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REVIEW

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Advancements in imaging techniques for monitoring the respiratory muscles

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Abstract

This review highlights the latest advancements in imaging techniques for monitoring respiratory muscles in critically ill patients. At the bedside, conventional ultrasound has been widely adopted to measure diaphragm thickness, thickening and excursion. It has also been used to assess extradiaphragmatic respiratory muscles, including parasternal intercostal and abdominal muscles. Advanced ultrasound-derived techniques have expanded its applications, enabling the evaluation of tissue velocity (tissue Doppler imaging), stiffness (shear wave elastography), and local tissue displacement (speckle tracking). Facility-based imaging modalities such as magnetic resonance imaging and chest tomography provide complementary insights into respiratory muscles structure and function, offering valuable information for evaluating the effects of therapeutic interventions. Finally, imaging techniques have emerged as valuable tools for evaluating the metabolic demands of respiratory muscles, with advanced methods such as positron emission tomography and contrast-enhanced ultrasound showing significant potential.

Keywords Ultrasound, Imaging techniques, Respiratory muscles, Diaphragm

Introduction

Respiratory muscle dysfunction is a common issue in critically ill patients, contributing to difficult weaning and poor outcomes [1]. Reliable assessment of respiratory muscle structure and function is therefore essential. Early detection of respiratory dysfunction is critical for optimizing and tailoring ventilation strategies to patients. New and innovative interventions are continually being developed to improve the management and prevention of respiratory muscle dysfunction in critically ill patients. Consequently, the availability of robust and reliable outcome measures is of particular importance for improving daily care and knowledge. Respiratory muscles may be functionally categorized into three main groups: the diaphragm, the chest wall muscles, and the abdominal muscles. These muscle groups exhibit variable architecture, topography, and functions, each playing a unique role in respiratory mechanics. Historically, bedside evaluation of respiratory muscles, including the diaphragm, has been limited to basic visual assessments, with direct and detailed examination proving nearly impossible. Existing and emerging imaging techniques have shown promises in evaluating respiratory muscle trophicity, function, metabolism, and perfusion. These modalities enable detailed assessment for diagnosis, monitoring, understanding pathophysiological changes, and evaluating responses to interventions. By advancing the capability to assess respiratory muscles at multiple levels, these imaging techniques hold the potential to significantly improve

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ICU care and patient outcomes. Within the ICU, the ideal imaging tool would need to be non-invasive, free of radiation exposure, readily available at the bedside, transportable, user-friendly, and cost effective. While facility-based chest computed tomography (CT) and magnetic resonance imaging (MRI) can be used to visualize respiratory muscles, they are challenging for critically ill patients. However, these techniques remain valuable for baseline and long-term assessment of respiratory muscle structure and function. Additionally, emerging developments in CT scans, MRI, and positron emission tomography (PET) imaging show promise for more comprehensive respiratory muscle assessment. Ultrasound imaging (US) meets nearly all of the above features [2]. Over the past decade, the use of US for diaphragm assessment in the ICU has significantly increased, with numerous studies published on the topic. Other portable methods recently introduced for skeletal muscle imaging such as shear wave elastography, contrast-enhanced ultrasound, or multispectral optical tomography also show potential for the assessment of the respiratory muscles.

In this review, we will explore both bedside and facility-based imaging techniques that have been used in the ICU or show promise for the assessment of respiratory muscles. For each imaging technique, we will provide an overview with an explanation of the technology as needed. When available, we will describe current applications for the assessment of respiratory muscles in the ICU. We will also provide insights regarding the potential of emerging techniques that are compatible with the ICU within research and/or clinical settings. We will describe the types of information gathered, such as muscle trophicity, architecture, movement, mechanics, hemodynamics, oxygenation, metabolism, fat content, fibrosis, and inflammation. Additionally, we will evaluate each technique's specificity, reproducibility, sensitivity to change, and readiness for clinical use. Finally, we will discuss the strengths, limitations, and perspectives of each technique for monitoring respiratory muscle function in critically ill patients.

Bedside imaging

Conventional ultrasound imaging

Diaphragm ultrasound is an accessible tool for bedside assessment of the diaphragm (Table 1 and Fig. 1). Two primary approaches are commonly used in adults and children: the intercostal approach for measuring diaphragm thickness and thickening, and the subcostal approach for evaluating diaphragm excursion. Diaphragm thickness is used as an index of trophicity, while thickening and excursion are used as a proxy of diaphragm function. The majority of studies exploring the diaphragm come from the adult population with a few reports conducted in children. It is worth noting that obese patients and pregnant women are usually not included in diaphragm studies which suggests that diaphragm ultrasound should be carefully used in these populations.

