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An Overview about Role of Ultrasound of the Diaphragm and of Parasternal Intercostal Muscle in the Assessment of Weaning

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Abstract:Background: Though it can save lives, mechanical ventilation (MV) has the potential to cause diaphragmatic dysfunction (DD) and myotrauma, which are injuries to the muscles of the diaphragm. Prolonged ventilation, weaning failures, and death are some of the worst negative effects linked to DD, which is why it is important to address. The main causes of myotrauma are patient-ventilator asynchrony (PVA) and insufficient mechanical ventilation (MV) support in responding to the patient's respiratory effort (over- or under-assistance). Myotrauma prevention techniques, such as MV with diaphragm protection, were developed in response to the recognition of these mechanisms. These treatments primarily center on titrating suitable degrees of inspiratory effort to minimize PVA and over- or under-assistance. In order to keep the diaphragm safe during MV, instruments that measure diaphragmatic effort and identify PVA are necessary. One non-invasive method for monitoring diaphragmatic function, evaluating PVA, and maybe even defining diaphragmatic effort with protected breathing is diaphragm ultrasonography. The purpose of this review is to give doctors a synopsis of DD's importance, the key mechanisms that cause myotrauma, and the most up-to-date methods for reducing myotrauma, with a focus on the use of ultrasound to monitor diaphragm function and its role in in the Assessment of Weaning from Mechanical ventilation.
Keywords:*Ultrasound, Diaphragm, mechanical ventilation*

Introduction

The goal of mechanical ventilation (MV) in cases of acute respiratory failure is to maintain an adequate gas exchange by either fully or partially replacing the action of the respiratory muscles. Several breathing methods have been proposed to decrease the mechanical stress imparted to the lungs [3] in response to the widely acknowledged potentially detrimental pulmonary effects [1,2] of MV. In more recent times, it has been found that mechanical ventilation (MV) can cause diaphragm injuries by many hypothesized mechanisms, which have been called "myotrauma" [4]. This, in turn, can lead to ventilator-induced diaphragmatic dysfunction (VIDD) [5].

The diaphragmatic force-generating capacity decreases with the use of MV [5], which starts soon after the initiation of the MV [6], progresses in a time-dependent way [7], and is affected by various MV modes and risk factors [7]. This phenomenon is defined as VIDD.

Since diaphragm dysfunction (DD) is frequent throughout the many stages of critical illness, including admission [8], early stages of mechanical ventilation (MV) [7], weaning [9,10,11], and recovery [12], its diagnosis is important in critically sick patients. Furthermore, there are a number of risk factors that might occur simultaneously with MV in severely sick patients, including sepsis, organ dysfunction, and drugs that can cause diaphragmatic injury [8,13,14,15]. Additionally, there is strong evidence that diaphragmatic dysfunction negatively affects critical illness patients' morbidity, such as challenges with weaning [7,8,9,10,11], readmission to the intensive care unit [16], and mortality [8,17].

Current research has focused on prioritizing MV care for critically sick patients in order to monitor diaphragm function in the ICU and minimize or avoid diaphragm myotrauma to prevent VIDD [18]. This is because diaphragmatic dysfunction is relevant to these patients.

Strategies to safeguard the diaphragm during MV are based on knowledge of the primary mechanisms involved in myotrauma [19,20].

In order to better understand how diaphragm ultrasonography can be used to evaluate diaphragmatic function and track diaphragmatic effort during protective breathing, this review will go into the current understanding of these topics.

2. Diaphragm Myotrauma-Mechanisms

Several clinical [7,22,23,24] and experimental research [25,26,27,28,29] have provided evidence of diaphragmatic muscle injury in critically sick mechanically ventilated patients, which has been extensively recognized and acknowledged [21].

Efforts have been undertaken to standardize nomenclature in order to ensure communication between researchers studying diaphragmatic dysfunction in critically ill patients. Myotrauma has thus been the descriptor of choice for the acute diaphragmatic muscle injury that might occur as a result of using a ventilator [4].

The latest research suggests that myotrauma is likely caused by various factors connected to improper MV management. These factors mostly include AVP and the insufficiency of ventilatory support in relation to the patient's breathing effort. What follows is a synopsis of the evidence supporting these mechanisms [4]:

1. Helping too much The condition known as myotrauma, which is characterized by weakening and disuse atrophy, is brought on by diminished respiratory drive and effort due to excessive respiratory assistance. Evidence of disuse atrophy on imaging investigations [23,34,35,36], functional impairment [7], and histological findings [24,32,33] make this type of myotrauma the most well-documented in the scientific literature. Note that even with assisted breathing modes, disuse atrophy can happen [37].
2. Without proper support When ventilatory support is inadequate or fails to alleviate the strain on the diaphragm due to elevated respiratory drive, a recognized type of muscle injury known as myotrauma (load-induced, concentric contraction) can happen. Concentric contraction causes considerable muscular tension due to the maintenance of strong respiratory attempts in the absence of support [23,38]. In experimental settings, inflammatory infiltration and disruption of sarcomere and sarcolemma characterize the diaphragmatic damage.
3. Eccentric myotrauma, also known as load-induced eccentric contraction, happens when the diaphragm contracts when the fibers are lengthening rather than shortening. When the diaphragm uses an expiratory brake to maintain the end-expiratory lung capacity, there is eccentric contraction during the expiratory phases of breathing. This happens in two cases: (1) when there is asynchrony, such as reverse triggering or early cycling, and (2) when there is inefficient effort.

4. In experimental models of expiratory myotrauma, it was found that using a high PEEP shortens the diaphragm's final expiratory length, which in turn can lead to sarcomere loss, longitudinal atrophy, and an impaired length-tension ratio [43].

3. Diaphragm Dysfunction-Recognition

Recent research has focused on the identification and early monitoring of diaphragmatic dysfunction in relation to the primary mechanisms of myotrauma, which has allowed for the creation of sensible measures that may reduce or avoid VIDD [41]. (**Figure 1**).

