed at 9 o'clock.	- Adjust depth to optimally capture excursion - Adjust gain and focus to optimize image quality - Place M line perpendicular to the diaphragm movement, focusing on the area with the greatest displacement - Adjust sweep speed to obtain at least 3 respiratory cycles within 1 frame	- Measure DE during tidal breathing in M-mode - Place the markers at the lowest (foot) and the highest point (apex) of the inspiratory slope and measure distance between both on the vertical axis DE: diaphragm excursion Value **DE:** tidal breathing, end-expiration (mean±SD) Right: Male: 2.0±0.5 cm; Female: 1.9±0.5 cm. Left: Male: 2.2±0.5 cm; Female: 1.9±0.5 cm. DE < 10-15 mm during tidal breathing → diaphragm dysfunction [6]

AAL: anterior axillary line; MCL: Mid-clavicular line; PSL: Parasternal line; MAL: Mid-axillary line; PAL: Posterior axillary line; DE: diaphragm excursion
*Right side is easiest and sufficient unless unilateral involvement is suspected

2. Intercostal ultrasound technique for measurement of diaphragm thickness

Using a high-frequency ultrasound probe (7–12 MHz, linear transducer), the intercostal approach involves positioning the transducer between the 8th and 11th intercostal spaces along the anterior or mid-axillary line. The probe is oriented perpendicular to the chest wall within the zone of apposition and aligned with the intercostal spaces to optimize diaphragmatic visualization on the ultrasound screen (Table 2). The pointer of the probe is directed toward the axilla to enhance imaging accuracy. In this view, the diaphragm appears as a tri-layered structure consisting of the pleural line, a central non-echogenic muscular or fibrous layer, and the peritoneal line. The echogenic pleural and peritoneal linings border the non-echogenic muscular layer, with a distinct fibrous line prominently displayed in the center of the image.

The thickness of the diaphragm is accurately measured in B-mode at both the end of expiration (DTee) and the peak of inspiration (DTpi). These measurements are conducted by placing calipers precisely at the internal borders of the pleural and peritoneal linings, careful to exclude these linings from the measurements. Alternatively, thickness can also be assessed in M-mode, which, while offering improved temporal resolution throughout the respiratory cycle, does not match B-mode's superior spatial clarity. The diaphragm thickening fraction (TFdi), which serves as an indicator of diaphragmatic contractility, is calculated with the formula: ((DTpi - DTee) ÷ DTee) x 100. For an accurate evaluation of TFdi, it is crucial to minimize or eliminate ventilator assistance, as mechanical support can artificially lower TFdi by reducing the load on the diaphragm [5].

It is important to note that diaphragmatic thickness does not consistently correlate with its functional capacity. The data relating TFdi to overall diaphragm function shows variability, indicating that TFdi may not reliably serve as the sole indicator of diaphragm health [7-9].

For clinical practitioners, ensuring the repeatability and accuracy of measurements such as diaphragmatic thickness (DT), diaphragm thickening fraction (TFdi), and hemidiaphragm excursion requires considerable experience. It is recommended that practitioners perform a minimum of 40 supervised examinations to develop the necessary proficiency for conducting these assessments independently [10].

Although left-sided diaphragmatic ultrasound is a viable technique, it is not as commonly utilized in clinical practice due to anatomical and technical challenges. The left hemidiaphragm is often obscured by gastric air, making visualization more difficult compared to the right-sided approach. Additionally, standardized measurement protocols and reference values for left-sided diaphragmatic excursion and thickening fraction remain less well-established. While alternative imaging techniques have been proposed, their reproducibility and feasibility in critically ill patients are still under investigation. Future research should aim to refine left-sided ultrasound protocols to enhance their clinical applicability in ICU settings.

CLINICAL APPLICATIONS OF DIAPHRAGMATIC ULTRASOUND IN CRITICAL CARE SETTINGS

Diaphragmatic ultrasound for respiratory failure

Diaphragmatic ultrasound (DUS) provides a non-invasive, bedside tool for assessing diaphragmatic function in patients with acute respiratory failure (ARF). By evaluating diaphragmatic excursion (DE) and thickening fraction (TFdi), DUS helps distinguish diaphragmatic weakness from other causes of respiratory failure. Patients with ARF due to neuromuscular disorders or diaphragmatic dysfunction often present with reduced DE <10–15 mm and TFdi <20% [6]. A reduction in diaphragm thickness can indicate muscle atrophy, however, an observed increase in thickness requires cautious interpretation. Factors such as edema and fibrosis could contribute to this increase, complicating the assessment of diaphragm health [18]. Additionally, abnormal paradoxical movement of the diaphragm suggests diaphragmatic paralysis, which can be confirmed using a sniff test or fluoroscopy if needed.

Critical appraisal: While DUS is a promising tool for diagnosing respiratory failure, its diagnostic thresholds require standardization. Studies suggest that DE and TFdi can predict weaning failure, but heterogeneous patient populations limit their generalizability.

