Application of Ultrasound in the Weaning Process of Mechanical Ventilation

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Conflict of interest: None declared

Funding: No funding sources

Abstract

Background: Weaning patients from mechanical ventilation (MV) is a complex process that may result in either success or failure. The use of ultrasound at the bedside to assess organs may help to identify the underlying mechanisms that could lead to weaning failure and enable proactive measures to minimize extubation failure. Moreover, ultrasound could be used to accurately identify pulmonary diseases, which may be responsive to respiratory physiotherapy, as well as monitor the effectiveness of physiotherapists' interventions. This article provides a comprehensive review of the role of ultrasonography of Parasternal Intercostal Muscle during the weaning process in critically ill patients.

Keywords: Parasternal Intercostal Muscle, Ultrasound, Mechanical Ventilation

Tob Regul Sci.™ 2023 ;9(1): 7164 - 7183

DOI: doi.org/10.18001/TRS.9.1.507

1. Introduction

In order to successfully wean a patient off of a ventilator, it is necessary to gradually reduce the patient's reliance on the device until the patient can breathe on their own. The steps involved in this procedure are as follows: extubation, correct weaning, and readiness testing [1]. According to the WIND trial, a patient is considered to have successfully weaned and extubated if they do not require reintubation for at least 48 hours following the endotracheal tube's removal [2,3] or if they do not retubinate or die within 7 days following extubation [4]. Recent research indicates that only 65% of babies are able to be weaned successfully; however, this number might fluctuate greatly depending on the patient's condition and level of preparedness [1]. Several pathophysiological variables can affect the outcome of weaning attempts [5]. Patients in critical care generally exhibit a constellation of symptoms, such as problems with the lungs and cardiovascular system, alterations to the chest wall, weak peripheral muscles, decreased respiratory drive, and neurological deficits that impact the changeover from mechanical ventilation to spontaneous breathing [6].

It is difficult to determine the optimal time to remove the airway from critically sick patients since doing so too soon raises the risk of weaning failure, which in turn increases the risk of reintubation and puts patients at risk of hemodynamic instability and respiratory distress [7]. Nevertheless, there are additional dangers, including tracheal injury, ventilator-associated infections, and barotrauma, as well as an increase in the duration of mechanical ventilation (MV), when extubation is delayed [8]. Thus, it is crucial for patient outcomes to ensure safe and effective weaning of patients.

Several bedside indices for successful weaning and extubation have been proposed in current guidelines. Weaning success can be predicted using any of these indices, although none of them have been shown to be optimal [2]. Weaning success can be better anticipated with the use of a spontaneous breathing trial (SBT) [9]. In patients with a normal body mass index (BMI), supplemental positive end-expiratory pressure (PEEP) of 5 cm H2O is not required during the observation period of patients breathing through a T-piece with reduced pressure support (PS) or adequate supplemental oxygen [3,10]. In particular, re-intubation is necessary for 20% of high-risk patients who have a successful SBT [10]. In high-risk patients, the rates of reintubation were not different when SBT was performed using a T-piece or pressure support ventilation (PSV) [11]. Weaning failure causes are not always easy to pin down, even though SBT is safe and can shorten the time MV is needed, which in turn reduces critical care expenditures and difficulties [12]. Because it provides real-time, non-invasive imaging of many bodily organs, ultrasonography enables direct bedside assessment of many of these reasons, including heart, lung, or muscle dysfunction. To observe its interior architecture and track its dynamic changes, it employs high-frequency sound waves that vary with the chosen probe [13].

The purpose of this review is to go over the various ways ultrasonography (US) can be used to evaluate the weaning process from MV. In this article, we shall examine its function in determining the efficacy of respiratory physiotherapy, airway preparedness, hemodynamic stability, and lung aeration.

2. Ultrasonographic Assessment during the Weaning Process

Improved weaning assessments, better clinical decision-making, and faster, more successful liberation from MV can all be achieved with the help of ultrasonography, which allows doctors to directly evaluate different organ functions at the bedside [3]. Intense care unit physicians require both fundamental and sophisticated ultrasonography abilities to examine these functions, as well as to successfully evaluate patients and wean them off of mechanical ventilation [14]. For the primary ultrasonographic indications of weaning failure, the timing of their usage, and how to administer US during the process, refer to Figure 1

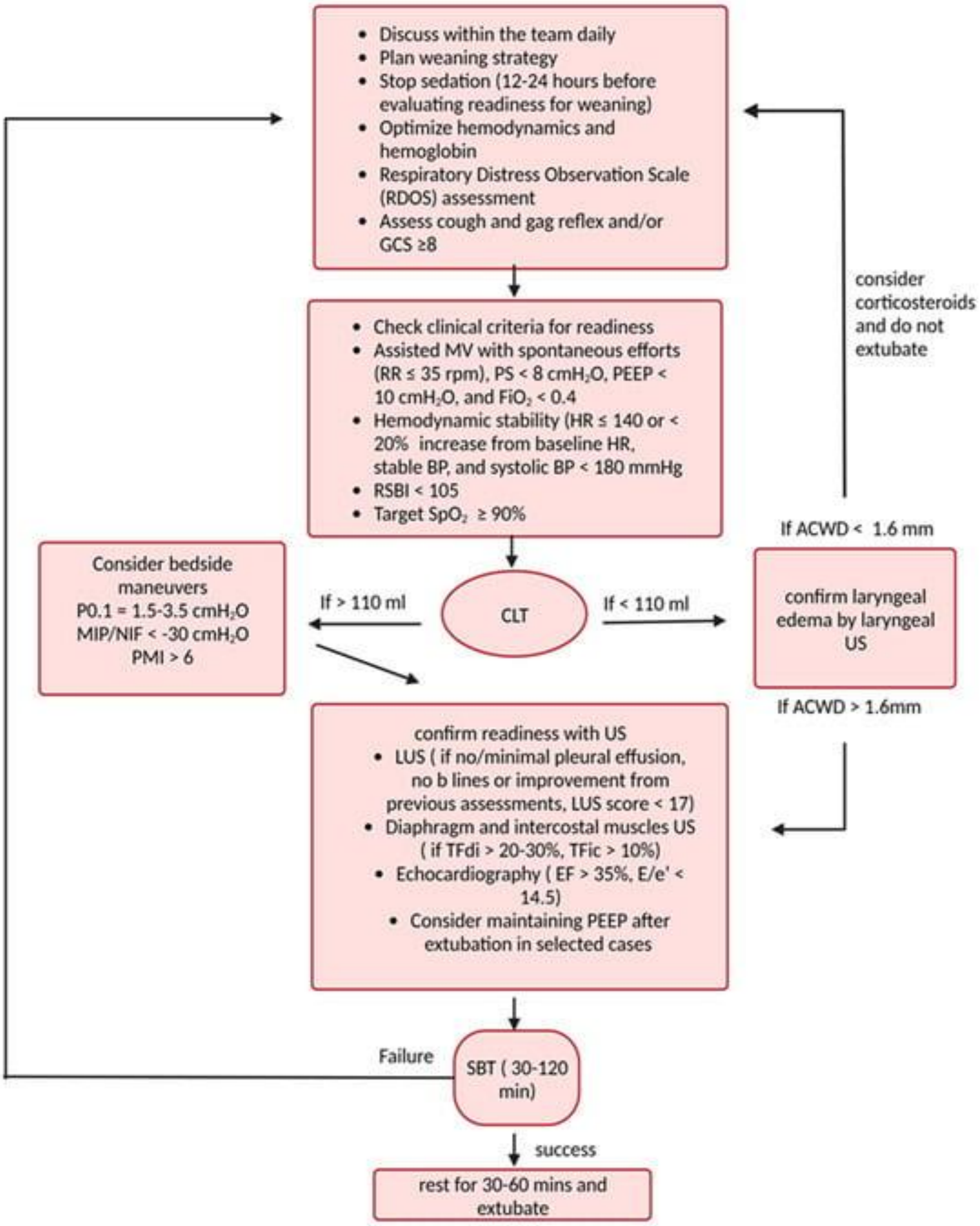

Figure 1. How to integrate ultrasound (US) into the process of weaning from mechanical ventilation. ACWD = air column width difference, BP = blood pressure, CLT = cuff leak test, EF = ejection fraction, E/e' = left ventricular filling pressure, FiO_2 = fraction of inspired oxygen, GCS = Glasgow coma scale, HR = heart rate, LUS = lung ultrasound, MIP = maximal inspiratory pressure, MV = mechanical ventilation, NIF = negative inspiratory force, PEEP = positive end-expiratory pressure, PMI = pressure muscle index, PS = pressure support, P0.1 = airway occlusion pressure to detect inspiratory effort at the bedside, RDOS = respiratory distress observation scale, RR = respiratory rate, RSBI = rapid shallow breathing index, SBT = spontaneous breathing trial, SpO_2 = peripheral saturation of oxygen, TFdi = diaphragmatic thickening fraction, TFic = intercostal muscle thickening fraction.