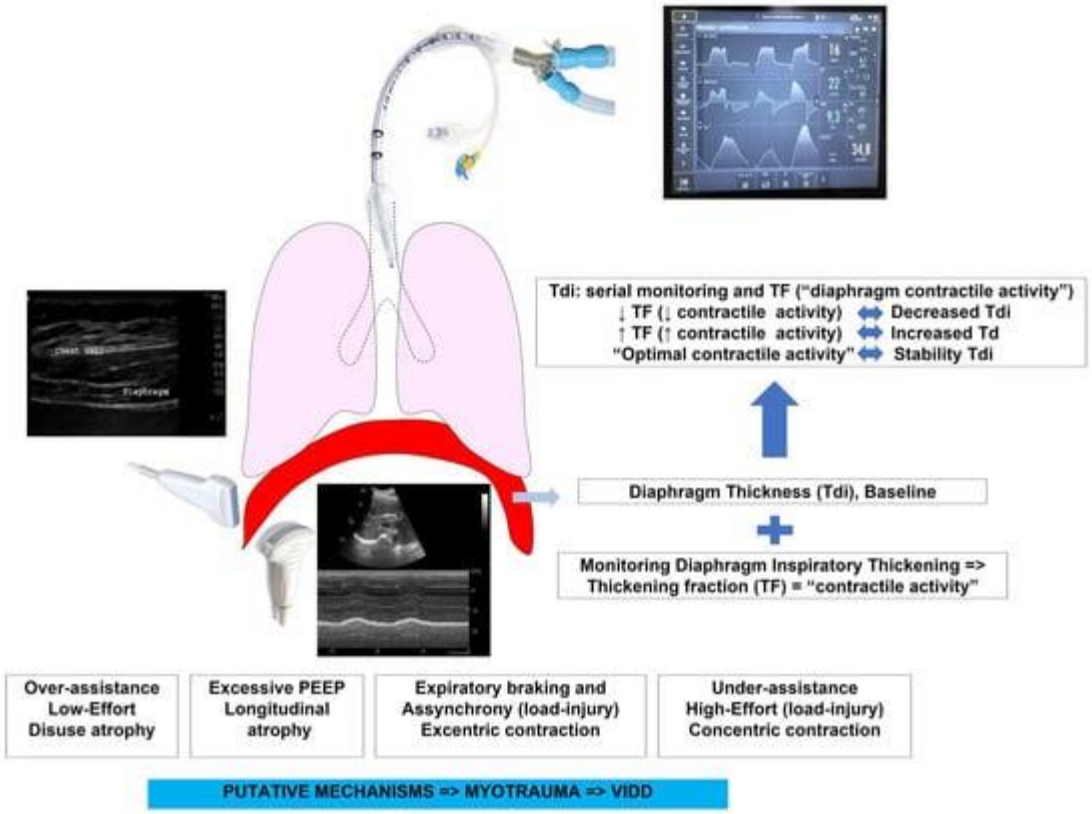

Figure 1. Possible rationale use of ultrasound to monitor diaphragm function in critically ill patients on mechanical ventilation (monitoring effort, assessing atrophy, assessing PVA). TF—thickening fraction; Tdi—diaphragm thickness; PEEP—positive end-expiratory pressure; VIDD—ventilator-induced diaphragmatic dysfunction.

A functional analysis of the diaphragm, with a focus on effort monitoring, is essential for any diaphragm protection plan [20]. Keeping an appropriate inspiratory diaphragmatic effort and limiting various kinds of AVP is the most supported strategy in the current literature [20,41].

The diaphragm's function and activity can be tracked using a variety of methods. Critically sick patients may benefit more or less from these methods depending on their specific characteristics [10,19,44]. Measurements of transdiaphragmatic pressure following magnetic stimulation of the phrenic nerves constitute the gold standard for evaluating diaphragm function. However, this method is not always accessible, necessitating the creation and use of more practical tests. One such test is diaphragmatic ultrasound, which has recently emerged [19,20,41,42].

4. Diaphragm Ultrasound-DUS

The many benefits of diaphragmatic ultrasonography have led to its recognition as a useful tool for evaluating diaphragm function, particularly in critically sick patients [45,46,47]: (a) Diverse ultrasound devices are readily available in intensive care units (ICUs); (b) Due to the portability of ultrasound machines, DUS can be

safely and reliably performed at the patient's bedside without invasive transportation; and (c) the technique has been refined to allow for rapid, accurate, reproducible, and repeatable execution.

The instruments that are utilized for DUS have undergone advancements, specifically, probes with improved resolutions. Reliable pictures of the diaphragm function could also be obtained thanks to the method's standardization and refinement [47,48,49].

4.1. A Concise Overview of Diaphragmatic Ultrasound

The diaphragm is a muscular and fibrous membrane that forms a dome shape. Inhalation relies on this primary muscle. The architecture and function of the diaphragm are the basis for its ultrasonic evaluation. Under inspiration, the diaphragm contracts by shortening, thickening, and stiffening its muscle fibers. This displacement of the entire diaphragm musculotendinous structure lowers the dome of the diaphragm, which in turn moves the abdominal contents caudally and expands the lower thoracic cavity [47].

Two acoustic windows allow the ultrasonography to examine the diaphragm [46,47,50]. (**Figure 2**):

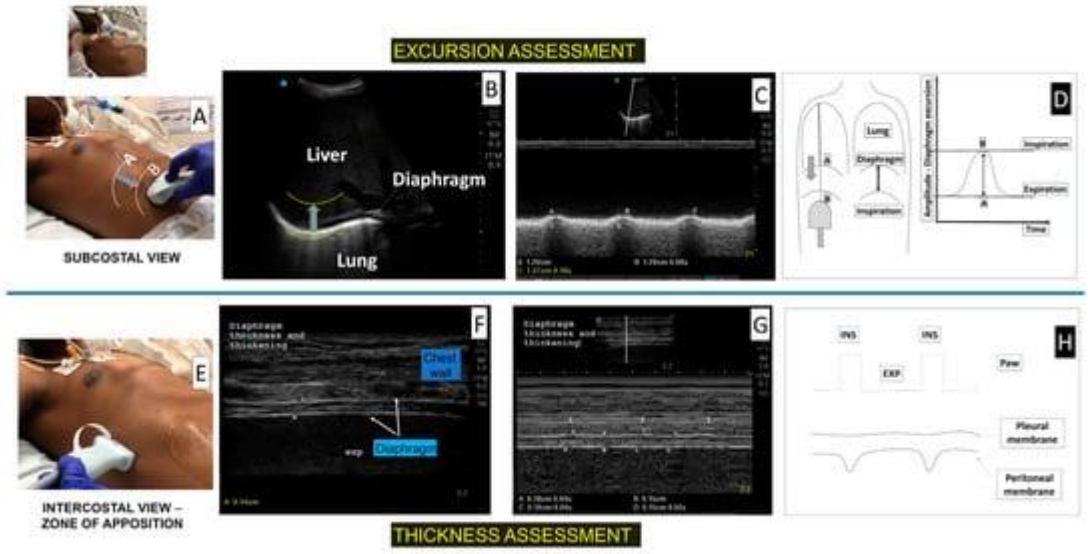

Figure 2. Diaphragm ultrasound to assess excursion and thickness – technique description in a critical care patient on mechanical ventilation. (Panel **A**): Probe positioning on subcostal area. (Panel **B**): Bidimensional view displaying the diaphragm as a white hyperechoic curved line (yellow traced) separating lung from liver. (Panel **C**): M-Mode view displaying a normal excursion during tidal breathing after a brief disconnection of the ventilatory support. (Panel **D**): Graphic illustrative of the excursion measurement. (Panel **E**): Probe positioning on the intercostal area (zone of apposition, ZA)—after positioning the linear probe perpendicularly to the costal wall, we rotated the probe (counterclockwise) to obtain the corresponding ultrasound image on the right. (Panel **F**): Bidimensional view displaying the diaphragm as a hypoechoic structure surrounded by 2 hyperechoic lines (pleural and peritoneal membranes). (Panel **G**): M-Mode view displaying a normal inspiratory thickening of diaphragm during tidal breathing in a critical care patient on mechanical ventilation (I = inspiration; points A and C represent end-inspiratory diaphragm thickness; points B and D represent end-expiratory diaphragm thickness. (Panel **H**): Graphic illustrative of the thickness and thickening measurement.

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A three-layer structure, the diaphragm is seen in the subcostal region as a deeply curved structure that separates the thorax from the abdomen. In the mid-axillary intercostal region, in the zone of apposition (ZA), the diaphragm is surrounded by two hyperechoic membranes, the peritoneum and pleura, and an inner layer of hypoechoic muscle.

Consequently, during the inspiratory contraction of the diaphragm, an ultrasound may reveal: (a) the diaphragm's excursion, or movement down into the subcostal region, during inspiration; (b) the muscle's

end-expiratory thickness, both at rest and during inspiration; and (c) the diaphragm's thickening and stiffening, as seen in the zone of abdominal wall motion.

If there is no suspicion of unilateral malfunction, then a bilateral examination of the right diaphragm is necessary in severely ill patients [48].

Several technical and methodological components of diaphragmatic ultrasonography were the primary focus of a recent expert gathering that aimed to establish a consensus. In order to standardize and universalize the performance of diaphragm ultrasonography, this consensus should be periodically consulted in its application.

During the excursion evaluation, a low-frequency probe (3.5-5 MHz) was placed below the right costal border, between the midclavicular and anterior axillary lines. The probe was then directed medial-cranially and dorsally, following the posterior third of the right hemidiaphragm in two-dimensional (2D) mode. The next step was to position the M-mode exploration line perpendicular to the diaphragm domus. This allowed us to measure the diaphragm mobility by placing calipers at the bottom and top of the diaphragmatic inspiratory slope, which allowed us to track the movement of anatomical structures over time [47,51,52].