The intercostal approach utilizes a linear array transducer (7–12 MHz) positioned perpendicular to the skin in the diaphragm's zone of apposition. The probe is typically placed along the midaxillary line or slightly anterior,

Table 1 Overview of imaging techniques for respiratory muscle assessment

	Trophicity	Function	Tissue changes	Blood flow/perfusion	Metabolism
Conventional ultrasound	Thickness	Thickening, excursion	Echogenicity (fat infiltration, fibrosis, and edema)	–	–
Speckle tracking	–	Strain	–	–	–
US shear wave elastography		Stiffening	Fibrosis	–	–
Contrast-enhanced ultrasound	–	–	–	Blood flow, perfusion	–
Multispectral optoacoustic tomography	–	–	Fat content, fibrosis, inflammation, edema	Blood flow, perfusion	Hemoglobin, glycogen
Computed tomography	Thickness, volume	Asymmetry	Fat content, fibrosis, Inflammation, edema		
Photon-counting computed tomography	Thickness, volume	Asymmetry	Fat content, fibrosis, Inflammation, edema		
Magnetic resonance imaging	Thickness, volume	Asymmetry, excursion	Fat content, fibrosis, Inflammation, edema	Blood flow, perfusion	
Positron emission tomography	–	–	–	–	Glucose consumption

The table summarizes the capabilities of imaging techniques for evaluating respiratory muscles, including their ability to measure trophicity (muscle structure), function, tissue changes (e.g., fibrosis, inflammation), blood flow/perfusion, and metabolic activity

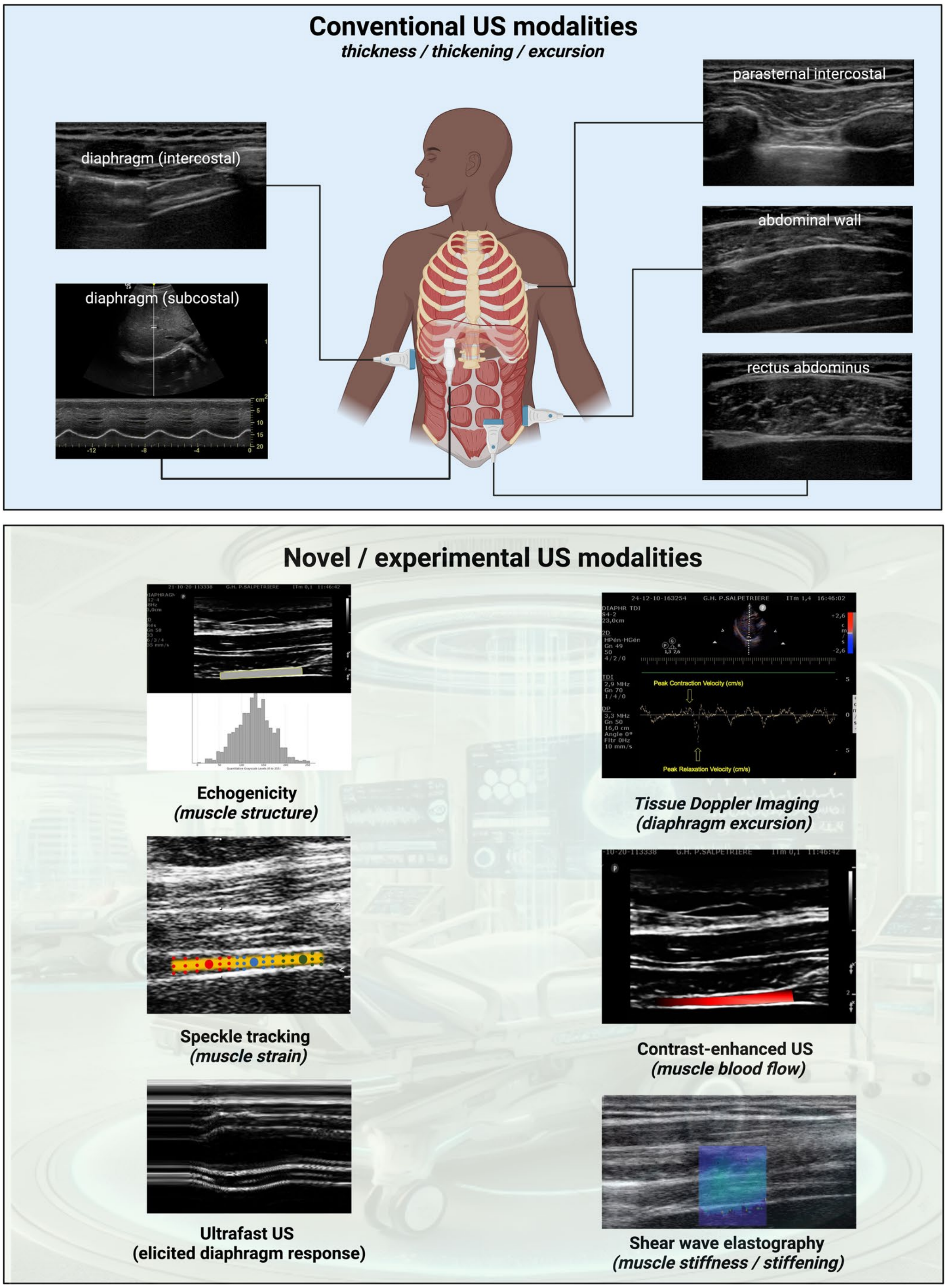

Fig. 1 Conventional and experimental ultrasound techniques to assess the diaphragm and other respiratory muscles. Conventional ultrasound methods focus on evaluating muscle trophicity and function, including thickness and thickening. Experimental ultrasound techniques expand this capability by exploring the muscle structure, velocity, strain, perfusion, stiffness/stiffening, and elicited diaphragm response.

