Lung
https://doi.org/10.1007/s00408-019-00309-1

STATE OF THE ART REVIEW

Lung Ultrasound for the Diagnosis and Management of Acute Respiratory Failure

Marjan Islam[1] · Matthew Levitus[2] · Lewis Eisen[2] · Ariel L. Shiloh[2] · Daniel Fein[1]

Received: 10 December 2019 / Accepted: 14 December 2019

Abstract

For critically ill patients with acute respiratory failure (ARF), lung ultrasound (LUS) has emerged as an indispensable tool to facilitate diagnosis and rapid therapeutic management. In ARF, there is now evidence to support the use of LUS to diagnose pneumothorax, acute respiratory distress syndrome, cardiogenic pulmonary edema, pneumonia, and acute pulmonary embolism. In addition, the utility of LUS has expanded in recent years to aid in the ongoing management of critically ill patients with ARF, providing guidance in volume status and fluid administration, titration of positive end-expiratory pressure, and ventilator liberation. The aims of this review are to examine the basic foundational concepts regarding the performance and interpretation of LUS, and to appraise the current literature supporting the use of this technique in the diagnosis and continued management of patients with ARF.

Keywords Lung ultrasound · Point-of-care ultrasound · Acute respiratory failure · Pneumothorax · Acute respiratory distress syndrome · Pneumonia · Pulmonary embolism · Diaphragmatic dysfunction

Introduction

Due to the failure of ultrasound waves to propagate through air, the clinical utility of lung ultrasound (LUS) was historically questioned [1]. Once it was realized that imaging artifacts originating from the pleural line could accurately differentiate pathology from non-diseased lung, LUS experienced widespread adoption [2]. In this review, we describe proper LUS technique, how LUS may be employed to determine the cause of acute respiratory failure (ARF), appraise the current literature regarding the diagnostic accuracy of LUS for specific etiologies of ARF, and outline how LUS may be utilized for the ongoing management of the critically ill patient with ARF.

✉ Marjan Islam
mislam@montefiore.org

[1] Division of Pulmonary Medicine, Albert Einstein College of Medicine, Montefiore Medical Center, Bronx, NY, USA

[2] Division of Critical Care Medicine, Albert Einstein College of Medicine, Montefiore Medical Center, Bronx, NY, USA

Pleural and Lung Ultrasound Technique

An understanding of thoracic anatomy is necessary in order to properly apply LUS to patient care. The parietal pleura abuts the ribs. In the absence of pathology, the visceral pleura abuts the parietal pleura and, with the aid of a thin layer of pleural fluid, these two surfaces move against each other during respiration. Although the parietal and visceral pleura are not distinguishable in the absence of pathology, they slide against each other with respiration, creating an interface visible on LUS. Beneath the visceral pleura are secondary pulmonary lobules, separated by interlobular septae which themselves are connected to the visceral pleural surface [3]. Alteration of interlobular septal spaces either through fluid, inflammatory processes, or scarring allows propagation of ultrasound waves and creation of imaging artifacts discernable on ultrasound. In addition to understanding the general structures of the lung, an ultrasonographer must further correlate chest wall and lung anatomy with imaging findings at multiple locations to create a map of underlying pathological findings [4].

Before LUS is initiated, one must consider appropriate transducer selection and machine settings depending on the clinical question. Low-frequency transducers visualize deep thoracic structures and may easily image

Published online: 01 January 2020

between rib interspaces, while high-frequency transducers are best utilized to evaluate the anterior surface of the pleura and lung. We recommend initially utilizing the "Abdomen" setting, with subsequent adjustments of depth and gain, as appropriate. Utilization of other preset imaging modes may employ dynamic-filters that may degrade the visualization of artifacts that are necessary to obtain and interpret LUS findings.

A sonographer may examine any region of the chest wall that one would typically auscultate. While numerous protocols have been proposed [5–7], we advocate that in most scenarios of undifferentiated ARF, a sequence similar to that initially described by Lichtenstein termed the Bedside Lung Ultrasound in Emergency (BLUE) protocol is appropriate [8] (Fig. 1). This involves examination of 4 interspaces on each hemithorax, with the proper identification and interpretation of sonographic patterns, such as the pleural line, A-lines, B-lines, alveolar consolidation, and pleural effusion, which we have summarized in Table 1.