As inspiration occurred, the diaphragm drooped craniocaudally toward the probe [46,47,50]. Accordingly, a malfunction was present if there was either no excursion at all or a significantly reduced amount (below lower limits) or if the patient moved paradoxically with respect to the probe.

Assessing diaphragmatic movement and eliminating passive inflation bias by ventilator pressure required briefly disengaging the ventilator (T-tube) or maintaining low levels of CPAP in patients on ventilatory support [46]. It is only during unsupported breaths that diaphragm excursion should be measured, since it could be caused by both the force of the diaphragm contraction and the ventilator's passive lung expansion [53,54].

If a patient is compliant, the best excursion can be determined during tidal breathing and maximal inspiratory effort to evaluate diaphragm dysfunction [55].

In order to measure the thickness of the diaphragm, a high-frequency linear probe (>7-10 MHz) was placed perpendicular to the side of the chest, lying between the midaxillary and anterior axillary lines, and between the 9th and 10th intercostal spaces (apposition zone-ZA). The diaphragm, a layer of hypoechoic inner muscle encased by pleura and peritoneum, is often visible two to four centimeters below the skin's surface on magnetic resonance imaging (MRI). At the end of expiration (Tdi,exp) and inspiration (Tdi,insp), the diaphragmatic pleura and peritoneum distance were measured using the 2D or M-mode, respectively, to determine the diaphragmatic thickness [47,56,57]. The usual diaphragm thickness in healthy individuals has been found to be around 1.5 mm [58], although, in extremely thin healthy women, values as low as 1.2 mm have been recorded [57]. The percentage change in diaphragm thickness during inspiration, expressed as the formula [(Tdi,insp) − (Tdi,exp)/(Tdi,exp)] × 100 [46,47,50], is called the diaphragm thickening fraction (TF).

Thickness fraction (TF) is a measure of diaphragm inspiratory activity (effort) [59,60,61], whereas thickness of the diaphragm (Tdi) can indicate atrophy.

Table S1 in the Supplementary Materials describes the normal ranges for diaphragmatic excursion, thickness, and thickening in healthy people.

4.2. Usage of Diaphragm Ultrasound for Monitoring Respiratory Muscles in Patients in Critical Illness

This review provides a synopsis of the current literature on ultrasonic evaluation of the diaphragm and intercostal spaces, with an emphasis on its potential therapeutic uses in the promotion of diaphragmatic protective MV measures. (**Table 1**).

4.2.1. To Diagnose Diaphragmatic Dysfunction

Ultrasound scanning of the diaphragm can detect malfunction. On dynamic ultrasound, diaphragmatic excursion abnormalities such as decreased mobility (below the reference value), absence, or paradoxical (mostly observed in deep breathing and sniff exercises) are diagnostic of diaphragmatic dysfunction [62]. The

most typical indicator of diaphragmatic dysfunction in severely sick patients on mechanical ventilation is a diaphragmatic excursion less than 10-11 mm [11,63]. (**Figure 3**).

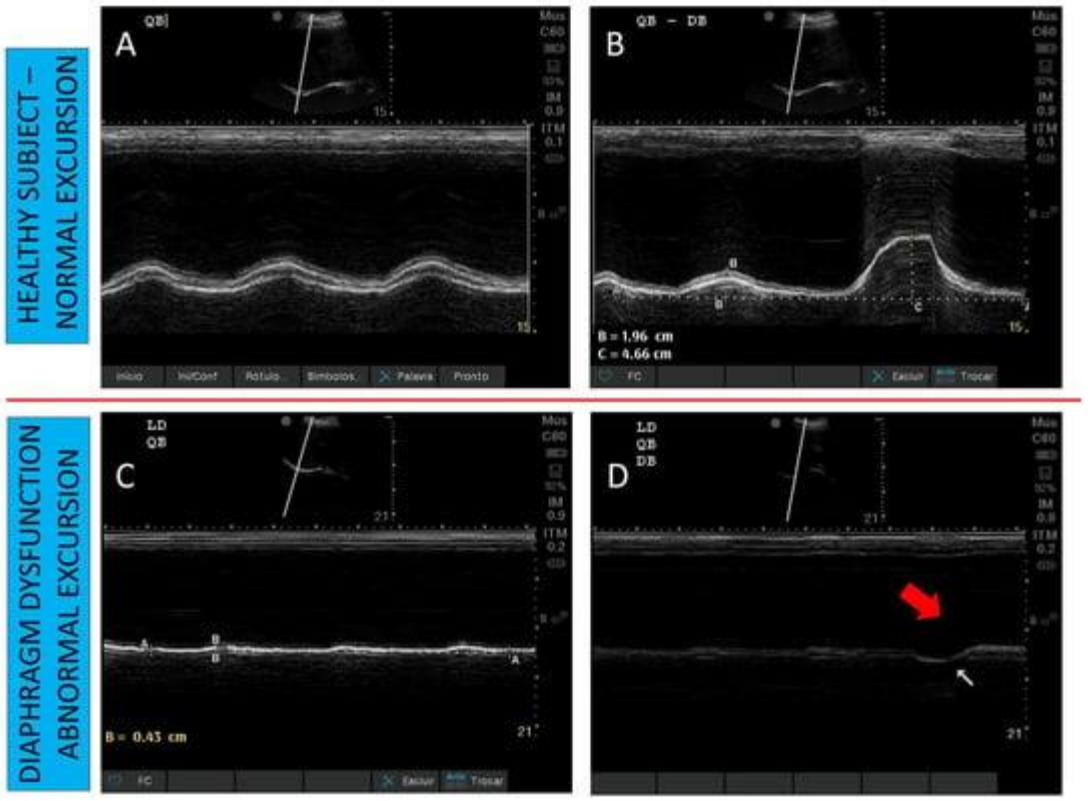

Figure 3. Diaphragm ultrasound to monitor dysfunction according to diaphragmatic excursion. (Panel **A**): Normal excursion during tidal breathing in a healthy subject. (Panel **B**): Normal excursion during tidal and deep breathing in a healthy subject. (Panel **C**): Reduced excursion during tidal breathing in a patient with diaphragm dysfunction. (Panel **D**): Absent excursion during tidal breathing, and paradoxical excursion during deep breathing (red arrow) in a patient with diaphragm dysfunction.

Longer MV and weaning periods, increased mortality, and ultrasound-diagnosed DD are all negative effects. Diaphragmatic thickening fraction values below 20% have also been employed for the diagnosis of DD [64]. Research has shown that patients on MV who are qualified for an SBT had a prevalence of 28-38% for DD [11,37], and that individuals on MV for extended periods have a prevalence of 34% [64]. The results for patients were worse when ultrasound revealed DD [11,63,64]. This included longer MV, weaning failures, and increased death.

The use of a diaphragm ultrasound to detect and track atrophy

The existence of histological atrophy, which is defined as a decrease in the diaphragm fiber cross-sectional area in diaphragm biopsies, can be observed even after a few hours of MV [7,21,24,37], as indicated in both experimental [31,76,77] and clinical investigations. This atrophy is a component of VIDD.

As a non-invasive surrogate for diaphragmatic muscle mass, measuring diaphragmatic thickness at the end of expiration (Tdi) has been utilized in multiple studies to evaluate diaphragmatic atrophy in critically sick patients, particularly those on mechanical ventilation (MV) [45,78]. Further, alterations in diaphragm structure, such as muscle thinning, which may be a sign of atrophy, can be revealed by many assessments of Tdi throughout the days of MV [22,23,34,35,36].

It is challenging to create a cut-off to diagnose atrophy in a single measurement because to the large range of values used to determine the lower limit of Tdi (between 1.6 and 2.3 mm) in both healthy individuals and critically ill patients on MV in different studies [56,57,58,78,79]. One indicator of diaphragm dysfunction is

atrophy, and there is more and more consistent evidence that serial thickness monitoring is relevant to characterize its presence [23,34,35,36,80]. When the diaphragm shrinks by 10% or more in consecutive DUS readings, this is considered atrophy [23,80].