2.1. Ultrasonographic Assessment of Lung Aeration

A potentially useful technology to assist with weaning is lung ultrasonography (LUS). Without transferring patients or exposing them to radiation, it gives an instantaneous insight of ventilation and lung aeration conditions right at the bedside. When trying to determine what variables connected to alterations in lung aeration could lead to weaning failure, LUS is the method of choice [15].

Lung ultrasonography (LUS) uses the air-to-fluid ratio inside the lung parenchyma to provide useful pictures. When air is completely absent (consolidation), LUS provides a clear picture of the lung tissue, which could be an indication of illness. On the flip side, a number of picture abnormalities might occur if air is present in the tissue. Irrespective of the precise underlying clinical condition, the artifact can depict either normally perforated lung tissue or relative hypoperforated lung tissue. Air loss (causing atelectasis) or fluid accumulation in the interstitial or alveolar spaces are two causes of reduced relative aeration [16].

Twelve thoracic areas, six on each side of the chest, are typically checked in a standard LUS evaluation. Each of these zones is then further divided into an upper and lower half, with the axillary lines serving as guidelines for the delineation. Afterwards, the ultrasound probe is guided through each of the twelve intercostal spaces, offering a consistent way to image the whole chest [17,18].

There are four distinct patterns that emerge from the LUS results, which indicate different levels of lung aeration. Various scoring methods have been suggested to somewhat quantify these differences. The BLUE procedure, which gives each step a score between 0 and 3, is the most used system in the intensive care unit (ICU) [3,19,20].

A total of twelve thoracic areas contribute to the total LUS score; a score of 0 indicates normal aeration throughout, while a score of 36 indicates consolidation throughout [19]. In order to evaluate lung aeration patterns, Bouhemad et al. initially developed the LUS score. Afterwards, it has also been utilized to forecast whether patients would be able to successfully wean off MV [8].

2.1.1. Application of LUS to Predict the Outcome of Weaning from Mechanical Ventilation

Most patients on mechanical ventilation still struggle with the issue of when to start the weaning process, as mentioned earlier. Because of this, LUS has recently been the subject of investigation for its possible value in gauging patient preparedness and forecasting weaning results. Predicting post-extubation distress after MV termination, which includes the requirement for reintubation or rescue noninvasive ventilation (NIV) within 48 hours, was the goal of a prospective research conducted by Soummer et al. One hundred patients were studied, with LUS measuring lung aeration before, during, and after a 60-minute SBT and again four hours following extubation. To measure lung aeration, the LUS score was employed. A one-hour SBT caused substantial derecruitment of the lung tissue, which was especially noticeable in patients who experienced discomfort after extubation. Additionally, among patients who were able to pass the SBT, a lower urinary output score (LUS) of 12 or less at the conclusion of the test clearly suggested a greater chance of success after extubation. On the other hand, post-extubation distress was strongly predicted by a LUS score of 17 or higher at the conclusion of the SBT [20].

Fifty intubated patients (aged 18 and up) who had been intubated for at least 48 hours and fulfilled the requirements for SBT were studied in a supplementary study by Shoaeir et al. to determine the potential of LUS in predicting weaning outcomes. All three times—before, during, and after extubation—lung aeration scoring using laser ultrasonography (LUS) were conducted. After the patients were extubated, they were observed closely for 48 hours to determine the outcome. Then, they were split into two groups: one that failed to wean and another that succeeded. Baseline LUS aeration ratings were substantially lower in the weaning success group compared to the weaning failure group. Furthermore, the weaning failure group showed significant changes in aeration ratings during the SBT. In the end, the findings showed that a LUS aeration score could be useful for predicting whether critically sick patients will fail to wean, as scores of 18 or higher were highly predictive of weaning failure, whereas values of 11 or lower were highly predictive of weaning success. Predicting weaning outcomes with scores between these values was not possible [21].

In 2017, Llamas-Álvarez et al. performed a thorough systematic review and meta-analysis on 1071 patients admitted to intensive care units and given mechanical ventilation for at least 24 hours. The results showed that using ultrasound of the lungs and diaphragm could help predict how well weaning would go. The small sample size, however, raises questions about the reliability of these results [22]. Additionally, Kundu et al.'s recent observational study highlighted LUS's potential capacity to predict weaning results. Weaning failure risk was consistently predicted by the study's inclusive ultrasound methodology, which included lung, diaphragm, and heart sonography [23].

We propose that LUS be integrated into ventilatory management clinical regimens on a regular basis. In controlled and assisted breathing, SBT, and other similar procedures, LUS is a useful tool because it gives real-time information about lung function. Decisions like whether to provide positive end expiratory pressure (PEEP) following extubation are greatly influenced by its use prior to extubation. Clinicians now have a non-invasive option for improving respiratory treatment in high-stakes situations by customizing therapies. It is crucial to highlight the need of conducting thorough clinical studies to confirm the effectiveness and dependability of LUS in these settings. This will ensure that evidence-based practices are integrated into normal clinical practice.

2.2. Ultrasonographic Assessment of Diaphragmatic Function

Breathing relies heavily on the diaphragm, the principal inspiratory muscle. When at rest, this muscle is responsible for nearly three quarters of the respiratory process. Nevertheless, diaphragm function can be impaired by severe situations such hypotension, inadequate oxygen levels, systemic infections, and the need for MV [24].

Diaphragmatic atrophy and dysfunction can be caused by MV. The patient's capacity to stop mechanical ventilation (MV) may be impacted by ventilator-induced diaphragmatic dysfunction (VIDD) [25]. Various risk variables and the type of ventilation employed determine the onset and progression of ventilator-induced dizziness (VIDD) [26]. Therefore, diaphragmatic function assessment is critical for predicting the patient's capacity to wean off MV and maintain spontaneous breathing.

Over the past forty years, ultrasound has been used as a non-invasive method to see the diaphragm at the bedside. However, ultrasonography has only lately been utilized to evaluate the diaphragm's size and function in patients undergoing MV [27,28]. Buoyancy (B-mode) and motion (M-mode) are the two primary modes of ultrasound imaging. M-mode is able to precisely detect the diaphragmatic displacement during the breathing cycle and captures the movement of structures over time using a dynamic graph, while B-mode offers detailed two-dimensional images of structures for anatomical examination. By employing these modes to see the diaphragm, we may evaluate its thickness (Tdi) with the B-mode and its excursion (E) with the M-mode [29,30]. It is usually enough to evaluate just the right diaphragm when screening severely sick individuals; however, if there is suspicion of left side malfunction, then both sides should be evaluated [31]. In most cases, the right side is easier to see clearly on an ultrasound because the liver has a good ultrasonic window, whereas the left side is more difficult since the spleen has a weak acoustic window [29,32].

2.2.1. Diaphragmatic Thickness (Tdi) and the Thickening Fraction (TFdi)

Measuring diaphragmatic thickness (Tdi) and diaphragmatic thickening fraction (TFdi) are crucial for evaluating diaphragmatic atrophy and contraction, respectively [33,34].