between the 8th and 11th ribs, ensuring minimal lung interference in the image [3]. Here, the diaphragm appears as three hyperechoic (bright) bands (pleura, fibrous layer, and peritoneum) with two intervening hypoechoic (dark) bands (Fig. 1). Notably, the fibrous layer may be incomplete or absent in some cases. To measure diaphragm thickness, calipers should be positioned as close as possible to the pleural and peritoneal lines without including them. The diaphragm thickening fraction is calculated as the percentage difference between end-inspiratory and end-expiratory thickness normalized to end-expiratory thickness. Normal reference values for diaphragm thickness at end-expiration (~ 1.5–2.0 mm) and maximal inspiration (~ 4.0–5.5 mm), as well as for diaphragm thickening fraction during tidal breathing (~ 50–70%) and deep breathing (~ 150–200%), have been published [4–7]. In general, women have a slightly thinner diaphragm. However, variations in technique, such as probe positioning and posture, can influence measurement of diaphragm thickness [2, 8–10]. The reproducibility of diaphragm thickness and thickening as measured by ultrasound is good [10, 11]. However, diaphragm thickness is a poor marker of the pressure generating capacity of the diaphragm (pressure time product of the transdiaphragmatic pressure, transdiaphragmatic pressure, twitch pressure) [12–14] nor it is associated weaning outcome. In mechanically ventilated patients, diaphragm thickness often decreases over time, correlating with adverse clinical outcomes [15, 16]. However, diaphragm atrophy, defined as reduced muscle fibre cross-sectional area, may not always manifest as a reduction in diaphragm thickness measured via ultrasound [17, 18]. This is because diaphragm thickness reflects not only muscle fibres but also connective tissue, vasculature, inflammatory changes, lipid accumulation, and oedema, all of which may be altered in critically ill patients. Unlike thickness, diaphragm thickening fraction is widely regarded in the literature as a surrogate marker of diaphragm function, effort, or contractility. However, its correlation with the pressure-generating capacity of the diaphragm is weak in healthy individuals and mechanically ventilated patients [10, 12, 14], with limited accuracy in diagnosing diaphragm weakness [19]. This variability underscores the limitations of using diaphragm thickening fraction to quantify effort. One potential contributing factor is that diaphragm thickness was shown to be linearly related to pulmonary volume with high inter-individual reference [20]. Nonetheless, diaphragm thickening fraction has been widely studied as a predictor of successful weaning. A recent meta-analysis of 19 studies reported a combined area under the ROC curve of 87% for diaphragm thickening fraction in predicting weaning success [21]. Patients with a diaphragm thickening fraction exceeding approximately 29% are considered to have a high likelihood of successful weaning [9, 22, 23]. In children, diaphragm ultrasound has potential value in predicting the weaning outcome with cut-off values of diaphragm thickening fraction associated with successful weaning ≥ 21% [24].

However, it is important to note that diaphragm ultrasound may not reliably predict extubation failure, particularly in patients at elevated risk of reintubation who have successfully passed a spontaneous breathing trial [25]. This emphasizes that diaphragm dysfunction represents only one component of the complex mechanisms underlying weaning failure [26].

The subcostal approach evaluates diaphragm excursion, which refers to the cranial-caudal displacement of the diaphragm (Fig. 1). A low-frequency phased-array or curved-array transducer (2–5 MHz) is placed below the ribs, between the midclavicular and anterior axillary lines. The diaphragm appears as a broad hyperechoic band overlying the liver on the right or spleen on the left. Visualizing the left diaphragm is often more challenging due to the limited acoustic window of the spleen. To measure excursion, the transducer is aligned perpendicular to the diaphragmatic dome, and motion is assessed in anatomical M-mode. Normal values have been published for tidal breathing (women 1.7 cm, men 1.9 cm), sniff manoeuvres (women 2.6 cm, men 2.9 cm), and maximal inspiration (women 5.4 cm, men 6.6 cm) [27]. This technique exhibits excellent intra- and interobserver reliability. In mechanically ventilated patients, diaphragm excursion shows a weak correlation with markers of pressure generating capacity [13, 28]. Nevertheless, a recent meta-analysis reported a combined AUC of 87% in predicting weaning success [21]. Patients with diaphragm excursion values above approximately 1 cm have a high probability of successful weaning [29]. Additionally, it has been proposed that diaphragm excursion may be used to detect patient-ventilator asynchronies [30]. The feasibility of this concept has been demonstrated in a case series in three patients and in healthy volunteers under non-invasive ventilation [30, 31]. Recently, a novel approach has been introduced that enables continuous non-operator real-time measurement of diaphragm excursion and velocity using ultrasound technology, which shows promise for predicting weaning failure with high reliability [32]. It is important to note that positive pressure ventilation can also cause caudal passive diaphragm displacement. Last, it should be noted that diaphragm thickness is not lower in sarcopenic patients as compared to non-sarcopenic patients but that diaphragm thickening fraction may be lower in COPD sarcopenic patients [33]. A large epidemiologic study in the general population (n = 3324) recently reported that waist circumference but not parameters of sarcopenia was independently associated with diaphragm thickness. Importantly, diaphragm thickness was not associated with all-cause mortality, confirming that diaphragm thickness should not be used as a marker of systemic sarcopenia [34]. In summary, conventional diaphragm ultrasound is a readily available, easy-to-perform, and reliable bedside tool with demonstrated utility in detecting diaphragm atrophy, predicting weaning outcomes, and identifying patient-ventilator asynchronies. While diaphragm thickening fraction is widely used, it cannot replace measurement of diaphragm effort, and an unchanged or increased diaphragm thickness does not exclude atrophy. These limitations should be considered when interpreting diaphragm ultrasound findings, especially in critically ill patients.