During MV, Goligher et al. [23] tracked 107 adult patients' diaphragm thickness changes. Low diaphragm contractile activity was linked to a decrease in diaphragm thickness (more than 10%) in 44% of patients within the first week, particularly in the first 72 hours after MV. The authors later reevaluated the potential impact of diaphragm atrophy on clinical outcomes of MV [22]. They discovered that atrophy increased the likelihood of problems, led to longer periods of ventilation, and necessitated admission to the intensive care unit.

Later on, additional research did find a correlation between atrophy and MV [35,36]. According to Schepens et al. [35], in a study of 54 adult patients admitted to the intensive care unit (ICU), diaphragm atrophy (a mean change in thickness of 32%) happens shortly after MV begins. The length of MV was correlated with the degree of atrophy [35]. In order to quantify diaphragm atrophy and identify risk factors, Zambon et al. [36] utilized ultrasound to evaluate the diaphragm thickness daily in 40 adult patients, starting from the first day of MV until discharge. A linear link was found between ventilator assistance and a steady decrease in diaphragm thickness, which was measured as a daily atrophy rate. This reduction ranged from -7.5% under regulated mechanical ventilation to +2.3% during spontaneous breathing.

Researchers Vivier et al. [80] measured serial diaphragm thickness in a group of critically sick patients over the course of five days. Diaphragm atrophy, defined as a drop in Tdi of 10% or more, was observed in 48% of patients and was linked to septic shock, organ failure, or invasive MV.

Dot et al. [66] looked at 35 ventilated organ donors to see if expiratory thickness (Tdi) measured by ultrasound could predict diaphragm atrophy, which was defined as a decrease in diaphragm fiber cross-section area (CSA) obtained through diaphragm biopsy. Atrophy was assessed using a single measurement of Tdi. Atrophy (lower CSA) was seen in every single donor group, while a significant drop in Tdi was noted in 74% of those individuals. A high positive predictive value of 96% and a low negative predictive value of 17% were shown by diaphragm Tdi measurement for evaluating the existence of diaphragm atrophy. This means that diaphragm Tdi can detect atrophy but cannot totally rule it out.

A single Tdi measurement, however, can yield useful information in the early stages of serious disease. An unfavorable clinical outcome was linked to a low diaphragmatic muscle mass (baseline Tdi of 2.3 mm or less) as evaluated by ultrasound in the first 36 hours after intubation in critically sick patients on mechanical ventilation, according to a recent study by Sklar et al. [78].

Chapter 4.2.3. Diaphragm-protective ventilation is being monitored by DUS.

Recent years have seen an improvement in our knowledge of the causes of ventilator-induced diaphragmatic dysfunction (VIDD). Along with efforts to prevent VIDD, research is currently focused on techniques to monitor diaphragm function. While early use of assisted ventilation (also known as "spontaneous breathing") appears to reduce the risk of ventilator-associated disease (VIDD), it can be difficult to ensure compliance with mechanical ventilation (MV) and "lung protection" regulations.

Furthermore, prior research has shown that even with assisted breathing, diaphragmatic atrophy can result from lack of use [37,67,77], suggesting that turning on the ventilator is insufficient to avoid this condition. Furthermore, contractility and diaphragm atrophy risk cannot be detected by clinical factors and ventilator settings. [67].

Physiological and epidemiological data primarily support the efficacy of strategies that titrate inspiratory effort and synchronize the patient-ventilator interaction in protecting the diaphragm and lung at the same time [19,20,41,42,44].

To optimize the respiratory effort to accomplish lung and diaphragm protective ventilation, recent research are currently evaluating the viability of techniques on titrating ventilation and sedation [81]. The inspiratory support was adjusted in a recent study [82] according to a range of transdiaphragmatic pressure swings that were predetermined to be "diaphragm-protective" (defined as 3-12 cm H2O). Patients were able to maintain

their predetermined "diaphragm-protective" effort for longer periods of time using this breathing effort-based technique, which did not compromise tidal volumes or transpulmonary pressures.

However, some writers have suggested that the DUS can be helpful in evaluating the diaphragm's contractile activity and, by extension, the respiratory effort [19,20,22,44], even if these earlier research relied on monitoring breathing pressures for respiratory effort titration.

The diaphragm thickening fraction (TF) can be used as a stand-in for the amount of respiratory effort, which is a measure of the diaphragm's contractile activity [22,49]. To lessen the impact of mechanical ventilation on the diaphragm, the ventilatory support can be fine-tuned to prevent either too much or too little support. Maintaining the diaphragm's contractile activity (effort) within physiological limits with ventilatory support titration may avert alterations in diaphragm configuration [22,23]. (**Figure 4**).

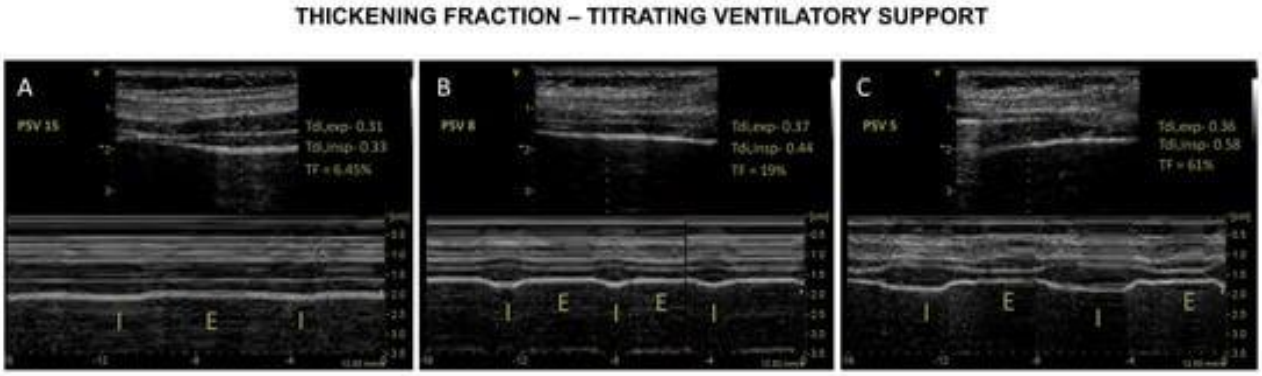

Figure 4. Diaphragm ultrasound to monitor effort. Titrating effort according to thickening fraction (TF). Panel **A**—Reduced TF suggestive of over-assistance (PSV 15 cm H_2O). Panel **B**—"Ideal" TF suggestive of appropriated effort (PSV 8 cm H_2O). Panel **C**—Increased TF suggestive of under-assistance (PSV 5 cm H_2O).

Goligher et al. [23] demonstrated that diaphragm thickness remained constant over time at contractile activity levels normally seen in healthy individuals during resting tidal breathing, even if the ideal level of diaphragmatic activity remains unknown. Diaphragm contractile activity was found to have a direct impact on the change in diaphragm thickness over time in this investigation. This study provides the first direct evidence that diaphragm thickness (Tdi) decreases with increasing contractile activity (TF) and increases with decreasing TF. Subsequent research on this population found that shorter breathing times and consistent muscle thickness were related with TFs between 15 and 30 percent in the early days of mechanical ventilation [22].

These results, in conjunction with research that found a link between TF and diaphragm effort [65,68], provide support for the hypothesis that a TF range of 15-30% may represent a safe limit for effort titration during MV [49].

It should be noted, nonetheless, that there is ongoing disagreement in the literature regarding the validity of using inspiratory thickening fraction (TF) and other aspects of diaphragm ultrasonography as a substitute for diaphragmatic effort.