The zone of apposition (ZA), where the diaphragm meets the thoracic cage, is the location where the transducer diode (Tdi) is put on a high-frequency linear probe with a frequency of at least 10 MHz. Between the midaxillary and anterior axillary lines, at the eighth or ninth intercostal space, position the probe perpendicular to the lateral chest wall [29,35]. An estimated 0.8–4.9 cm separates the skin from the diaphragm in this region. Diaphragmatic dilation is more common in people who are overweight [31]. Multiple studies published the reference values for Tdi in individuals with serious illnesses. While Goligher et al. discovered an average Tdi of 2.4 ± 0.8 mm [36], Schepens et al. obtained a somewhat lower value of 1.9 ± 0.4 mm [37].

A hypoechoic structure, the diaphragm is bounded by the hyperechoic membranes of the peritoneum and pleura. Because they demarcate boundaries, the lines depicting the outer layers are not considered for calculating thickness. One way to find the fibrous layer in the middle of the diaphragm is to look for a third hyperechoic line inside the non-echogenic layer [35]. The distance between the diaphragmatic pleura and the peritoneum is used to measure Tdi at the end of expiration (Tdi-exp) and inspiration (Tdi-insp) using the B-mode or M-mode [26].

Inspiratory thickening is intimately related to diaphragmatic function. It is crucial to evaluate diaphragmatic thickness at the end of inspiration (Tdi-insp) and at the end of expiration (Tdi-exp) for improved diagnosis of diaphragmatic dysfunction (DD). The thickness at the conclusion of inspiration divided by the thickness at the end of expiration is known as the thickening ratio (TR). The thickening fraction (TFdi), which was also utilized by certain researchers, was determined by multiplying the following formula by 100 [35]:

The formula for TFdi is (Tdi−insp)−(Tdi−exp)(Tdi−exp). AThe formula for TFdi is Tdi minus insp minus (Tdi minus exp)times Tdi minus exp.

2.2.2. Diaphragmatic Excursion (E)

The front subcostal area, between the mid-clavicular line and the anterior axillary line, is where a low-frequency convex or phased array probe (1-5 MHz) is placed to assess diaphragmatic excursion (E). Enhanced depth is achieved at the expense of diminished spatial resolution due to the lower frequency [29,38]. The spleen window can be used to evaluate the left hemidiaphragm, whereas the liver window can be used to evaluate the right hemidiaphragm. In order to evaluate the right hemi-diaphragmatic excursion, it is necessary to position the probe at an angle that is medially, cranially, and dorsally oriented. This will ensure that the ultrasound beam reaches the posterior part of the diaphragm, and in B-mode, the right hemidiaphragm will appear as a thick, curved, hyperechoic line. Next, to get the most out of the adventure, make sure the M-mode exploration line is perpendicular to the diaphragmatic dome. Placing the transducer in its designated spot is essential, as is instructing the patient to engage in deep breathing, voluntary sniffing, and quiet breathing. Placing calipers at the bottom and top of the inspiratory slope of the diaphragm is necessary to measure the diaphragmatic excursion amplitude [38]. If the diaphragm is hard to see through the subcostal window, you can always try moving the spleen and liver instead. Because of this, it is advised to use a low-frequency probe to create an intercostal window at the zone of apposition in B- or M-mode [39,40]. Rather than trying to measure it precisely, this technique is preferable for describing the diaphragm's movement, since there can be variances in how it and the area below it move together [41,42].

Passive displacement and active displacement are indistinguishable during assisted ventilation owing to driving pressures, hence measuring excursion is only possible in patients who are breathing on their own [29]. The values of excursion rise during forced inspiratory breathing because it is favorably correlated with lung inspiratory volumes [28]. In addition, diaphragmatic excursion may be accurately assessed in either a recumbent or supine position and varies with age, sex, weight, and healthy volunteers [43]. Using 757 healthy subjects, Kabil et al. established a normal range of diaphragmatic excursion in a 2022 study. The average hemi-diaphragmatic excursion on the right side was 5.54 ± 1.26 cm for deep breathing, 2.90 ± 0.63 cm for sniffing, and 2.32 ± 0.54 cm for quiet breathing, according to their findings. On the left side, it was 5.30 ± 1.21 cm for deep breathing, 2.97 ± 0.56 cm for sniffing, and 2.35 ± 0.54 cm for quiet breathing, according to their findings [43].

The diaphragm descends toward the probe when inspiration occurs. Diaphragm dysfunction is indicated by diminished or nonexistent movement, movement that deviates from the probe, or movement that is lower than normal reference values [26]. Visualizing E during tidal breathing is very successful (>95%), but it becomes more challenging, particularly on the left side, during maximal breathing [44].

Weaning off of mechanical ventilation using diaphragmatic ultrasound (2.2.3).

As part of the weaning process, clinicians conduct readiness testing to see if a patient is likely to handle the transition. This testing may involve objective clinical criteria as well as physiological assessments, such as diaphragmatic ultrasonography. There is inconclusive evidence about the prognostic value of diaphragmatic ultrasonography for determining readiness to wean from MV [26]. Diaphragmatic thickening fraction values of 20 to 30% or more and diaphragmatic excursion cut-off values of 10 to 13 mm or more have been predicted for effective extubation in multiple investigations [49,50,51,52,53, 54]. It is difficult to draw firm conclusions regarding the efficacy of diaphragmatic ultrasound for predicting weaning success due to the large amount of variation across studies in terms of the definitions of weaning or extubation failure, patient position during ultrasonography, type of SBT, and the outcome measure (E, TFdi, or both). A number of meta-analyses and systematic reviews have been performed in recent years to determine whether diaphragmatic ultrasound is helpful in predicting whether weaning will be successful or not in patients having MV. The results of these studies have shown that diaphragmatic ultrasound is reasonably accurate in making these predictions [55,56,57]. In a meta-analysis involving 1,204 patients, Parada Gereda et al. 2023 drew on 19 trials along these lines. Diaphragmatic excursion had an area under the summary receiver operating characteristic (ROC) curve of 0.87, a sensitivity of 80%, and a specificity of 80% for predicting weaning success. The TFdi has an area under the ROC curve of 0.87, a sensitivity of 85%, and a specificity of 75%. To further assess the function of diaphragm ultrasound as a predictor of MV weaning, additional research is required, as these trials displayed a high degree of heterogeneity [58].

Pressure support ventilation (PSV) is one example of assisted mechanical ventilation (AMV) that is frequently used to alleviate respiratory muscle strain and avoid muscular atrophy in critically ill patients [59]. The quantity of effort generated by the patient's inspiratory muscles varies, and the remaining work is supplied by the ventilator [60]. Fatigue and pain could come from insufficient support, whereas ventilator-induced diaphragm dysfunction and patient-ventilator asynchrony can occur from excessive support. It is not possible to directly evaluate the diaphragm in a clinical situation, and it is difficult to measure the patient's effort with aided breathing. At this point, diaphragmatic ultrasonography was being considered by researchers as a potential tool to accomplish this goal. The purpose of the pilot study by Umbrello et al. was to compare the efficacy of TFdi and E in order to determine the weight that patients' efforts should be given during AMV. The researchers found that TFdi, rather than E, was a good measure of how the inspiratory muscle effort changed in response to changes in the PS level during AMV, whereas E is not a good measure for quantifying diaphragmatic contractile activity. If this holds true in a bigger patient group with other disorders, further research is required to confirm it [63].

To conclude, diaphragm ultrasonography should be a part of MV weaning strategies. During the transition from controlled to assisted ventilation, this can be particularly helpful in achieving smoother mechanical ventilation changes, which in turn optimizes the patient's reaction during weaning. The possible uses and advantages of diaphragm ultrasonography in clinical practice can be better understood with the help of thorough investigations.

2.2.4. Tissue Doppler Imaging

An ultrasonographic method called tissue Doppler imaging (TDI) can identify changes in the frequency of ultrasound signals reflected by structures in motion. Although it has long been used to measure heart function, its use to evaluate the diaphragm in both adults and newborns is a relatively new phenomenon [64,65]. It was recently shown by Soilemezi et al. and Cammarota et al. that parameters derived from TDI could distinguish between patients who finished the weaning study and those who didn't [66,67]. Nevertheless, additional clinical research regarding the function of TDI in foretelling extubation failure are necessary to validate these findings.