Parasternal intercostal muscles. The parasternal intercostals are essential muscles of inspiration, exhibiting a similar intensity of neural activation to the diaphragm during eupnoea and hypercapnia [35]. Therefore, ultrasound examination of the parasternal intercostals is of particular interest. Typically, a 10–15 MHz linear array transducer is used, positioned at the level of the second intercostal space in a cranio-caudal orientation, 3–8 cm lateral to the sternum [36–39]. The parasternal intercostal muscles are visible as two hyperechoic bands running from the anterior and posterior aspects of the ribs, separated by a more hypoechoic muscular portion. Similar to diaphragm US, thickness of the parasternal intercostal muscles can be determined at expiration and inspiration, and thickening fraction can be calculated. The inter-rater and intra-rater reliability of this technique was reported to be good to excellent [36, 37]. In mechanically ventilated patients, parasternal thickening fraction decreases with higher levels of pressure support. Studies have investigated the utility of parasternal thickening fraction in predicting weaning failure. Reported cut-off values range from 7.6 to 13.2%, with an AUC between 72 and 88% [36, 40, 41]. In most studies, these diagnostic values were comparable to the diagnostic performance of diaphragm ultrasound. Calculating the ratio of parasternal intercostal thickening fraction to diaphragm thickening fraction has been shown to enhance diagnostic accuracy, with cut-off values between 0.35 and 0.44 and an AUC of 88–92% [36, 41, 42].

Abdominal wall muscles. Ultrasound imaging enables visualization of the abdominal wall muscles, including the obliquus externus abdominis, obliquus internus abdominis, transversus abdominis, and rectus abdominis (Fig. 1). These muscles play an important role in active expiration and cough and have been linked to weaning failure [43]. A 10–15 MHz linear array transducer in a transverse orientation is used to visualize the obliquus externus abdominis, obliquus internus abdominis, and transversus abdominis muscles in one image. The transducer is placed midway between the costal margin and the iliac crest along the anterior axillary line, where the muscles are identified as three layers separated by hyperechoic fasciae. The rectus abdominis is imaged by positioning the transducer 2 cm above the umbilicus and 2 cm lateral to the midline. Data on the value of abdominal wall muscle ultrasound in critically ill patients remain limited. One study demonstrated that abdominal muscle thickness and thickening fraction are measurable in mechanically ventilated patients, with moderate reproducibility. Increased thickening fraction was observed during failed SBT [44]. However, further research is needed to elucidate the clinical significance of abdominal wall muscle ultrasound in critically ill populations.

Muscle echogenicity

The quantification of muscle ultrasound echogenicity (also referred to as echo intensity or echodensity) using grayscale or backscatter analysis of a region of interest has been extensively used as a proxy measure to estimate muscle alterations including fibrosis, fat infiltration, or inflammation. Echogenicity analysis of skeletal muscles is a well-established and reliable method for screening, diagnosing, and monitoring neuromuscular disorders [45, 46]. In critically ill patients, alterations in muscle echogenicity have been associated with the development of ICU-acquired weakness [47–49], although not all studies have found this association [50]. Increases in diaphragm echogenicity during the early course of mechanical ventilation have been associated with prolonged mechanical ventilation [51]. However, technical limitations may affect the interpretation of these findings. Different ultrasound machines were used, and the healthy control group was significantly younger. It is well-documented that both ultrasound settings (e.g. gain, frequency, focal depth) and age significantly impact echogenicity values, including those of the diaphragm [52]. Other higher-order texture descriptors have also been described, offering the advantage of being less affected by variables such as gain [53]. However, their application in respiratory muscles within the ICU has not yet been reported.

Speckle tracking

Speckle tracking is a technique used to estimate local tissue displacement over time by following a unique, small group of pixels (termed “kernels”) across sequentially acquired images. This method, originally applied for cardiac ultrasound, leverages the inherent grainy patterns in ultrasound, known as speckle patterns, which serve as local “footprints” of tissue. The spatial derivation of displacement maps provides strain, representing tissue deformation relative to its initial length [54]. Speckle tracking has been applied to the quantification diaphragm function using two approaches. First, with the intercostal approach, longitudinal strain is calculated to estimate muscle shortening within the plane of the muscle fibres. Studies in healthy subjects have demonstrated that diaphragm longitudinal strain and strain rate are feasible and reproducible [55], with strong correlations to transdiaphragmatic pressure [14]. Among mechanically ventilated patients, a longitudinal diaphragm strain of less than −21% has been shown to be a reliable predict successful weaning (AUC = 0.794) [56]. However, this metric does not outperform the rapid shallow breathing index. Second, speckle tracking imaging has also been used to automatically track diaphragm excursion via the subcostal approach. This method's technical feasibility has been demonstrated [57, 58]. In critically ill patients, it showed a moderate correlation with manual diaphragm excursion measurements and provided a moderate diagnostic value in predicting weaning failure [59]. In addition to diaphragm assessment, speckle tracking has been applied to measure longitudinal strain of the parasternal intercostal muscles. This approach has proven to be feasible and reliable in both healthy individuals and mechanically ventilated patients [60]. Notably, a parasternal intercostal longitudinal strain of less than −6% exhibited strong predictive performance for weaning success (AUC = 0.91). However, these findings require validation in future studies. Current speckle tracking techniques for respiratory muscles face limitations, as most algorithms and software are designed for cardiac applications. Assumptions embedded in these algorithms—such as myocardial-specific geometry and displacement patterns—impede accurate tracking of longitudinal diaphragm strain and make the analysis labour-intensive. Further clinical and technical studies are warranted to determine whether speckle tracking of the diaphragm and/or parasternal intercostals offers additional value beyond conventional ultrasound measures.