Diaphragmatic ultrasound for weaning

DUS plays a pivotal role in predicting successful liberation from mechanical ventilation. Research indicates that a diaphragmatic thickening fraction (TFdi) below 30–35% and a diaphragmatic excursion (DE) measuring less than 10–15 mm are associated with an increased likelihood of weaning failure from mechanical ventilation [11, 19]. Serial DUS assessments during spontaneous breathing trials (SBTs) provide real-time feedback on diaphragmatic performance, guiding clinicians in extubation decisions [12].

Critical appraisal: While TFdi and DE thresholds predict weaning outcomes, operator dependency and interobserver variability remain challenges. Some studies propose artificial intelligence (AI)-assisted ultrasound analysis to standardize measurements and reduce variability. Some observational data indicate that diaphragmatic ultrasound may predict failures in non-invasive ventilation (NIV) [13]; however, the absence of prospective studies restricts its use in decision-making for intubation in NIV patients.

Diaphragmatic ultrasound for monitoring effort

DUS provides real-time insights into inspiratory effort, especially in spontaneously breathing ICU patients. It allows quantification of diaphragmatic workload and identification of patient-ventilator asynchrony (PVA). Patients receiving non-invasive ventilation (NIV) or high-flow nasal oxygen (HFNO) may benefit from DUS-based titration of support.

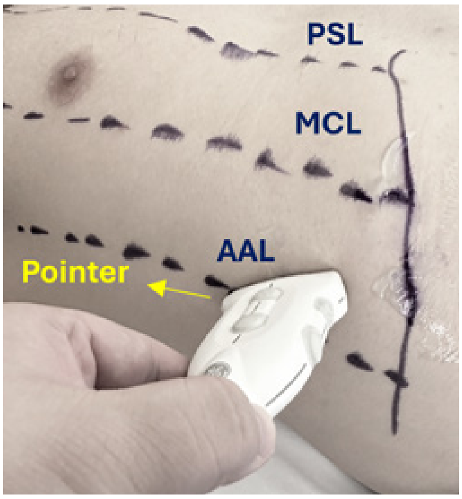
Critical appraisal: Limited prospective studies exist on using DUS for effort monitoring in non-intubated patients. However, preliminary evidence suggests that DUS can aid in optimizing inspiratory effort and preventing diaphragmatic fatigue.

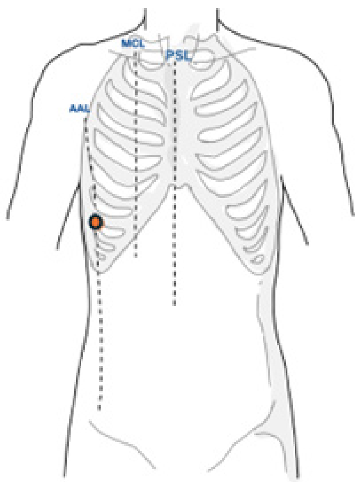
Table 2. Intercostal approach of ultrasound technique for diaphragmatic evaluation.

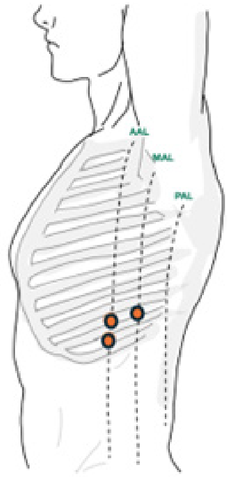
Preparation

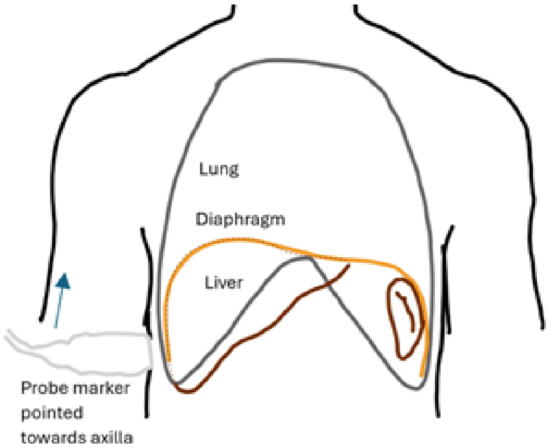
Patient position – Adjust the patient in a semi-recumbent position (30-45°)

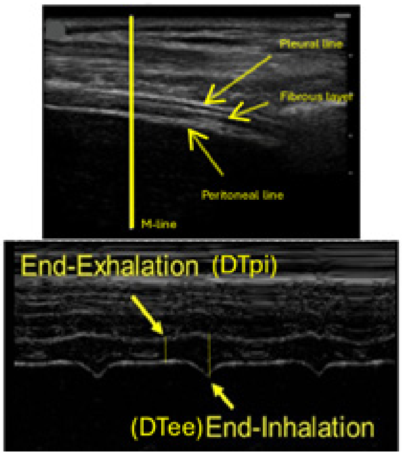
Ventilator setting – Adequate respiratory drive (e.g., $P_{0.1}$ > 2 cmH_2O, minimized sedation), Minimal ventilator support or Spontaneous breathing trial