2.2.5. Speckle Tracking Ultrasound

Ultrasound speckle tracking over time is the basis of Speckle Tracking Ultrasound (STUS), another name for strain imaging. In ultrasound imaging, these spots stand for areas of muscle that have rather consistent gray patterns. For the STUS program to function, it follows a cluster of speckles during the whole contractile cycle and compares the displacement and deformation of each cluster to the others. "Strain" describes the total amount of deformation and "strain rate" measures how fast it is happening [26,32]. There is a robust relationship between strain, strain rate, and trans-diaphragmatic pressure in healthy persons, according to a recent study by Oppersma et al. [68]. STUS has a distinct advantage over TDI due to its insensitivity to changes non the angle between the direction of tissue motion and the ultrasonic beam. Additional research is needed to determine the validity of STUS in evaluating diaphragmatic movement in different situations, especially in patients with aberrant diaphragmatic function or severe sickness. To confirm its usefulness, comparative studies with electromyography or trans-diaphragmatic pressure measures might be required [26,32].

2.2.6. Shear Wave Elastography

An novel technology that has recently been used for diaphragm evaluation is shear wave elastography (SWE). The ultrasonic probe is used to create a focused acoustic impulse beam, which causes the tissue to distort. This causes the generation of a quantifiable shear wave, which can subsequently be transformed into an SM. Tissue stiffness increases with increasing SM [26]. Clinical relevance of using SWE to evaluate the diaphragm may lie in the fact that changes in muscular stiffness may reflect alterations in muscle physiology, including fibrosis or damage [32-40]. Any change in diaphragmatic stiffness assessed by SWE reflected changes in Pdi, according to a recent study on healthy subjects by Bachasson et al. [69]. The study also indicated that the mean SM was linked with the mean trans-diaphragmatic pressure (Pdi). Recent research by Fossé et al. supports the idea that SWE can replace Pdi in mechanically ventilated patients, confirming the findings of Bachasson et al. that Pdi and SM of the diaphragm are correlated [40-45]. Hence, SWE could provide a novel method for measuring diaphragmatic effort. When contrasted with the evaluation of echogenicity, which is very susceptible to variations in ultrasonic parameters like gain and contrast, SWE stands head and shoulders above the competition [46-50].

2.3. Ultrasonographic Assessment of the Airway for Weaning Readiness

Damage to the laryngotracheal junction, or throat, can occur in patients having endotracheal intubation [50-55]. With a frequency ranging from 3% to 30% [55-60], laryngeal edema is one of the most common consequences. In clinical settings, it may be observed as difficulty breathing or inspiratory stridor. This problem has a domino effect: reintubation increases the risk of nosocomial pneumonia, intensive care unit length of stay, and death [61-79].

Female sex [80], intubation difficulties or trauma [81], prolonged intubation [82], and self-extubation [83] are some of the intubation-related variables that may increase the likelihood that a patient may develop laryngeal edema during the procedure. Early diagnosis of patients with laryngeal edema is crucial for reducing the frequency of extubation failure and reintubation; hence, an objective evaluation of airway readiness is necessary.

An example of this is the cuff leak test (CLT), which indirectly evaluates the patency of the upper airway by measuring the amount of air that leaks around the endotracheal tube after deflating it. One easy way to anticipate laryngeal edema after extubation is with this test. Miller and Cole found that post-extubation stridor owing to laryngeal edema is more likely to develop in patients with a smaller cuff leak volume [82]. While the CLT's negative predictive value is strong, Engoren et al. discovered that it has a low positive predictive value. Therefore, even though CLT is a simple and safe technique, its contentious outcomes could influence doctors' decisions, especially when CLT is successful [83]. Ultrasound, on the other hand, has recently become a highly effective and noninvasive method of inspecting and imaging the airways in the head and neck region [84]. By comparing the width of the acoustic shadow at the level of the vocal cords when the endotracheal balloon cuff is inflated and deflated, laryngeal ultrasound can measure the air column width (ACW), which is also known as the air column width difference (ACWD). Predicting post-extubation laryngeal edema using these parameters has been suggested.

The purpose of the prospective study by Ding et al. was to examine the relationship between upper airway ultrasonography measures of the ACW and post-extubation stridor. The 51 patients who were going to be extubated had their measurements taken no more than 24 hours before to the procedure. After cuff deflation, patients who had an ACW of 4.5 (0.8) mm were found to have post-extubation stridor, whereas patients without stridor had an ACW of 6.4 (2) mm, according to the authors' report [85]. Both ACWD and CLT are predictors of the development of laryngeal edema, according to an observational study by Sutherasan et al. Additionally, a safe extubation threshold was established by the researchers to be 1.6 mm for ACWD. This figure had a sensitivity of 70.6% and a specificity of 70.2%. To sum up, when it comes to laryngeal edema, ACWD shows promise as a technique for predicting effective extubation [86].

Stridor is a clinical sign of post-extubation laryngeal edema; in a prospective clinical experiment, Sahbal et al. compared CLT with an ultrasound measure of ACWD to predict this condition. A higher likelihood of post-extubation stridor was linked to ACWD values lower than 0.9 mm. With a sensitivity of 88%, specificity of 82%, PPV of 86%, and NPV of 83%, this threshold showed remarkable performance. Furthermore, a suggested CLT cut-off level of 110 mL was established, below which post-extubation stridor was significantly more likely to occur. The sensitivity, specificity, PPV, and NPV of this 110 mL cut-off were 68%, 89%, and 69%, respectively [87].

Patients who experienced post-extubation stridor had lower ACWD readings, according to a recent systematic analysis by Tsai et al. [88]. The research included 11 observational studies and demonstrated a sensitivity of 80% and specificity of 81%. These results highlight the critical role of ultrasound, and especially ACWD assessment, in predicting the development of post-extubation stridor. Still, further standardized multicenter trials with cutoff values and definitions are required to clarify upper airway ultrasonography's function during weaning.

Finally, we recommend adding laryngeal ultrasound to the evaluation of weaning readiness in order to detect laryngeal edema following the CLT, especially in cases when the leak is less than 110 mL. This can help in deciding whether to continue with the evaluation or to give corticosteroids to reduce the swelling

2.5. Hemodynamic Assessment through Echocardiography

In order to successfully manage patients and detect weaning failure caused by cardiovascular difficulties quickly, it is crucial to understand the changes in cardiac physiology that occur during MV and its termination. The ability of the pulmonary system and the heart's pumping function to endure these alterations is crucial for a successful weaning process [89]. Weaning off MV is like a cardiac stress test in that it puts the heart through its paces through spontaneous breathing; as a result, critically ill patients run the risk of hemodynamic compromise [89].

Positive pressure MV gives way to spontaneous breathing as the baby begins to wean. The venous return pressure gradient, right ventricular preload, and left ventricular preload are all raised as a result of this change, which generates a negative intrathoracic pressure. Furthermore, because the left ventricle is surrounded by more pressure when the negative pressure is present, the left ventricular afterload is raised. In addition, the change raises both the labor of breathing and adrenergic tone, the latter of which is a result of elevated serum catecholamine levels [90,91]. Increasing PAOP, left ventricular filling pressure, and pulmonary edema are clinical manifestations of cardiovascular failure that may result from this [89,92]. During weaning, these hemodynamic changes can impact the heart's systolic and diastolic functions, which can have harmful consequences for patients with cardiovascular diseases or reveal cardiovascular dysfunction in patients with normal resting cardiovascular function [89].

Predicting weaning results is possible with the use of trans-thoracic echocardiography (TTE), a non-invasive, real-time, and cost-effective method of monitoring important hemodynamic parameters. One possible use of transthoracic echocardiography (TTE) is to forecast weaning success by measuring the heart's systolic and diastolic functions. The ejection fraction is a simple way to measure the systolic function. To evaluate diastolic function, one can use pulse wave Doppler to examine the mitral inflow profile, where the early wave (E) indicates passive ventricular filling and the late wave (A) active atrial contraction; another method is to examine the mitral annulus using tissue Doppler imaging in healthy individuals, which allows for an accurate assessment of left ventricular relaxation (e' wave) and left ventricular filling pressure (E/e' ratio). $E/A \leq 1$ and $E/e' \leq 13$ suggest low filling pressures or poor relaxation patterns. When $E/A > 1$ and $E/e' > 13$, it indicates high filling pressures or pseudo-normal patterns. Increased filling pressure with restrictive patterns is indicated by an $E/A > 2$ value [13,93].