Tissue Doppler imaging (TDI)

TDI is an ultrasound technique usually employed by echocardiologists to quantify myocardial motion velocity. While TDI has been used to measure the high-amplitude, low-velocity signal of cardiac tissue motion, it has recently been proposed to also explore diaphragm displacement. It provides complementary information to conventional ultrasound indices but the added value of TDI variables has not been specifically investigated so far. The TDI images are typically obtained with a 2–4 MHz phased array probe placed in the subcostal position between the midclavicular and anterior axillary lines. The cursor should be maintained as perpendicular as possible to the observed hemidiaphragm. TDI can provide several measurements: (1) peak contraction velocity, (2) peak relaxation velocity, (3) velocity–time integral and (4) maximum relaxation rate (Fig. 1). Those measurements are associated with excellent intra- and interobserver reproducibility [61]. TDI derived indices have been compared in critically ill patients to transdiaphragmatic pressure during a spontaneous breathing trial. Except for the velocity time integral, all TDI indices significantly differed between patients with weaning success and those with weaning failure. Patients with weaning failure patients exhibited higher peak contraction and relaxation velocities, with peak contraction velocity showing strong correlation with peak transdiaphragmatic pressure ($R^2 = 0.73$). One interesting feature of TDI is notably to assess relaxation properties of the diaphragm. It is usually calculated as the slope of the perpendicular line from the steepest portion of the descending part of the transdiaphragmatic pressure curve and therefore requires esophageal and gastric balloons. However, TDI has technical limitations since measurements are particularly dependent on ultrasound settings and probe position and so far, only a few studies have been conducted in the ICU.

Ultrasound shear wave elastography (SWE)

Quantitative elastography techniques measure muscle elasticity by calculating the velocity of the shear waves that result from mechanical perturbations applied on the tissue [62]. The velocity of this propagation is directly related to the shear modulus of the tissue, that is, the stiffer the tissue, the faster the shear wave propagation. Magnetic resonance elastography offers excellent spatial resolution but has long acquisition time limiting its application in the respiratory muscles during ventilation. Ultrasound shear wave elastography (SWE) uses an ultrafast imaging modality combined with a transient and remote mechanical vibration generated by radiation force induced by a focused ultrasonic beam. SWE can provide real-time quantitative estimation of passive and or active muscle force induced by changes in length or contraction. In muscle, shear modulus measured along muscle fibers using SWE has been shown to be linearly related to the Young's modulus measured using state-of-the-art techniques [63]. Changes in diaphragm shear modulus during submaximal isovolumetric inspiratory efforts has been shown to be linearly associated to changes in inspiratory mouth pressure ($r^2 > 0.95$) [64] and to changes in transdiaphragmatic pressure during both isovolumetric inspiratory efforts ($r = 0.82$) and ventilation against inspiratory loads ($r = 0.70$) [65]. In the ICU, a moderate correlation with transdiaphragmatic pressure during pressure-support ventilation was observed at the group level ($R = 0.45$, $p < 0.001$) [66]. More specifically, patients with a non-significant correlation had higher respiratory rates than those with a significant correlation (median: 25 vs. 21 breaths/min). This limitation is due to the restricted sampling rate of SWE, limiting its use in tachypneic patients. Specific technological developments are thus required to make SWE available for all ICU patients. Good within and between-day reproducibility of shear modulus in diaphragm and other respiratory muscle at different levels of contraction has been shown in healthy participants [67]. Good inter-operator reproducibility and intra-operator reliability were reported in diaphragm within the ICU, although only end-expiratory diaphragm shear modulus was assessed [68, 69]. Off note, very good reproducibility (i.e., intrasession, intersession, and/or inter-rater) of SWE has been reported in locomotor muscle at rest, during passive lengthening [70, 71], and contractions [72]. Another important consideration is that SWE measurements are highly sensitive to probe pressure and handling. While this sensitivity is less problematic when assessing the diaphragm due to its deeper anatomical location, it can pose significant challenges when evaluating more superficial respiratory muscles. In another work, combination of SWE and conventional US within a radiomics approach was shown to efficiently predict weaning outcome with AUC > 84% although this remain to be confirmed in larger studies [73].

Beyond the quantification of respiratory muscle work, the use of SWE has been explored for assessing changes in the mechanical properties of the muscles, providing insights into both physiological and pathophysiological processes. For instance, increased muscle stiffness as assessed with SWE has been associated with fibrosis in mice in locomotor muscles [74] and in the diaphragm [75]. A decrease in resting muscle stiffness after fatiguing contractions has also been reported in human locomotor muscle but this has never been reported in the respiratory muscles. Within a large longitudinal and translational study in mechanically ventilated patients, Aarab et al. reported an increase or decrease in end-expiratory diaphragm shear modulus (51% vs. 41% of patients with > 10% change) [68]. Interestingly, the increase in diaphragm thickness was associated with a decrease in shear modulus—authors suggested a potential relation with muscle damage, but this remains to be confirmed. In piglets, authors reported a decrease in shear modulus after three days of mechanical ventilation that was associated with force loss, myofiber atrophy, and increased lipid droplets accumulation. Crucially, changes in muscle fat content can significantly impact shear wave velocity measurements by altering the speed of sound, potentially affecting the accuracy of assessments [62]. Speed of sound estimation is thus emerging as a potential biomarker for muscle fatty degeneration [76, 77] that may potentially be used within the ICU. Additionally, the specificity of resting muscle shear modulus may be limited, as multiple processes that influence tissue stiffness can occur simultaneously and potentially compete [74]. Shear wave dispersion estimation has been linked to inflammation in rat's heart [78] and locomotor muscles and its potential for detecting inflammation in mechanically ventilated patients remains to be investigated. In pediatric patients, ultrasound and shear wave elastography have proven to be useful in the evaluation of sarcopenia. Additional markers derived from SWE, such as elastic anisotropy, present promising new avenues for research [79].