Since the advent of bilateral magnetic stimulation of phrenic nerves, the measurement of transdiaphragmatic pressure (Pdi), which stands for the specific strength of the diaphragm muscles, has been regarded as the gold standard for diaphragm function [83]. Nevertheless, Pdi measurement has been overlooked in clinical settings because of its challenging use (esophageal and stomach catheters not being readily available, being invasive, and requiring expert interpretation) [84]. One non-invasive method that has been suggested to evaluate diaphragm function is ultrasound, which could help with this [45]. The shortening of muscle fibers during inspiration is facilitated by diaphragmatic contraction and can be quantified and detected in the apposition zone using ultrasonography. One measure of the increase in diaphragm thickness during inspiration is the diaphragm thickening fraction (TF) [46]. Research has shown that people with diaphragmatic paralysis do not experience any thickening of the diaphragm on ultrasonography, which

supports the idea that inspiratory diaphragmatic thickening is a reflection of the magnitude of diaphragmatic effort [54, 85].

When it comes to TF's capacity to gauge diaphragmatic exertion, though, there are conflicting conclusions. In their study of 12 patients who needed scheduled non-invasive ventilation (NIV) following extubation, Vivier et al. [68] looked into the possibility that the thickening fraction (TF) could be a measure of cardiac output. The transdiaphragmatic pressure-time product (PTPdi) was used to assess the effort of breathing in this investigation. At5,10, and 15 cm H2O, patients were assessed while breathing on their own and while receiving NIV. Changes in diaphragmatic thickening correspond with the diaphragmatic work of breathing, as the authors discovered a substantial association between TF and PTPdi.

In a study conducted by Umbrello et al. [54], the effectiveness of using ultrasound-visible diaphragmatic contractile activity (TF) and traditional measures of inspiratory muscle effort (PTPes and PTPdi) during assisted mechanical ventilation (MV) was examined in 25 patients admitted to the intensive care unit (ICU) following major elective surgery. The patients met the criteria for a trial of spontaneous breathing with pressure support (PS) ventilation at different levels of PS (0, 5, and 15 cmH2O). During tidal breathing, the authors noticed that diaphragm TF, PTPes, and PTPdi all decreased in tandem with rising PS levels. There was a strong correlation between diaphragm TF and PTPes and PTPdi. The diaphragm excursion was uncorrelated with any index.

In a validation research, Goligher et al. [45] looked at five healthy people to see how EAdi, the diaphragm's electrical activity, was related to the diaphragm thickening fraction. Positive correlations were found between the TFdi and EAdi. The lack of diaphragm thickening at inspiratory volumes less than 50% of inspiratory capacity is an indication that, at clinically significant inspiratory volumes, diaphragm thickening is due to muscular contraction and not passive insufflation.

Umbrello et al. [73] compared the fluctuation in diaphragm thickening (TF) and parasternal intercostal thickening (TFic) with that in esophageal (Delta Pes) and transdiaphragmatic (Delta Pdi) measurements and their derivatives (esophageal pressure-time products (PTPes), transdiaphragmatic (PTPdi), and work of breathing (WOB)) in 21 critically ill patients on mechanical ventilation (MV) with pressure support (PS). Baseline, 25%, and 50% reduction levels of PS were all measured. The authors discovered a slight link between TF and esophageal PTP. However, after removing patients with diaphragm dysfunction, as described by the Gilbert score, this correlation became stronger.

The links between thickening fraction and respiratory effort were not found in the research cited below, in contrast to the aforementioned investigations [45,54,68,73].

Using 13 healthy volunteers and an inspiratory overload protocol ranging from 0 to 50% of maximal inspiratory pressure, Oppersma et al. [86] validated speckle tracking (strain and strain rate) to compare the inspiratory diaphragmatic effort to the diaphragm thickening fraction. Not only that, but EAdi and Pdi, or transdiaphragmatic pressures, were documented as well. Gradual diaphragm loading caused strain and strain rate to rise. While inspiratory load fluctuations had no effect on TF and it did not connect with EAdi or Pdi, strain and strain rate were substantially linked with Pdi and EAdi, respectively.

In a study conducted by Poulard et al. [87], the diaphragmatic thickening fraction (TF) and transdiaphragmatic pressure (Pdi; the PTPdi was calculated) were examined in 14 healthy subjects and 25 mechanically ventilated (MV) patients with varying pressure support settings. The subjects were given varying amounts of external inspiratory threshold load variations. They discovered a moderate correlation between TF and alterations in Pdi and PTPdi in healthy individuals. The limited correlation between changes in Pdi and TF in MV patients suggests that TF could not deduce the pressure output.

The possibility that the ultrasound-measured diaphragmatic excursion (DE) and thickening fraction (TF) could represent the change in esophageal pressure (Delta Pes) during CPAP ventilation in 46 patients admitted to the hospital with COVID-19 pneumonia was recently explored by Steinberger et al. [88]. Delta Pes was not found to be associated with DE or TF, although there was a slight link between changes in Pes oscillation and changes in TF between PEEP and ZEEP.

These contentious conclusions might originate from a variety of sources. (1) Study population heterogeneity: Goligher and Oppersma [45,86] looked at healthy people, Poullard [87] at a combination of healthy people and people on mechanical ventilation; however, other studies focused on certain patient groups, such as those requiring planned non-invasive ventilation after extubation [68], patients admitted to the intensive care unit after major elective surgery who were eligible for a surgical blood transfusion [73] and patients with COVID-19 pneumonia on continuous positive airway pressure (CPAP) [88]). In order to determine effort, the investigations used varying protocols of inspiratory loading in healthy people [86,87], who were able to recruit their respiratory muscles in a variety of ways. Three, different combinations of lung volume and chest wall compliance could be the focus of patient investigations [54,68,73]. There was no testing for diaphragm dysfunction (DD) in the Steinberg trial [88], but DD may affect the correlation between diaphragm thickening and inspiratory effort in severely sick patients [73]. (5) The association between the thickening fraction and a variety of PTPdi values is well-known; this could indicate that individuals differ in the amount of diaphragmatic contraction and the work of breathing that results from it [86].

While these debates highlight the need for caution when using TF as a replacement for respiratory effort, we are of the belief that TF provides a reasonable alternative for measuring respiratory effort, which is crucial for avoiding diaphragmatic myotrauma, based on Goligher's findings that link changes in diaphragm configuration (as measured by Tdi) with diaphragmatic contractile activity (as measured by thickening fraction) [22,23].

5. Patient–Ventilator Asynchrony (PVA)

When there is a discrepancy in the amount, velocity, pressure, or time that the patient exerts themselves and the amount of air that the ventilator really delivers, this is called patient-ventilator asynchrony (PVA) [89].

PVA is underrecognized and untreated despite its prevalence; it affects as many as 25% of patients on mechanical ventilation [49,90,91].

Problems with breathing, auto-PEEP, pulmonary gas exchange, sleep (both quantity and quality), and worse outcomes (more sedation and neuromuscular blockade use, longer MV, longer duration of MV, and increased mortality) are all linked to PVA [90,92,93,94,95].

PVAs typically arise from an imbalance in the inspiratory flow, a mismatch between the patient and ventilator during the phases of the inspiratory cycle's trigger (ineffective effort, self-trigger, and double trigger) and its end (premature or delayed cycling) as well as an imbalance in the inspiratory flow itself (insufficient or excessive) [89].

PVA may influence diaphragm function and is thought to be one of the pathways connecting myotrauma (MV) to diaphragm weakening [19].

In a perfect world, the diaphragm would allow for the patient and ventilator to work in perfect harmony, without any asynchrony [89]. It has only been recently proven that measuring respiratory effort is necessary when performing MV with diaphragm and lung protection [41]. Since the DUS measures the diaphragm's contractile activity, or thickness fraction, it can be a useful tool for assessing respiratory effort and identifying structural changes in the muscle [4].