Ultrasoundography has the potential to detect lung illnesses amenable to respiratory physiotherapy and track the efficacy of this treatment. Lung auscultation and chest x-rays are the standard methods of evaluation for this condition. But there are research that demonstrate these tools don't have the most accurate diagnoses. Because of this, LUS has become a reliable and sensitive alternative to traditional methods of diagnosing common chest diseases and tracking the progress of patients undergoing respiratory physiotherapy [93].

As an example, physiotherapists can manage mechanically ventilated patients with lung consolidation featuring fluid bronchograms by utilizing techniques like huffing or exsufflation to increase expiratory flow rates, in addition to adjusting the ventilator settings. During this procedure, LUS can also be utilized to evaluate how well the treatment is working. Signs that the treatment is working include smaller consolidations and the ability to see air bronchograms instead of fluid ones [93].

3. Conclusions

Bedside weaning examinations can make use of ultrasound, a non-invasive imaging technology that is easily available. Despite its potential, more high-quality studies are required to determine its function during weaning and to provide definitive cut-off values for identifying patients at high risk of weaning failure.

References:

1. Jaber, S.; De Jong, A. Weaning from mechanical ventilation in intensive care units: A call for new international consensus guidelines. *Lancet Respir. Med.* 2023, *11*, 398–400. [Google Scholar] [CrossRef] [PubMed]

2. Girard, T.D.; Alhazzani, W.; Kress, J.P.; Ouellette, D.R.; Schmidt, G.A.; Truwit, J.D.; Burns, S.M.; Epstein, S.K.; Esteban, A.; Fan, E. An official American Thoracic Society/American College of Chest Physicians clinical practice guideline: Liberation from mechanical ventilation in critically ill adults. Rehabilitation protocols, ventilator liberation protocols, and cuff leak tests. *Am. J. Respir. Crit. Care Med.* 2017, *195*, 120–133. [Google Scholar] [CrossRef] [PubMed]

3. Mayo, P.; Volpicelli, G.; Lerolle, N.; Schreiber, A.; Doelken, P.; Vieillard-Baron, A. Ultrasonography evaluation during the weaning process: The heart, the diaphragm, the pleura and the lung. *Intensive Care Med.* 2016, *42*, 1107–1117. [Google Scholar] [CrossRef] [PubMed]

4. Beduneau, G.; Pham, T.; Schortgen, F.; Piquilloud, L.; Zogheib, E.; Jonas, M.; Grelon, F.; Runge, I.; Terzi, N.; Grange, S. Epidemiology of weaning outcome according to a new definition. The WIND study. *Am. J. Respir. Crit. Care Med.* 2017, *195*, 772–783. [Google Scholar] [CrossRef] [PubMed]

5. Heunks, L.M.; Van Der Hoeven, J.G. Clinical review: The ABC of weaning failure—A structured approach. *Crit. Care* 2010, *14*, 1245. [Google Scholar] [CrossRef] [PubMed]

6. McConville, J.F.; Kress, J.P. Weaning patients from the ventilator. *N. Engl. J. Med.* 2012, *367*, 2233–2239. [Google Scholar] [CrossRef] [PubMed]

7. Matamis, D.; Soilemezi, E.; Tsagourias, M.; Akoumianaki, E.; Dimassi, S.; Boroli, F.; Richard, J.-C.M.; Brochard, L. Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. *Intensive Care Med.* 2013, *39*, 801–810. [Google Scholar] [CrossRef]

8. Bouhemad, B.; Liu, Z.-H.; Arbelot, C.; Zhang, M.; Ferarri, F.; Le-Guen, M.; Girard, M.; Lu, Q.; Rouby, J.-J. Ultrasound assessment of antibiotic-induced pulmonary reaeration in ventilator-associated pneumonia. *Crit. Care Med.* 2010, *38*, 84–92. [Google Scholar] [CrossRef]

9. Baess, A.I.; Abdallah, T.H.; Emara, D.M.; Hassan, M. Diaphragmatic ultrasound as a predictor of successful extubation from mechanical ventilation: Thickness, displacement, or both? *Egypt. J. Bronchol.* 2016, *10*, 162–166. [Google Scholar] [CrossRef]

10. Boles, J.-M.; Bion, J.; Connors, A.; Herridge, M.; Marsh, B.; Melot, C.; Pearl, R.; Silverman, H.; Stanchina, M.; Vieillard-Baron, A. Weaning from mechanical ventilation. *Eur. Respir. J.* 2007, *29*, 1033–1056. [Google Scholar] [CrossRef]

11. Thille, A.W.; Gacouin, A.; Coudroy, R.; Ehrmann, S.; Quenot, J.-P.; Nay, M.-A.; Guitton, C.; Contou, D.; Labro, G.; Reignier, J. Spontaneous-breathing trials with pressure-support

ventilation or a T-piece. *N. Engl. J. Med.* 2022, *387*, 1843–1854. [Google Scholar] [CrossRef]

12. Fossé, Q.; Poulard, T.; Niérat, M.-C.; Virolle, S.; Morawiec, E.; Hogrel, J.-Y.; Similowski, T.; Demoule, A.; Gennisson, J.-L.; Bachasson, D. Ultrasound shear wave elastography for assessing diaphragm function in mechanically ventilated patients: A breath-by-breath analysis. *Crit. Care* 2020, *24*, 669. [Google Scholar] [CrossRef]

13. Santangelo, E.; Mongodi, S.; Bouhemad, B.; Mojoli, F. The weaning from mechanical ventilation: A comprehensive ultrasound approach. *Curr. Opin. Crit. Care* 2022, *28*, 322–330. [Google Scholar] [CrossRef]

14. Robba, C.; Wong, A.; Poole, D.; Al Tayar, A.; Arntfield, R.T.; Chew, M.S.; Corradi, F.; Douflé, G.; Goffi, A.; Lamperti, M. Basic ultrasound head-to-toe skills for intensivists in the general and neuro intensive care unit population: Consensus and expert recommendations of the European Society of Intensive Care Medicine. *Intensive Care Med.* 2021, *47*, 1347–1367. [Google Scholar] [CrossRef] [PubMed]

15. Bellani, G.; Mauri, T.; Pesenti, A. Imaging in acute lung injury and acute respiratory distress syndrome. *Curr. Opin. Crit. Care* 2012, *18*, 29–34. [Google Scholar] [CrossRef] [PubMed]

16. Via, G.; Storti, E.; Gulati, G.; Neri, L.; Mojoli, F.; Braschi, A. Lung ultrasound in the ICU: From diagnostic instrument to respiratory monitoring tool. *Minerva Anestesiol.* 2012, *78*, 1282–1296. [Google Scholar]

17. Karthika, M.; Wong, D.; Nair, S.G.; Pillai, L.V.; Mathew, C.S. Lung ultrasound: The emerging role of respiratory therapists. *Respir. Care* 2019, *64*, 217–229. [Google Scholar] [CrossRef]

18. Doerschug, K.C.; Schmidt, G.A. Intensive care ultrasound: III. Lung and pleural ultrasound for the intensivist. *Ann. Am. Thorac. Soc.* 2013, *10*, 708–712. [Google Scholar] [CrossRef] [PubMed]

19. Mojoli, F.; Bouhemad, B.; Mongodi, S.; Lichtenstein, D. Lung ultrasound for critically ill patients. *Am. J. Respir. Crit. Care Med.* 2019, *199*, 701–714. [Google Scholar] [CrossRef]

20. Soummer, A.; Perbet, S.; Brisson, H.; Arbelot, C.; Constantin, J.M.; Lu, Q.; Rouby, J.J. Ultrasound assessment of lung aeration loss during a successful weaning trial predicts postextubation distress. *Crit. Care Med.* 2012, *40*, 2064–2072. [Google Scholar] [CrossRef] [PubMed]

21. Shoaeir, M.; Noeam, K.; Mahrous, A.; Alaa, A. Lung aeration loss as a predictor of reintubation using lung ultrasound in mechanically ventilated patients. *Biolife* 2016, *4*, 514–520. [Google Scholar]