Ultrafast ultrasound

Plane wave imaging allows ultrasound to achieve extremely high frame rates (up to 1000 Hz) compared to conventional focused imaging (typically 25 Hz). This enables the capture of brief events lasting just a few hundred milliseconds. Ultrafast US enables SWE described above and has also been used to capture the right hemidiaphragm's response to cervical magnetic stimulation in healthy participants [80]. The quantified twitch diaphragm tissue velocity was shown to be linearly associated with twitch transdiaphragmatic pressure and showed good within-day reliability [80]. This technique offers a specific, non-volitional assessment of diaphragm contractility. However, its feasibility, reliability, and sensitivity to changes in ICU settings have yet to be thoroughly investigated. These techniques also require specialized equipment and expertise, which currently limit their broader application.

Contrast-enhanced US (CEUS)

CEUS uses microbubble contrast agents to enhance ultrasound imaging for assessing blood flow dynamics in tissues. It is highly sensitive to perfusion changes and has been validated in studies on cardiac, organ, and skeletal muscles [81, 82]. Recently, CEUS has been adapted to measure diaphragmatic blood flow under varying inspiratory loads in healthy participants and showed excellent sensitivity to changes in muscle work and between-day reliability [83]. Currently, CEUS measures relative, not absolute, changes in blood flow and is limited to a single diaphragm regions, which may not capture overall perfusion. The need for patient cooperation (e.g. 15-s apnea) may limit its use in mechanically ventilated ICU patients, warranting further research on its feasibility in these settings.

Multispectral optoacoustic tomography (MSOT)

Multispectral optoacoustic tomography (MSOT) is an advanced imaging technique that combines optical and ultrasound technologies to visualize tissue composition and function. By emitting laser pulses at multiple wavelengths, MSOT induces ultrasonic waves within tissues, which are then detected to reconstruct high-resolution images. This method enables the assessment of various physiological parameters, including hemodynamics, oxygenation, metabolic activity, collagen, and lipid content [84]. While primarily applied to peripheral muscles in exercise contexts [85] or myopathies, there is potential to extend MSOT to respiratory muscles in the ICU. However, the capability of MSOT in deep structures such as the diaphragm remains to be investigated. Currently, the availability of MSOT adapted for use within clinical settings is limited, and high costs further restricts its use.

Facility-based imaging modalities

The techniques discussed below are not currently relevant in the ICU as they lack clinical validation. However, they may become valuable for monitoring survivors after discharge to track the evolution of respiratory muscle weakness. This could improve knowledge and support the development of preventive strategies to be implemented during the acute phase in intensive care.

Computed tomography (CT)

Chest CT plays a critical role in diagnosing diaphragmatic pathologies (Fig. 2). It helps identify lesions along the phrenic nerve (e.g., tumors, lymphadenopathy, thymomas), while excluding causes of an elevated hemidiaphragm (effusions, abscesses, masses). Additionally, it aids in distinguishing conditions mimicking respiratory muscle weakness, such as interstitial lung disease or shrinking lung syndrome in lupus. Multiplanar reconstructions provide enhanced visualization of hernias, ruptures, or eventrations by highlighting direct defects and indirect signs, such as organ displacement [86, 87]. CT-based metrics are highly informative for assessing respiratory muscle structure and function. These include diaphragmatic thickness (< 1.5 mm) measured at the L1 vertebral level, asymmetry (> 2 mm), and excursion (mean 2.5 cm), all of which are useful for detecting atrophy or dysfunction in conditions like COPD and critical illness [88, 89]. Fatty infiltration measured by CT in the paraspinal muscles has also been shown to predict mortality in ECMO patients, emphasizing its prognostic significance [90].

Photon-counting CT (PCCT)

PCCT represents a significant innovation in respiratory muscle imaging, which will enable high-resolution, low-dose evaluation of diaphragmatic thickness and fatty infiltration [91, 92]. When combined with smart nanoparticles, spectral PCCT could facilitate metabolic imaging and targeted therapy delivery, offering new prospects for managing critically ill patients. While CT provides high spatial resolution, its radiation exposure and inability to assess motion limit its use for continuous monitoring.