The primary processes linked to myotrauma include, as mentioned earlier, the following: eccentric contraction during expiration, longitudinal atrophy, over-assistance leading to suppression of respiratory effort and disuse atrophy, and under-assistance leading to high effort and load injury during inspiratory concentric contraction and the expiratory phase, respectively.

Eccentric contraction is the main cause of muscular damage linked with PVA [4]. When there is a mismatch between the inspiratory and expiratory phases of a patient's breathing, it can lead to inefficient effort during inspiration, which in turn can cause eccentric or plyometric contractions (contractions that happen during fiber stretching) and damage to the diaphragm muscle fibers [96,97].

Visual examination of the mechanical ventilator's airflow, volume, and pressure data may indicate asynchrony, but this approach may miss PVAs [1,12].

By accurately assessing the patient's inspiratory muscle work and ventilatory supply, esophageal pressure monitoring (Pes) is the gold standard for detecting PVA. But Pes monitoring is still in its infancy due to its technological challenges and frequent unavailability (e.g., strict control of esophageal balloon volume and placement) [89,98].

Similar to Pes in terms of its limits to use in everyday practice (unavailability, invasiveness, specific training for interpretation) [49], diaphragmatic electrical activity (EAdi) is another instrument advised for monitoring PVA and is also regarded a reference technique [99]. Auto-triggering, double-triggering, early-or late-cycling, and wasted attempts are all things that EAdi monitoring can pick up on.

As the variations in pleural pressure are determined by the inspiratory diaphragmatic activity (contraction), some have proposed that DUS can be utilized to detect PVA by simultaneously monitoring the diaphragm's function and breathing pattern [48,49].

Three patients were evaluated for patient-ventilator asynchrony by Soilemezi et al. [100] using airway pressure and diaphragmatic displacement (DUS) recorded simultaneously. In this method, three examples of asynchrony detection are shown: (a) a patient with double triggering, where the ventilator delivers two breaths for every one the patient makes an effort; (b) a patient with ineffective efforts, where the inspiratory effort of the next breath is triggered by mechanical breaths rather than intrinsic positive end-expiratory pressure (when the patient's efforts are triggered by long insufflation times and a shortened expiratory phase caused by excessive ventilatory assistance and long insufflation times). Because continuous recordings are not readily available, this technique has a significant restriction.

When an aided breathing cycle is detected without inspiratory thickening, simultaneous measurement of TF and Paw may imply an auto-trigger PVA [48,49].

In order to find PVA, Vivier et al. studied the efficacy and precision of a novel approach that uses ultrasound to detect diaphragm excursion (DE) or thickness in conjunction with airway pressure. When compared to diaphragm EMG, this method (particularly diaphragm thickening) improved the accuracy and feasibility of detecting patient-ventilator asynchronies compared to flow and pressure waveform analysis alone [101].

It should be mentioned that additional research is necessary to establish the precise function of DUS [46,100], even though it could be a viable alternative to detect the majority of PVA types [49].

6. Role of Ultrasound of the Diaphragm in the Assessment of Weaning

As the ventilatory assistance is gradually reduced during weaning off MV, the respiratory muscles, especially the diaphragm, are challenged. There is an increase in morbidity and mortality associated with unsuccessful weaning from MV [102,103].

An insufficient respiratory system capability is the primary reason why weaning fails [104]. Finding out whether patients are good candidates for weaning helps minimize two problems: first, the needless use of MV with all its hazards, and second, the risks and complications of early weaning. In order to determine if patients are prepared to wean off of MV, this characterization makes use of clinical criteria, often known as "readiness testing" [103]. Yet, there are cases when readiness testing raises doubts about the patient's weaning abilities; in such cases, physiological tests and weaning predictors can help determine whether the patient is ready to wean or not [104].

Ultrasound evaluation of diaphragmatic function has been utilized as a weaning predictor, mainly as a diagnostic tool for predicting the outcome of extubation [50,105].

Using the DUS to evaluate weaning prediction has been the focus of a great deal of research; in fact, meta-analyses and systematic reviews have been published on the topic [50,105,106,107].

Diaphragm excursion cut-off values between 11 and 14 mm [11] and a thickening fraction of less than 30 to 36 percent [108] were associated with successful extubation or weaning failure in the first research.

In a recent study, however, Vivier et al. [80] evaluated the reliability of diaphragmatic excursion and thickness as extubation predictors. In 191 patients who were able to undergo a successful SBT, a DUS was conducted prior to extubation using a T-tube. There was no correlation between diaphragmatic dysfunction, which is defined as excursion less than 10 mm or thickness less than 30%, and a higher likelihood of

extubation failure. Additionally, a recent study by Vetrugno et al. [109] showed that in 57 COVID-19 patients who were weaned off MV, diaphragm thickening fraction (TF) did not indicate weaning failure.

Assuming the results are contentious, drawing broad inferences about the utility of DUS to forecast weaning from MV is not permitted at this time.

Population and study design variability, as well as the characterisation of the variables under examination, appear to be the main sources of disagreement. The following factors greatly affect the comparability of outcome measures: (1) the timing of the ultrasound assessment in respect to the spontaneous breathing test (SBT), (2) the patient's position during the SBT, (3) the lack of standardization in the diaphragm evaluation technique with ultrasound in ventilatory support patients (PEEP levels, pressure support), and (4) the different definitions of SBT failure, weaning failure, or extubation failure.

In addition, a large number of patients whose diaphragmatic dysfunction was detected on DUS may be safely removed from the ventilator. it seems that variables other than diaphragmatic function dictate extubation in individuals undergoing a successful SBT [10].

Additional research is required to standardize certain points in the technical aspect [48] and also to address the clinical question [110]. Despite the fact that diaphragmatic ultrasound is a promising diagnostic tool, its role in predicting weaning remains unclear. Here are some suggestions: - Patients at high risk of weaning failure should undergo DUS before SBT.

DUS is most useful for predicting weaning success or failure or for determining why a weaning attempt was unsuccessful when done after an SBT has begun or finished.

7. Novel Techniques and Future Developments for Functional Imaging and Quantification of Tissue Properties

7.1. Tissue Doppler Imaging

Tissue Doppler Imaging (TDI) is a relatively new ultrasound technology that has only lately found utility in evaluating the diaphragm in adults [111] and neonates [112]. It is already extensively used to evaluate cardiac function.

In a study that has received little attention, Soilemezi et al. [113] reported intriguing findings. The researchers studied a group of healthy volunteers (n = 20) to describe the pattern, report normal values, and evaluate the repeatability of diaphragmatic TDI waveform velocities during contraction and relaxation. Additionally, this study compared instances of successful and unsuccessful weaning and recorded the pattern and values of diaphragmatic TDI in 106 intubated patients in the intensive care unit who opted for a spontaneous breathing test. In a subgroup of 24 patients, the authors correlated TDI measurements with parameters derived from transdiaphragmatic pressure (Pdi). Normal volunteers, patients with successful and unsuccessful weaning, and the results showed the patterns of diaphragmatic contraction and relaxation as measured by the TDI. Notably, compared to healthy individuals and weaning success patients, weaning failure patients showed noticeably higher PCV and TDI-MRR velocities; hence, weaning failure was more likely when PCV and TDI-MRR values were higher. Also, in the Pdi-evaluated patient subgroup, TDI PCV showed strong correlations with peak Pdi, PTPdi, Pdi-MRR, and TDI-MRR. This study provides new information about the non-invasive physiological behavior of individuals experiencing weaning failure.

In their study, Cammarotta et al. [111] examined 100 adult participants who successfully completed a 30-minute spontaneous breathing trial (SBT) to see if the diaphragmatic function, as measured by TDI (exion velocity and acceleration), could be used to distinguish the success of extubation (after 48 hours). At the conclusion of the SBT, the TDI test was run. They discovered that: (1) TDI values, which were obtained at the end of an SBT, might predict which patients were more likely to have extubation failure within 48 hours after the procedure (those patients had considerably higher dTDI variables compared to those patients who were successfully extubated). After a successful SBT, the inspiratory peak and mean velocity were strong indicators of extubation failure; TDI evaluation was doable and reproducible.