22. Tenza-Lozano, E.; Llamas-Alvarez, A.; Jaimez-Navarro, E.; Fernández-Sánchez, J. Lung and diaphragm ultrasound as predictors of success in weaning from mechanical ventilation. *Crit. Ultrasound J.* 2018, *10*, 12. [Google Scholar] [CrossRef]

23. Kundu, R.; Baidya, D.; Anand, R.; Maitra, S.; Soni, K.; Subramanium, R. Integrated ultrasound protocol in predicting weaning success and extubation failure: A prospective observational study. *Anaesthesiol. Intensive Ther.* 2022, *54*, 156–163. [Google Scholar] [CrossRef] [PubMed]

24. Tashiro, N.; Hasegawa, T.; Nishiwaki, H.; Ikeda, T.; Noma, H.; Levack, W.; Ota, E. Clinical utility of diaphragmatic ultrasonography for mechanical ventilator weaning in adults: A study protocol for systematic review and meta-analysis. *Health Sci. Rep.* 2023, *6*, e1378. [Google Scholar] [CrossRef] [PubMed]

25. Grosu, H.B.; Im Lee, Y.; Lee, J.; Eden, E.; Eikermann, M.; Rose, K.M. Diaphragm muscle thinning in patients who are mechanically ventilated. *Chest* 2012, *142*, 1455–1460. [Google Scholar] [CrossRef] [PubMed]

26. Santana, P.V.; Cardenas, L.Z.; Albuquerque, A.L.P.d. Diaphragm Ultrasound in Critically Ill Patients on Mechanical Ventilation—Evolving Concepts. *Diagnostics* 2023, *13*, 1116. [Google Scholar] [CrossRef] [PubMed]

27. Doust, B.D.; Baum, J.K.; Maklad, N.F.; Doust, V.L. Ultrasonic evaluation of pleural opacities. *Radiology* 1975, *114*, 135–140. [Google Scholar] [CrossRef] [PubMed]

28. Turton, P.; ALAidarous, S.; Welters, I. A narrative review of diaphragm ultrasound to predict weaning from mechanical ventilation: Where are we and where are we heading? *Ultrasound J.* 2019, *11*, 2. [Google Scholar] [CrossRef]

29. Haaksma, M.; Atmowihardjo, L.; Heunks, L.; Spoelstra-de Man, A.; Tuinman, P. Ultrasound imaging of the diaphragm: Facts and future. A guide for the bedside clinician. *Neth. J. Crit. Care* 2018, *26*, 6. [Google Scholar]

30. De Rosa, S.; Umbrello, M.; Pelosi, P.; Battaglini, D. Update on Lean Body Mass Diagnostic Assessment in Critical Illness. *Diagnostics* 2023, *13*, 888. [Google Scholar] [CrossRef]

31. Haaksma, M.E.; Smit, J.M.; Boussuges, A.; Demoule, A.; Dres, M.; Ferrari, G.; Formenti, P.; Goligher, E.C.; Heunks, L.; Lim, E.H. EXpert consensus On Diaphragm UltraSonography in the critically ill (EXODUS): A Delphi consensus statement on the measurement of diaphragm ultrasound-derived parameters in a critical care setting. *Crit. Care* 2022, *26*, 99. [Google Scholar] [CrossRef] [PubMed]

32. Tuinman, P.R.; Jonkman, A.H.; Dres, M.; Shi, Z.-H.; Goligher, E.C.; Goffi, A.; de Korte, C.; Demoule, A.; Heunks, L. Respiratory muscle ultrasonography: Methodology, basic and advanced principles and clinical applications in ICU and ED patients—A narrative review. *Intensive Care Med.* 2020, *46*, 594–605. [Google Scholar] [CrossRef]

33. Gottesman, E.; McCool, F.D. Ultrasound evaluation of the paralyzed diaphragm. *Am. J. Respir. Crit. Care Med.* 1997, *155*, 1570–1574. [Google Scholar] [CrossRef] [PubMed]

34. Cohn, D.; Benditt, J.O.; Eveloff, S.; McCool, F.D. Diaphragm thickening during inspiration. *J. Appl. Physiol.* 1997, *83*, 291–296. [Google Scholar] [CrossRef] [PubMed]

35. Boussuges, A.; Rives, S.; Finance, J.; Brégeon, F. Assessment of diaphragmatic function by ultrasonography: Current approach and perspectives. *World J. Clin. Cases* 2020, *8*, 2408. [Google Scholar] [CrossRef]

36. Goligher, E.C.; Laghi, F.; Detsky, M.E.; Farias, P.; Murray, A.; Brace, D.; Brochard, L.J.; Sebastien-Bolz, S.; Rubenfeld, G.D.; Kavanagh, B.P. Measuring diaphragm thickness with ultrasound in mechanically ventilated patients: Feasibility, reproducibility and validity. *Intensive Care Med.* 2015, *41*, 642–649. [Google Scholar] [CrossRef]

37. Schepens, T.; Verbrugghe, W.; Dams, K.; Corthouts, B.; Parizel, P.M.; Jorens, P.G. The course of diaphragm atrophy in ventilated patients assessed with ultrasound: A longitudinal cohort study. *Crit. Care* 2015, *19*, 422. [Google Scholar] [CrossRef]

38. Santana, P.V.; Cardenas, L.Z.; Albuquerque, A.L.P.d.; Carvalho, C.R.R.d.; Caruso, P. Diaphragmatic ultrasound: A review of its methodological aspects and clinical uses. *J. Bras. Pneumol.* 2020, *46*, e20200064. [Google Scholar] [CrossRef]

39. Haji, K.; Royse, A.; Green, C.; Botha, J.; Canty, D.; Royse, C. Interpreting diaphragmatic movement with bedside imaging, review article. *J. Crit. Care* 2016, *34*, 56–65. [Google Scholar] [CrossRef]

40. Houston, J.G.; Morris, A.D.; Howie, C.A.; Reid, J.L.; McMillan, N. Technical report: Quantitative assessment of diaphragmatic movement—A reproducible method using ultrasound. *Clin. Radiol.* 1992, *46*, 405–407. [Google Scholar] [CrossRef]

41. Haji, K.; Royse, A.; Tharmaraj, D.; Haji, D.; Botha, J.; Royse, C. Diaphragmatic regional displacement assessed by ultrasound and correlated to subphrenic organ movement in the critically ill patients—An observational study. *J. Crit. Care* 2015, *30*, 439.e7–439.e13. [Google Scholar] [CrossRef] [PubMed]

42. Toledo, N.S.; Kodaira, S.K.; Massarollo, P.C.; Pereira, O.I.; Dalmas, J.C.; Cerri, G.G.; Buchpiguel, C.A. Left hemidiaphragmatic mobility: Assessment with ultrasonographic measurement of the craniocaudal displacement of the splenic hilum and the inferior pole of the spleen. *J. Ultrasound Med.* 2006, *25*, 41–49. [Google Scholar] [CrossRef] [PubMed]

43. Scarlata, S.; Mancini, D.; Laudisio, A.; Benigni, A.; Raffaele, A.I. Reproducibility and Clinical Correlates of Supine Diaphragmatic Motion Measured by M-Mode Ultrasonography in Healthy Volunteers. *Respiration* 2018, *96*, 259–266. [Google Scholar] [CrossRef] [PubMed]

44. Boussuges, A.; Gole, Y.; Blanc, P. Diaphragmatic motion studied by m-mode ultrasonography: Methods, reproducibility, and normal values. *Chest* 2009, *135*, 391–400. [Google Scholar] [CrossRef]

45. Vivier, E.; Muller, M.; Putegnat, J.-B.; Steyer, J.; Barrau, S.; Boissier, F.; Bourdin, G.; Mekontso-Dessap, A.; Levrat, A.; Pommier, C. Inability of diaphragm ultrasound to predict extubation failure: A multicenter study. *Chest* 2019, *155*, 1131–1139. [Google Scholar] [CrossRef]