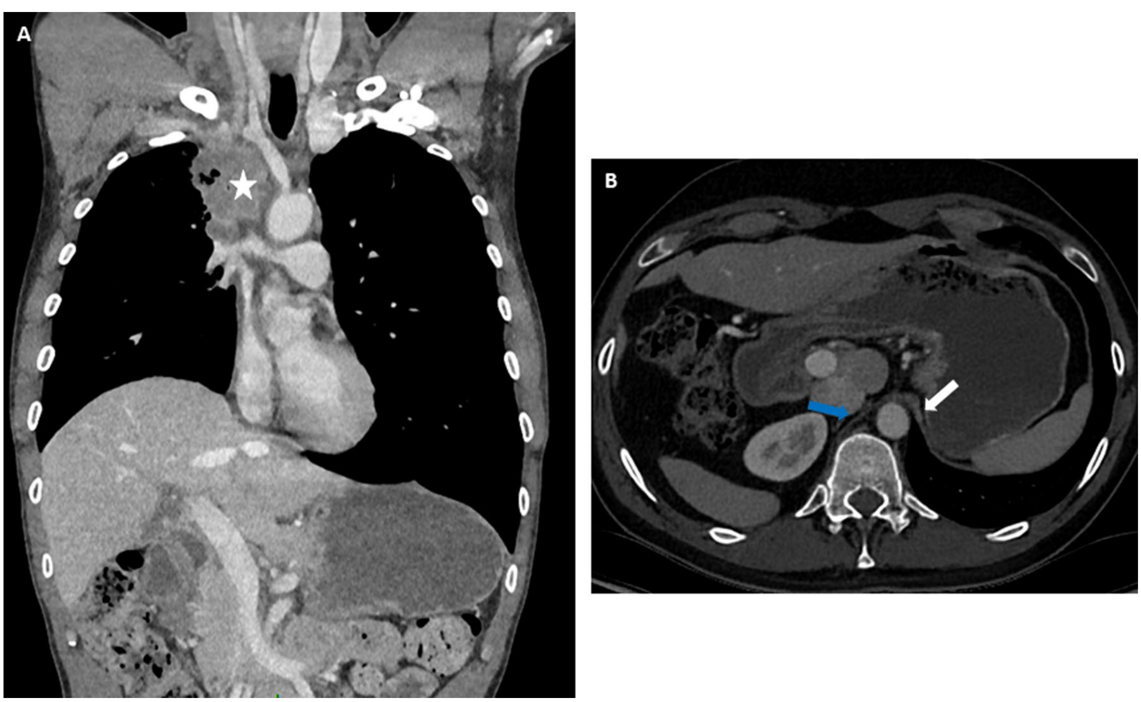

Fig. 2 Chest CT scan in a 52-year-old male with lung cancer. **A** Elevation of the right hemidiaphragm due to an apical tumor mass (star) of the right upper lobe invading the right phrenic nerve. **B** Complete eventration due to phrenic nerve involvement by the tumor mass, causing amyotrophy of the right diaphragmatic muscle, which is pronounced on the right crus (blue arrow) and shows a clear disparity compared to the left crus (white arrow).

Magnetic resonance imaging (MRI)

Dynamic MRI offers unparalleled insights into diaphragmatic function, quantifying excursion and velocity during ventilation [93–96] (Fig. 3). Studies confirm that body posture significantly impacts diaphragm mobility, with limited displacement in prone positioning [97]. Compared to ultrasound, MRI provides a more precise assessment of diaphragmatic dysfunction, particularly in the deeper crural regions of the diaphragm, which are anatomically less accessible to conventional ultrasonography [98]. MRI also appears to be a valuable research tool to evaluate the geometry and structure of the diaphragm during PEEP titration [99]. Recent advancements, including 3D and 4D MRI, enhance evaluation by analyzing shape, curvature, and volume changes during respiration [100, 101]. These techniques enable earlier detection of dysfunction, such as reduced excursion and thickness in COPD [102] and identify abnormalities in diaphragm excursion and curvature before symptoms appear, especially in neuromuscular disorders [101]. Parametric imaging techniques, such as T1/T2 mapping and short tau inversion recovery i.e. STIR sequences, offer precise assessment of inflammation, fat infiltration, and disease progression, particularly in idiopathic inflammatory myopathies [103, 104]. MRI elastography quantifies muscle stiffness and may allow early detection of diaphragmatic alterations, such as fibrosis [105]. This approach holds promise for assessing diaphragm dysfunction in critically ill patients, although further validation is required. Comprehensive functional and parametric MRI of the diaphragm and other respiratory muscles facilitates early diagnosis by evidencing inflammation and edema, which may be relevant, for instance, in idiopathic inflammatory myopathies and could allow