Probe	Position and imaging	Measurements
- 7-12 MHz, linear transducer  - The ultrasound probe is positioned at the antero- or mid-axillary line between the 8th and 11th intercostal spaces, perpendicular to the chest wall at the zone of apposition and aligned with the intercostal space. The pointer of the probe is directed toward the axilla to optimize visualization. - *Right side is easiest	- Adjust depth to optimally capture excursion - Adjust gain and focus to optimize image quality - The pointer of the probe is directed toward the axillar. - Place M line perpendicular to the tri-layered structure of diaphragm movement, focusing on the area with the greatest displacement - Adjust sweeping speed to obtain at least 3 respiratory cycles within 1 frame	- Measure thickness at end inspiration (DTpi) and end-expiration (DTee) of the same respiratory cycle in B mode or M mode - Place the calipers perpendicular to the fiber direction closet at the internal margin of the pleural and peritoneal lining without including them - Calculate TFdi = ((DTpi - DTee) ÷ DTee) x 100 - To achieve representative results, obtain at least 3 measurements with a difference of <10% **Thickness:** tidal breathing, end-expiration (mean±SD) Right: Male: 2.1±0.4 mm; Female: 1.9±0.4 mm Left: Male: 2.0±0.4 mm; Female: 1.7±0.3 mm **TFdi:** tidal breathing (mean±SD) Right: Male: 32±15%; Female: 35±16% Left: Male: 30±14%; Female: 33±15% TFdi < 20%: diaphragm dysfunction TFdi < 25-33%: predicts weaning failure

AAL: anterior axillary line; MCL: Mid-clavicular line; PSL: Parasternal line; MAL: Mid-axillary line; PAL: Posterior axillary line; DE: diaphragm excursion
*Right side is easiest and sufficient unless unilateral involvement is suspected

Diaphragmatic ultrasound for ventilator-induced diaphragmatic dysfunction (VIDD)

Prolonged mechanical ventilation (MV) contributes to ventilator-induced diaphragmatic dysfunction (VIDD), characterized by atrophy, contractile failure, and loss of diaphragm strength. Serial DUS assessments allow early detection of VIDD, enabling 'diaphragm protective ventilation strategies [9] such as:

- Reducing ventilatory support to maintain minimal diaphragmatic activity.
- Adjusting tidal volume (VT) and positive end-expiratory pressure (PEEP) to prevent diaphragm overdistension.
- Incorporating diaphragm-protective ventilation protocols.

Critical appraisal: While DUS is valuable in detecting VIDD, optimal weaning strategies remain an area of ongoing research. The role of neuromuscular electrical stimulation (NMES) in diaphragmatic rehabilitation requires further study.

In our practice, we use DUS routinely in patients undergoing weaning trials or facing extubation challenges, especially when neuromuscular weakness is suspected.

We recommend conducting serial DUS assessments at key points, including at the start of ventilation, every 48 hours during spontaneous breathing trials (SBTs), and just before extubation to predict weaning success. However, DUS has some limitations, such as operator dependency and interobserver variability. Thus, it requires proper training for accurate use. Additionally, the diaphragm thickening fraction (TFdi) may not always correlate with diaphragmatic strength, so it should be used alongside other respiratory monitoring methods, like the rapid shallow breathing index (RSBI).

CONCLUSION

Diaphragmatic ultrasound (DUS) is a valuable, non-invasive tool for monitoring diaphragmatic function in critically ill patients, especially those on mechanical ventilation. It helps detect patient-ventilator asynchronies, which are often missed during routine monitoring and can lead to poor outcomes [14]. Continuous diaphragm monitoring using operator-independent devices is a promising development, and new parameters like diaphragm strain and stiffness, measured through techniques like speckle tracking and shear-wave elastography, are expected to improve the accuracy of DUS in clinical settings [15, 16].

Moving forward, efforts should focus on improving training, optimizing protocols, and addressing limitations through advancements in automated image processing and artificial intelligence to standardize measurements. By integrating DUS into routine ICU practice, we can enhance ventilator management, improve weaning outcomes, and reduce diaphragmatic dysfunction in critically ill patients.

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DECLARATION FOR IMAGE INCLUSION

The ultrasound and patient reference images included in this review article are original depictions created and captured by the reviewer to enhance the understanding of the content discussed. All images were taken by the reviewer, who also acted as the subject for any patient references included in the article. These images are intended solely for educational and illustrative purposes, adhering to ethical and professional standards. No third-party identifiable data has been included, ensuring full compliance with privacy regulations. This article, including all images, has been submitted to the committee with the assurance that the reviewer is both the creator and subject of all images used."

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