46. Lu, Z.; Xu, Q.; Yuan, Y.; Zhang, G.; Guo, F.; Ge, H. Diaphragmatic dysfunction is characterized by increased duration of mechanical ventilation in subjects with prolonged weaning. *Respir. Care* 2016, *61*, 1316–1322. [Google Scholar] [CrossRef]

47. Kim, W.Y.; Suh, H.J.; Hong, S.-B.; Koh, Y.; Lim, C.-M. Diaphragm dysfunction assessed by ultrasonography: Influence on weaning from mechanical ventilation. *Crit. Care Med.* 2011, *39*, 2627–2630. [Google Scholar] [CrossRef]

48. Mariani, L.F.; Bedel, J.; Gros, A.; Lerolle, N.; Milojevic, K.; Laurent, V.; Hilly, J.; Troché, G.; Bedos, J.P.; Planquette, B. Ultrasonography for screening and follow-up of diaphragmatic dysfunction in the ICU: A pilot study. *J. Intensive Care Med.* 2016, *31*, 338–343. [Google Scholar] [CrossRef]

49. Alam, M.J.; Roy, S.; Iktidar, M.A.; Padma, F.K.; Nipun, K.I.; Chowdhury, S.; Nath, R.K.; Rashid, H.-O. Diaphragm ultrasound as a better predictor of successful extubation from mechanical ventilation than rapid shallow breathing index. *Acute Crit. Care* 2022, *37*, 94–100. [Google Scholar] [CrossRef] [PubMed]

50. Eltrabili, H.H.; Hasanin, A.M.; Soliman, M.S.; Lotfy, A.M.; Hamimy, W.I.; Mukhtar, A.M. Evaluation of diaphragmatic ultrasound indices as predictors of successful liberation from mechanical ventilation in subjects with abdominal sepsis. *Respir. Care* 2019, *64*, 564–569. [Google Scholar] [CrossRef] [PubMed]

51. Elshazly, M.I.; Elkorashy, R.I.; Ismail, M.S.; Ismail, J.H.; Assal, H.H. Role of bedside ultrasonography in assessment of diaphragm function as a predictor of success of weaning in mechanically ventilated patients. *Tuberc. Respir. Dis.* 2020, *83*, 295. [Google Scholar] [CrossRef]

52. Li, S.; Chen, Z.; Yan, W. Application of bedside ultrasound in predicting the outcome of weaning from mechanical ventilation in elderly patients. *BMC Pulm. Med.* 2021, *21*, 217. [Google Scholar] [CrossRef] [PubMed]

53. Gok, F.; Mercan, A.; Kilicaslan, A.; Sarkilar, G.; Yosunkaya, A.; Funda, G.; Kılıçaslan, A. Diaphragm and lung ultrasonography during weaning from mechanical ventilation in critically ill patients. *Cureus* 2021, *13*, e15057. [Google Scholar] [CrossRef] [PubMed]

54. Blumhof, S.; Wheeler, D.; Thomas, K.; McCool, F.D.; Mora, J. Change in diaphragmatic thickness during the respiratory cycle predicts extubation success at various levels of pressure support ventilation. *Lung* 2016, *194*, 519–525. [Google Scholar] [CrossRef]

55. Le Neindre, A.; Philippart, F.; Luperto, M.; Wormser, J.; Morel-Sapene, J.; Aho, S.L.; Mongodi, S.; Mojoli, F.; Bouhemad, B. Diagnostic accuracy of diaphragm ultrasound to predict weaning outcome: A systematic review and meta-analysis. *Int. J. Nurs. Stud.* 2021, *117*, 103890. [Google Scholar] [CrossRef]

56. Mahmoodpoor, A.; Fouladi, S.; Ramouz, A.; Shadvar, K.; Ostadi, Z.; Soleimanpour, H. Diaphragm ultrasound to predict weaning outcome: Systematic review and meta-analysis. *Anaesthesiol. Intensive Ther.* 2022, *54*, 164–174. [Google Scholar] [CrossRef]

57. Llamas-Alvarez, A.M.; Tenza-Lozano, E.M.; Latour-Perez, J. Diaphragm and lung ultrasound to predict weaning outcome: Systematic review and meta-analysis. *Chest* 2017, *152*, 1140–1150. [Google Scholar] [CrossRef]

58. Parada-Gereda, H.M.; Tibaduiza, A.L.; Rico-Mendoza, A.; Molano-Franco, D.; Nieto, V.H.; Arias-Ortiz, W.A.; Perez-Terán, P.; Masclans, J.R. Effectiveness of diaphragmatic ultrasound as a predictor of successful weaning from mechanical ventilation: A systematic review and meta-analysis. *Crit. Care* 2023, *27*, 174. [Google Scholar] [CrossRef]

59. Esteban, A.; Anzueto, A.; Frutos, F.; Alía, I.; Brochard, L.; Stewart, T.E.; Benito, S.; Epstein, S.K.; Apezteguía, C.; Nightingale, P. Characteristics and outcomes in adult patients receiving mechanical ventilation: A 28-day international study. *JAMA* 2002, *287*, 345–355. [Google Scholar] [CrossRef] [PubMed]

60. Hess, D.R. Ventilator waveforms and the physiology of pressure support ventilation. *Respir. Care* 2005, *50*, 166–186. [Google Scholar] [PubMed]

61. Thille, A.W.; Cabello, B.; Galia, F.; Lyazidi, A.; Brochard, L. Reduction of patient-ventilator asynchrony by reducing tidal volume during pressure-support ventilation. *Intensive Care Med.* 2008, *34*, 1477–1486. [Google Scholar] [CrossRef] [PubMed]

62. Hudson, M.B.; Smuder, A.J.; Nelson, W.B.; Bruells, C.S.; Levine, S.; Powers, S.K. Both high level pressure support ventilation and controlled mechanical ventilation induce diaphragm dysfunction and atrophy. *Crit. Care Med.* 2012, *40*, 1254. [Google Scholar] [CrossRef] [PubMed]

63. Umbrello, M.; Formenti, P.; Longhi, D.; Galimberti, A.; Piva, I.; Pezzi, A.; Mistraletti, G.; Marini, J.J.; Iapichino, G. Diaphragm ultrasound as indicator of respiratory effort in critically ill patients undergoing assisted mechanical ventilation: A pilot clinical study. *Crit. Care* 2015, *19*, 161. [Google Scholar] [CrossRef]

64. Cammarota, G.; Boniolo, E.; Tarquini, R.; Vaschetto, R. Diaphragmatic excursion tissue Doppler sonographic assessment. *Intensive Care Med.* 2020, *46*, 1759–1760. [Google Scholar] [CrossRef]

65. Maurizio, R.; Rinaldi, V.E.; Camerini, P.G.; Salvatori, C.; Leonardi, A.; Bini, V. Right Diaphragmatic Peak Motion Velocities on Pulsed Wave Tissue Doppler Imaging in Neonates: Method, Reproducibility, and Reference Values. *J. Ultrasound Med.* 2019, *38*, 2695–2701. [Google Scholar] [CrossRef]

66. Soilemezi, E.; Savvidou, S.; Sotiriou, P.; Smyrniotis, D.; Tsagourias, M.; Matamis, D. Tissue Doppler imaging of the diaphragm in healthy subjects and critically ill patients. *Am. J. Respir. Crit. Care Med.* 2020, *202*, 1005–1012. [Google Scholar] [CrossRef]

67. Cammarota, G.; Boniolo, E.; Santangelo, E.; De Vita, N.; Verdina, F.; Crudo, S.; Sguazzotti, I.; Perucca, R.; Messina, A.; Zanoni, M. Diaphragmatic kinetics assessment by tissue doppler imaging and extubation outcome. *Respir. Care* 2021, *66*, 983–993. [Google Scholar] [CrossRef] [PubMed]

68. Oppersma, E.; Hatam, N.; Doorduin, J.; van der Hoeven, J.G.; Marx, G.; Goetzenich, A.; Fritsch, S.; Heunks, L.M.A.; Bruells, C.S. Functional assessment of the diaphragm by speckle tracking ultrasound during inspiratory loading. *J. Appl. Physiol.* 2017, *123*, 1063–1070. [Google Scholar] [CrossRef]