Despite the promising early findings, there is still a long way to go before the procedure is standardized. This includes things like identifying the ROI of the diaphragmatic movement, controlling for confounding variables like rib cage compliance and the activation of accessory inspiratory and expiratory muscles [114].

section 7.2. STUS, or Speckle Tracking Ultrasound

While there are established ways to measure diaphragmatic excursion, diaphragm thickness, and thickening fraction (TF) on ultrasound, these methods only measure the transverse axis deformation of diaphragmatic muscle tissue and do not evaluate the 'longitudinal' shortening of the muscle, which is the movement in the direction of the contracting fibers.

One novel analytic approach that has found widespread usage in echocardiography is speckle tracking ultrasound (STUS) [115]. STUS enables the observation of longitudinal muscle fiber contractions.

Muscle tissue that shows a consistent gray pattern on ultrasonography is called a speckle. Following a cluster of speckles during the contractile cycle and monitoring their displacement and deformation (the movement of the speckles relative to each other) is the basis of the STUS software's analysis. "Strain" refers to the extent of deformation, while "strain rate" quantifies the rate of deformation. Tracking can distinguish between passive movement and active contraction, and STUS is thought of as being somewhat angle independent due to its ability to follow specific areas of interest.

Various scenarios were used to test the applicability of STUS in investigating diaphragm movement.

Using inspiratory thickening fraction (TF) and diaphragm deformation (transverse strain) in STUS as a measure of respiratory load, Hatam et al. [116] examined 13 healthy adults who underwent NIV with CPAP (CPAP 5, PSV 5, 10, and 15) or without assistance (spontaneous breathing). They discovered that transverse strain was positively linked with TF and that both transverse strain and TF were considerably elevated under CPAP and PSV.

In a study conducted by Oppersma et al. [86], the researchers examined the use of speckle tracking ultrasonography to measure diaphragm contractility. Thirteen healthy volunteers were subjected to an inspiratory overload protocol, with the pressure levels ranging from zero to fifty percent of the maximal inspiratory pressure. In addition, the thickening fraction, EAdi, and Pdi, or transdiaphragmatic pressures, were documented. They discovered that as the diaphragm was loaded more gradually, strain and strain rate rose, but TF remained constant. There was a strong correlation between strain and strain rate with Pdi and EAdi, but no such correlation with TF. When it came to measuring diaphragmatic contractility during inspiratory threshold loading, STUS outperformed traditional ultrasound methods (TF) in this research.

Using diaphragm thickness, thickening fraction (TF), and excursion (diaphragm caudal displacement), Orde et al. [117] compared the usefulness of STUS parameters (longitudinal strain) for analyzing diaphragmatic contraction in healthy individuals (n = 50). Right diaphragmatic longitudinal strain was shown to be moderately correlated with TF, whereas strain and excursion were found to be weakly correlated. For TF, excursion, and strain, the inter- and intra-rater reliability was satisfactory.

Xu Q et al. [118] conducted a study to assess the practicality and repeatability of using STUS to measure diaphragm longitudinal strain (DLS). The study included 25 healthy subjects and 20 patients on mechanical ventilation. The second study sought to determine if the maximum DLS could be used to predict weaning outcomes. The third study was a multicenter retrospective involving 96 patients who chose to wean, 56 of whom were successfully weaned. Under eupnea, deep breathing, and MV settings, intra- and inter-operator dependability ranged from good to exceptional. Both diaphragmatic excursion (DE) and diaphragmatic thickening fraction (TF) showed a somewhat linear relationship with DLS. The area under the receiver operating characteristic (ROC) curves of DLS was comparable to that of TF for the prediction of successful weaning, but it was not better than the rapid shallow breathing index.

In order to identify diaphragm dysfunction, which would be indicated by a reduction in strain and strain rate parameters, Fritsch et al. [119] assessed the practicability of STUS for a diaphragm evaluation in a group of 20 patients following a coronary artery bypass graft treatment. Before surgery, within 24 hours, and 48 hours following extubation, all patients underwent three separate ultrasonographic evaluations. Results showed

that strain, the deformation of the diaphragm, decreased after around 24 hours, whereas strain rate, the contractile velocity, stayed the same or even went up. A shift in the pattern of diaphragmatic fiber recruitment, which may indicate heightened activation of type II fibers, was thought to be responsible for the accelerated strain rate.

The STUS has not been validated in a major study, despite the encouraging results. Moreover, STUS analysis software is "closed boxes" that must be opened in order to reveal myocardial deformation. It was difficult to apply the results to a clinical setting because many studies relied on offline analysis, which took a lot of time. It is possible that more research comparing STUS to electromyography or transdiaphragmatic pressure measures in patients with impaired diaphragmatic functionand/or severe sickness is required.

7.3. Elastography via Shear Waves

Using a focused acoustic impulse beam produced by the ultrasound probe, shear wave elastography (SWE) causes tissue deformation and the quantification of a shear wave, which is then converted into shear modulus (SM), a novel method for evaluating the diaphragm.

The SM is a novel way to translate qualitative data regarding the diaphragm muscle's characteristics because it conveys tissue biomechanical information. Tissue stiffness is increased with increasing SM.

The diaphragmatic contractile activity was replicated by SWE in two prior investigations involving healthy volunteers.

At 15, 30, 45, 60, and 75% of the maximal inspiratory mouth pressure, Chino et al. [120] examined the diaphragm function using SWE (shear modulus, SM) in 14 healthy male volunteers. The tests were conducted at varying levels of submaximal inspiratory effort. The researchers discovered that when mouth pressure increased, diaphragm SM also increased, but surprisingly, the rate of SM rise decreased. Bachasson et al. [121] found similar results when they compared the measurement of transdiaphragmatic pressure (Pdi) with SWE (diaphragm shear modulus quantification, SMdi) in order to evaluate diaphragm function in 15 healthy volunteers who were put through an inspiratory load protocol. Aarab et al. [122] examined the relationship between changes in diaphragm thickness and changes in shear modulus (SM) in patients admitted to the intensive care unit (ICU). They also described histological and force-producing changes in the diaphragm in an experimental model. The researchers discovered that the mean Pdi was correlated with the mean SMdi and that changes in diaphragm stiffness measured by SWE mirrored changes in Pdi. The piglets that were part of this translational trial were mechanically ventilated and included 102 critically unwell patients (n = 88), with transdiaphragmatic pressure and diaphragmatic biopsies taken from them. Diverse patterns of diaphragm design modifications were noted in the study. In terms of thickness (86% of patients) and SM (92% of patients), it was usual for patients to experience a change of more than 10% from the beginning. The SM went up for 51% of patients, stayed the same for 8%, and went down for 41%. In patients in critical care, there was an inverse relationship between SM alterations and diaphragm thickness changes. An interesting observation was that in the experimental model, weakening, lipid buildup, and diaphragm atrophy were all linked to a lower SM.

Despite the importance of SWE research, further work is required to standardize the technique (ideal probe location, influence of lung volume, moment of measurement of MS in relation to the respiratory cycle, etc.) and to expand studies in different models and scenarios to understand the method's pathophysiology [123]. Aarab's [122] findings are noteworthy and seem to support the concepts of diaphragmatic myotrauma.