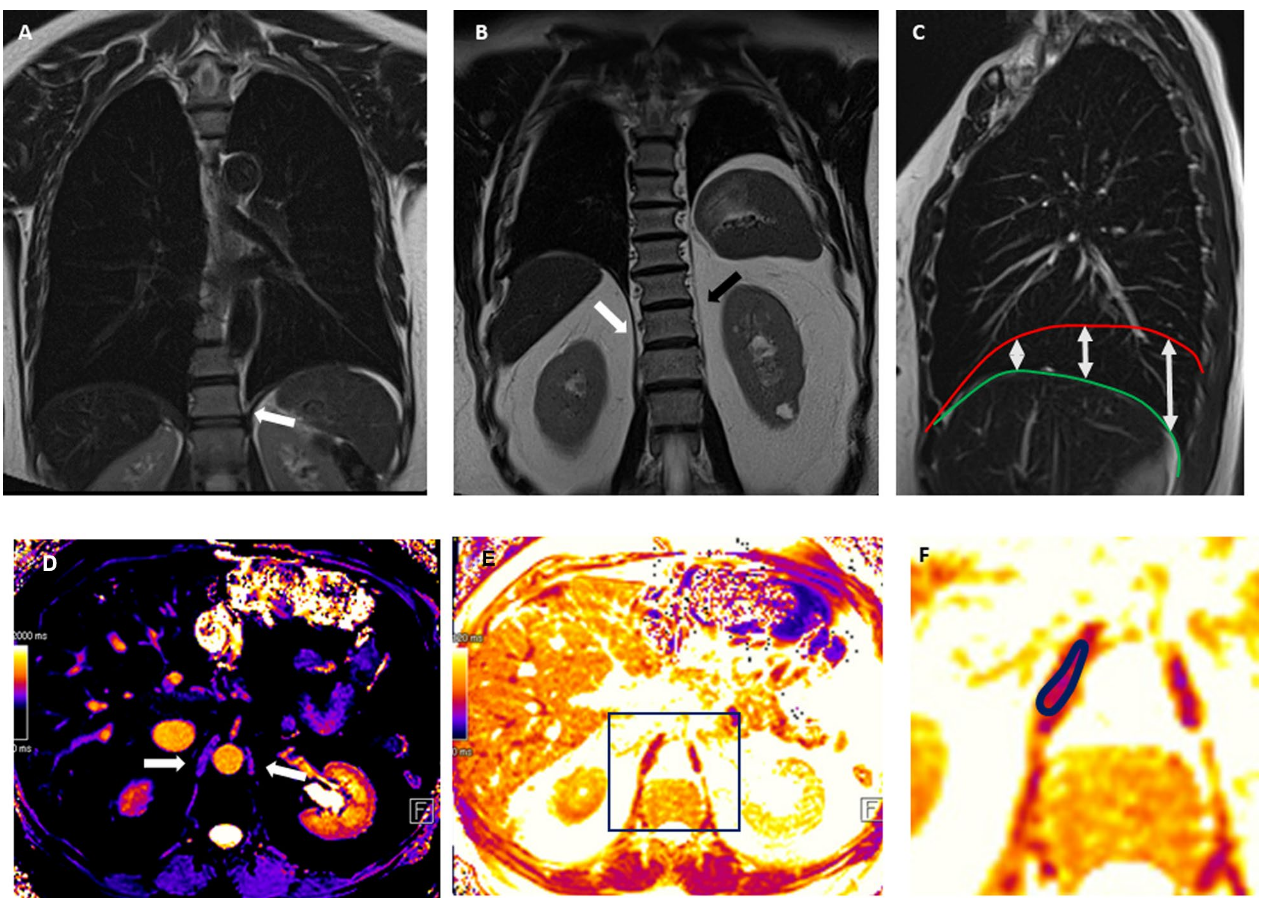

Fig. 3 **A** MRI FIESTA (Fast Imaging Employing Steady-State Acquisition) sequence in the coronal plane of a normal diaphragm, used to assess the continuity and thickness of the diaphragm (white arrow). **B** Elevation of the left diaphragmatic dome with preserved continuity of the muscle, demonstrating diaphragmatic atrophy (black arrow) compared to the contralateral side (white arrow). **C** Dynamic MR imaging of the diaphragm showing normal excursion during full expiration (red) and full inspiration (green), revealing an anteroposterior gradient with maximal excursion in the posterior portion. **D** Axial T1 mapping sequence without contrast injection for tissue characterization, focused on the diaphragmatic crura (white arrows). **E** T2 mapping sequence on the diaphragmatic crura for tissue characterization. **F** Zoom of E, showing ROI measurement to assess T2, illustrating how T2 is measured and quantified in routine clinical practice

to monitor treatment efficacy. Low-field MRI offers a cost-effective, bedside-friendly solution for evaluating respiratory muscles in critically ill patients but it has a lower image resolution compared to high-field systems [106]. Portable MRI may have the potential to facilitate regular, non-invasive assessments of diaphragm structure in critically ill patients though its feasibility and accuracy remain to be fully validated. Advances in portable MRI systems, combined with standardized protocols and open designs, aim to address logistical challenges in ICU settings while preserving diagnostic accuracy [107].

Positron emission tomography

PET combined with CT or MRI may be used to study metabolism in skeletal muscles. Increased ^{18}F-FDG uptake in respiratory muscles has been associated with conditions like ARDS [108], lung cancer surgery [109], COPD [110], and in smokers, indicating inflammation or compensatory mechanisms. Despite its cost and resolution limitations compared to MRI or CT, this approach may provide valuable insights into diaphragmatic metabolic activity, potentially aiding in the early detection and management of respiratory muscle dysfunction in intensive care. PET-MRI combines PET's metabolic insights with MRI's structural and motion analysis, offering potential for assessing respiratory muscles, including diaphragmatic morphology and metabolism [111]. Currently, no studies have focused on respiratory muscles in critical care. Its high cost and limited accessibility hinder widespread ICU use, though future advancements could enhance its applicability in this setting.

Clinical aspects and perspectives

Assessing respiratory muscle structure and physiology at the bedside is a pivotal aspect in the management of patients presenting with acute respiratory failure, should they be intubated or not. Currently, conventional ultrasound indices provide useful information regarding the structure and activity of respiratory muscles. However, the modalities of image acquisition and measurements are highly operator dependent and available only at the time of the evaluation. This is a clear limit for a large-scale implementation. Improving the reproducibility of measurements and making them non operator dependent by dedicated devices and with artificial intelligence would be a great step toward a reliable continuous monitoring with several clinical applications in intubated and non-intubated patients. Likewise, chest electrical impedance tomography that provides a continuous assessment of regional lung ventilation at the bedside, portable and miniaturized imaging techniques of the respiratory muscles could play a useful role to explore the respiratory muscle function and structure in ICU patients. Such advancements could facilitate the investigation of therapeutic interventions, including drugs and medical devices [112], on respiratory muscles while enabling streamlined, point-of-care evaluations directly at the bedside.

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