69. Bachasson, D.; Dres, M.; Niérat, M.-C.; Gennisson, J.-L.; Hogrel, J.-Y.; Doorduin, J.; Similowski, T. Diaphragm shear modulus reflects transdiaphragmatic pressure during isovolumetric inspiratory efforts and ventilation against inspiratory loading. *J. Appl. Physiol.* 2019, *126*, 699–707. [Google Scholar] [CrossRef]

70. Dres, M.; Dubé, B.-P.; Goligher, E.; Vorona, S.; Demiri, S.; Morawiec, E.; Mayaux, J.; Brochard, L.; Similowski, T.; Demoule, A. Usefulness of parasternal intercostal muscle ultrasound during weaning from mechanical ventilation. *Anesthesiology* 2020, *132*, 1114–1125. [Google Scholar] [CrossRef]

71. Umbrello, M.; Formenti, P.; Lusardi, A.C.; Guanziroli, M.; Caccioppola, A.; Coppola, S.; Chiumello, D. Oesophageal pressure and respiratory muscle ultrasonographic measurements indicate inspiratory effort during pressure support ventilation. *Br. J. Anaesth.* 2020, *125*, e148–e157. [Google Scholar] [CrossRef] [PubMed]

72. Lichtenstein, D.A. Lung ultrasound in the critically ill. *Ann. Intensive Care* 2014, *4*, 1. [Google Scholar] [CrossRef] [PubMed]

73. Wallbridge, P.; Parry, S.M.; Das, S.; Law, C.; Hammerschlag, G.; Irving, L.; Hew, M.; Steinfort, D. Parasternal intercostal muscle ultrasound in chronic obstructive pulmonary disease correlates with spirometric severity. *Sci. Rep.* 2018, *8*, 15274. [Google Scholar] [CrossRef] [PubMed]

74. Formenti, P.; Umbrello, M.; Dres, M.; Chiumello, D. Ultrasonographic assessment of parasternal intercostal muscles during mechanical ventilation. *Ann. Intensive Care* 2020, *10*, 120. [Google Scholar] [CrossRef] [PubMed]

75. Sarwal, A.; Parry, S.M.; Berry, M.J.; Hsu, F.-C.; Lewis, M.T.; Justus, N.W.; Morris, P.E.; Denehy, L.; Berney, S.; Dhar, S. Interobserver reliability of quantitative muscle sonographic analysis in the critically ill population. *J. Ultrasound Med.* 2015, *34*, 1191–1200. [Google Scholar] [CrossRef] [PubMed]

76. Thomas, R.; Kumar, E.V.; Kameswaran, M.; Shamim, A.; Al Ghamdii, S.; Mummigatty, A.P.; Okafor, B. Post intubation laryngeal sequelae in an intensive care unit. *J. Laryngol. Otol.* 1995, *109*, 313–316. [Google Scholar] [CrossRef] [PubMed]

77. Fan, T.; Wang, G.; Mao, B.; Xiong, Z.; Zhang, Y.; Liu, X.; Wang, L.; Yang, S. Prophylactic administration of parenteral steroids for preventing airway complications after extubation in adults: Meta-analysis of randomised placebo controlled trials. *BMJ* 2008, *337*, a1841. [Google Scholar] [CrossRef]

78. Epstein, S.K.; Ciubotaru, R.L. Independent effects of etiology of failure and time to reintubation on outcome for patients failing extubation. *Am. J. Respir. Crit. Care Med.* 1998, *158*, 489–493. [Google Scholar] [CrossRef]

79. Torres, A.; Gatell, J.M.; Aznar, E.; El-Ebiary, M.; Puig de la Bellacasa, J.; González, J.; Ferrer, M.; Rodriguez-Roisin, R. Re-intubation increases the risk of nosocomial pneumonia in patients needing mechanical ventilation. *Am. J. Respir. Crit. Care Med.* 1995, *152*, 137–141. [Google Scholar] [CrossRef]

80. Ho, L.; Harn, H.; Lien, T.; Hu, P.; Wang, J. Postextubation laryngeal edema in adults risk factor evaluation and prevention by hydrocortisone. *Intensive Care Med.* 1996, *22*, 933–936. [Google Scholar] [CrossRef]

81. Jaber, S.; Chanques, G.; Matecki, S.; Ramonatxo, M.; Vergne, C.; Souche, B.; Perrigault, P.-F.; Eledjam, J.-J. Post-extubation stridor in intensive care unit patients: Risk factors evaluation and importance of the cuff-leak test. *Intensive Care Med.* 2003, *29*, 69–74. [Google Scholar] [CrossRef]

82. Miller, R.L.; Cole, R.P. Association between reduced cuff leak volume and postextubation stridor. *Chest* 1996, *110*, 1035–1040. [Google Scholar] [CrossRef]

83. Engoren, M. Evaluation of the cuff-leak test in a cardiac surgery population. *Chest* 1999, *116*, 1029–1031. [Google Scholar] [CrossRef]

84. Shih, J.-Y.; Lee, L.-N.; Wu, H.-D.; Yu, C.-J.; Wang, H.-C.; Chang, Y.-L.; Yang, P.-C. Sonographic imaging of the trachea. *J. Ultrasound Med.* 1997, *16*, 783–790. [Google Scholar] [CrossRef]

85. Ding, L.; Wang, H.; Wu, H.-D.; Chang, C.; Yang, P. Laryngeal ultrasound: A useful method in predicting post-extubation stridor. A pilot study. *Eur. Respir. J.* 2006, *27*, 384–389. [Google Scholar] [CrossRef]

86. Sutherasan, Y.; Theerawit, P.; Hongphanut, T.; Kiatboonsri, C.; Kiatboonsri, S. Predicting laryngeal edema in intubated patients by portable intensive care unit ultrasound. *J. Crit. Care* 2013, *28*, 675–680. [Google Scholar] [CrossRef]

87. Sahbal, M.A.; Mohamed, K.A.; Zaghla, H.H.; Kenawy, M.M. Laryngeal ultrasound versus cuff leak test in prediction of post-extubation stridor. *Egypt. J. Crit. Care Med.* 2017, *5*, 83–86. [Google Scholar] [CrossRef]

88. Tsai, W.-W.; Hung, K.-C.; Huang, Y.-T.; Yu, C.-H.; Lin, C.-H.; Chen, I.-W.; Sun, C.-K. Diagnostic efficacy of sonographic measurement of laryngeal air column width difference for predicting the risk of post-extubation stridor: A meta-analysis of observational studies. *Front. Med.* 2023, *10*, 1109681. [Google Scholar] [CrossRef] [PubMed]

89. Routsi, C.; Stanopoulos, I.; Kokkoris, S.; Sideris, A.; Zakynthinos, S. Weaning failure of cardiovascular origin: How to suspect, detect and treat—A review of the literature. *Ann. Intensive Care* 2019, *9*, 6. [Google Scholar] [CrossRef] [PubMed]

90. Oh, T.; Bhatt, S.; Lin, E.; Hutchinson, R.; Low, J. Plasma catecholamines and oxygen consumption during weaning from mechanical ventilation. *Intensive Care Med.* 1991, *17*, 199–203. [Google Scholar] [CrossRef] [PubMed]

91. Lemaire, F.; Teboul, J.-L.; Cinotti, L.; Giotto, G.; Abrouk, F.; Steg, G.; Macquin-Mavier, I.; Zapol, W.M. Acute left ventricular dysfunction during unsuccessful weaning from mechanical ventilation. *Anesthesiology* 1988, *69*, 171–179. [Google Scholar] [CrossRef]

92. Teboul, J.-L. Weaning-induced cardiac dysfunction: Where are we today? *Intensive Care Med.* 2014, *40*, 1069–1079. [Google Scholar] [CrossRef]

93. Nagueh, S.F.; Smiseth, O.A.; Appleton, C.P.; Byrd, B.F.; Dokainish, H.; Edvardsen, T.; Flachskampf, F.A.; Gillebert, T.C.; Klein, A.L.; Lancellotti, P. Recommendations for the evaluation of left ventricular diastolic function by echocardiography: An update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Eur. J. Echocardiogr.* 2016, *17*, 1321–1360. [Google Scholar]