8. Limitations

When interpreting the results of an ultrasonography study on diaphragm function, it is important to keep in mind the method's limits, despite its many benefits. Both the patient's posture [56] and the operator's skill with ultrasound [124] play crucial roles in the acquisition and interpretation of the images. Recent research by Garofalo et al. [126] and other studies involving critical care patients [127] indicate that training can improve ultrasound skills with a relatively short learning curve and satisfactory outcomes [108,125]. This is particularly true when the training combines theory and practice. In regards to the concerns regarding patient positioning, while different positions can affect the diaphragm thickness in healthy individuals,

Baldwin et al. [79] found good reproducibility (ICC = 0.990, 95% confidence interval: 0.918-0.998) when measuring the end-expiratory diaphragm thickness in a semi-recumbent position, which is typical for critically ill patients. Measurement consistency (guarantee repeatability) can be improved by demarcating the placement of the ultrasonic probe [23]. This is done in light of the worry over fluctuations in diaphragm thickness along the surface of the muscle [129,130] in serial measurements. Because of the smaller window of the spleen [23] and intensive care unit patients [45], it is acknowledged that viewing the left diaphragm is more challenging. A surprising number of critically ill patients actually have changes in the pleura (effusions) and/or the lungs (consolidations or atelectasis) that make hemidiaphragms easier to spot than one would think [46]. A recent expert agreement states that when evaluating critically ill patients, it is permissible to unilaterally check the right hemidiaphragm instead of the complete diaphragm, unless there is suspicion of unilateral involvement, in which case bilateral assessment of the diaphragm is necessary [48]. Obese people may have trouble seeing their diaphragms with ultrasound because of a narrow acoustic window [47,131,132]. The DUS does not directly measure ventilatory force, likely due to the fact that other inspiratory muscles of the ribcage may partially contribute to ventilation, interfering with the diaphragm's contribution [51], although a correlation between the thickening fraction and inspiratory strength has been observed in healthy subjects [57]. The use of ultrasound to evaluate diaphragmatic function has, nevertheless, shown a plethora of significant clinical implications for the prognosis of severely sick patients. A group of experts got together not long ago to document the key points about the ultrasound technique that need to be understood in order to make the right interpretation, with the goal of overcoming the tool's primary limitations [48]. The referenced works do not all adhere to the same standards whether it comes to research design, method standardization, patient selection, or comparison with a reference gold standard method.

9. Future Directions

The widespread use of ultrasonography in clinical practice is still in its early stages, despite the fact that it has undergone considerable evolution in recent times. Potentially better transducers and machine setups should allow for better visualization and assessment of factors in critical disease. More research comparing sonographic diaphragm findings with non-invasive:

-Histological findings of the muscle,

-Interaction with other respiratory muscles,

-Reference tools for PVA detection, and

-Baseline measures of respiratory effort (such as work of breathing, PTP) and fatigue (such as TTI and relaxation rate). Also, a technical improvement that allows automated image acquisition can make it a genuine monitoring tool.

Ultrasonographic Assessment of Parasternal Intercostal Muscles

When the diaphragm is weak, patients may try to make up for it by engaging the parasternal muscles. Using diaphragmatic ultrasonography in conjunction with measurements of parasternal intercostal muscle thickening (Tic) and intercostal muscle thickening fraction (TFic), one may anticipate whether or not a patient will be able to wean off MV [70].

A linear probe (10–15 MHz) placed three to five centimeters laterally from the sternum can evaluate the parasternal intercostal muscles. Placing the probe transversely in the sagittal plane, exactly between the 2nd and 3rd ribs, is the correct orientation. The linear probe, for instance, is angled at a right angle to the front surface of the thorax in the longitudinal scan of a patient lying down with a 20° head-up tilt [70,71]. Because it is more practical, most ultrasound assessments of the parasternal intercostal muscles are carried out on the right side of the body [72]. The evaluation of intercostal muscles can be accomplished using M-mode and B-mode ultrasonographic techniques, which are similar to diaphragmatic ultrasonography.

B-Mode Ultrasonography

The pleural line, which is an identifiable part of the "bat sign" [72], is readily seen in B mode. A three-layered, biconcave structure, the parasternal intercostal muscle is visible just above the pleural line. Two linear hyperechoic membranes, one extending from each side of the neighboring ribs, and one in the middle

showing muscle echotexture make up these layers [70,73]. This mode allows for the measurement of the intercostal muscle thickness (Tic) between the muscle fascial borders of the inner and outermost hyperechogenic layers. At the craniocaudal midpoint between the ribs, however, when the curvature difference is at its minimum, thickness measurements should be taken [74].

Additionally, ultrasonography provides indirect qualitative information on muscle composition through the use of grayscale [75]... Furthermore, increased echogenicity in muscles is an indicator of lower quality muscles [73]. To standardize the methodologies, a strict ultrasound setup must be determined before acquiring the image, as echogenicity assessments are more influenced by observer-dependent factors compared to other metrics [74].

M-Mode Ultrasonography

In the same way that the TFdi may be evaluated, the inspiratory muscle contraction can be located using M-mode ultrasonography. Inhalation causes the fibers of the muscles to contract, which leads to a noticeable increase in muscular thickness. The total mass of the muscle stays the same when the rib cage is lifted and pushed forward by this contraction. In the same way as the diaphragm thickening fraction (TFdi) is calculated, the parasternal intercostal muscle-thickening fraction (TFic) can be determined by multiplying the following formula by 100 [74]:

TFic=(Tic−insp)−(Tic−exp)(Tic−exp)TFic=Tic−insp−(Tic−exp)Tic−exp

2.3.3. Application of Parasternal Intercostal Muscle Ultrasound in the Weaning Process

Diaphragmatic ultrasonography has been the subject of a great deal of research on the topic of MV weaning prediction [52,53,54]. Despite this, there is a dearth of research on the topic of parasternal intercostal muscle ultrasonography as a tool for gauging weaning success.

Patients who have weak diaphragms may try to make up for it by engaging their parasternal muscles more than usual. When looking at patients on mechanical ventilation, Dres et al. found that TFic values were associated with an increased risk of failing to complete an SBT. When comparing patients who did and did not pass the SBT, we found that those who did not had lower TFdi values and higher TFic values. And TFic levels changed with ventilation support level, being higher in people with diaphragmatic dysfunction compared to those without trouble. If the TFic value is more than 8%, it signifies diaphragm dysfunction, and if it is more than 10%, it means the weaning process is going to fail [70]. In line with these results, Umbrello et al. found that low TFdi values were linked to high TFic values, which implies that the intercostal muscles are recruited due to the increased respiratory exertion caused by diaphragmatic dysfunction, as validated by the Gilbert index. On the other hand, depending on the amount of mechanical assistance, lower TFdi readings can indicate either a lack of inspiratory effort or an increase in inspiratory effort by accessory respiratory muscles. We can differentiate between the two possibilities when weaning from MV by using ultrasound to measure TFic. Patients without diaphragmatic dysfunction had lower TFic (~5%), and larger TFdi (>30%), according to this study [71]. Additionally, Umbrello et al. investigated whether a shift in TFdi or TFic may be utilized to gauge inspiratory effort in critically sick patients when mechanical support levels are decreased. Excluding individuals with diaphragm dysfunction from the analysis led to a significant improvement in the TFdi assessment of inspiratory effort, which was previously only satisfactory. In addition, they discovered that TFic was useful for evaluating inspiratory effort at the bedside, especially when the TFdi was low [71].

The current evidence is preliminary, but parasternal intercostal ultrasound, when combined with other parameters after proper training, may help clinicians predict weaning outcomes, especially in patients who use their accessory respiratory muscles without assistance. Nevertheless, there is a lack of data to determine the most reliable reference values for weaning result prediction. In order to evaluate patients' progress while switching from controlled to assisted ventilation and to create evidence-based guidelines in the intensive care unit, we suggest that future research look at the effects of integrating parasternal intercostal ultrasonography with diaphragm ultrasound.

10. Conclusions

Many negative outcomes in severely sick patients on mechanical ventilation are associated with diaphragm dysfunction, which occurs often. Strategies to prevent myotrauma have recently given rise to the idea of diaphragm protection. The foundation of this protection technique is monitoring diaphragmatic function and diagnosing malfunction. One additional and possibly valuable technology is diaphragm ultrasonography, which could let you monitor the diaphragm's function at the bedside and adjust the ventilator settings for safe diaphragm ventilation.

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