Lung Ultrasound to Facilitate Diagnosis in Patients with Acute Respiratory failure

The presentation of ARF without an obvious diagnosis presents a common problem for intensivists, where delay in diagnosis can be life-threatening. Fortunately, employing the BLUE protocol and identifying the foundational patterns described (Table 1) can determine an etiology rapidly and accurately [8]. For a patient in ARF, there is now robust data to support the use of LUS to diagnose pneumothorax, acute respiratory distress syndrome (ARDS), cardiogenic pulmonary edema (CPE), pneumonia, and pulmonary embolism (PE). We provide a suggested algorithm for a systematic diagnostic approach to ARF using LUS in Fig. 2.

Pneumothorax

The pleural line represents the apposition of the visceral and parietal pleura and is identified as a curvilinear, hyperechoic line beneath the ribs (Table 1). Lung sliding is identified as a to-and-fro shimmering of the visceral and parietal pleura moving against each other during respiration. In a critically ill patient, the finding of lung sliding, lung pulse, lung point, and B-lines can all be used to determine whether a patient has a pneumothorax at the point of interrogation with excellent sensitivity and adequate specificity compared to chest X-ray (Table 2). The absence of lung sliding may be suggestive, though not specific for pneumothorax as this finding can also be found in hyperinflated lungs or as a sequela of conditions resulting in pleural adhesion (i.e., pneumonia, pleurodesis). In such situations, the presence of lung pulse (the synchronous beating of the pleura with the cardiac cycle, Fig. 3c) or B-lines can rule-out pneumothorax [17]. Lung point is characterized by the alternation between normal and abolished lung sliding with respiration. This finding represents the contact point between aerated lung and the air collection of the pneumothorax, making it 100% specific for pneumothorax (Fig. 3d) [18]. Orientation of the probe in the transverse plane may further facilitate visualization of lung point when there is high pre-test probability for pneumothorax. When there is a very large pneumothorax, where no visceral pleura is in contact with the parietal pleural, no lung point is seen [19]. M (motion)-mode can be used to supplement the examiner's evaluation for pneumothorax. The to-and-fro movement of lung sliding gives a granular artifact on M-mode termed "sea-shore sign" (Fig. 3a), while its absence provides a linear artifact known as "bar-code sign" (Fig. 3b).

The accuracy of LUS for diagnosis of pneumothorax compared to chest radiography has been evaluated by four recently published meta-analyses [20–23]. LUS achieved

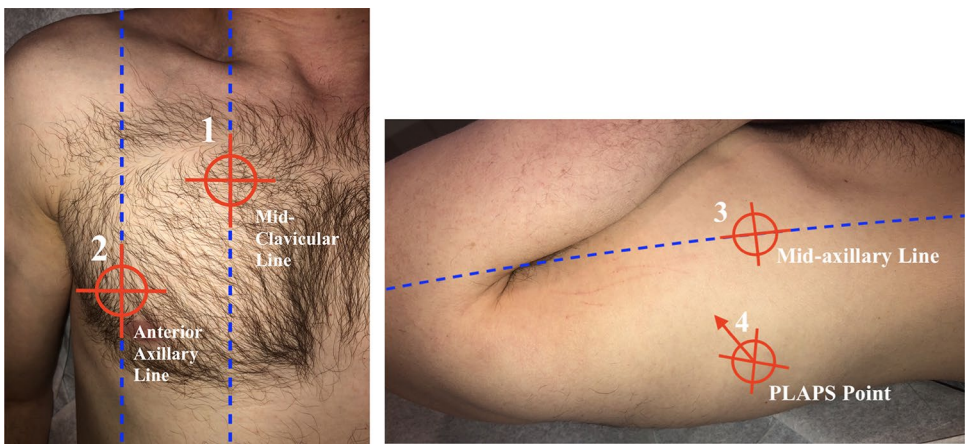


Fig. 1 The BLUE Points. Point 1 is located on the mid-clavicular line, at the second intercostal space; Point 2 is located on the anterior axillary line, at the fifth intercostal space; Point 3 is located along the diaphragm, at the mid-axillary line; and Point 4 (known as the posterolateral alveolar pleural syndrome (PLAPS) point) is located on the most posterior point along the diaphragm, where the transducer is tilted anteriorly (arrow)

Table 1 The foundational sonographic signs of lung ultrasound

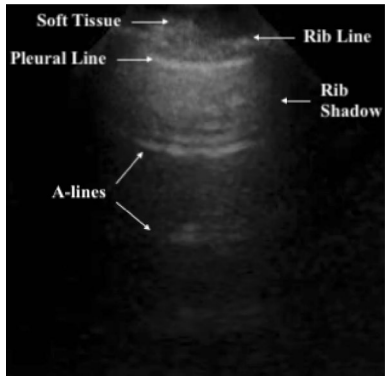
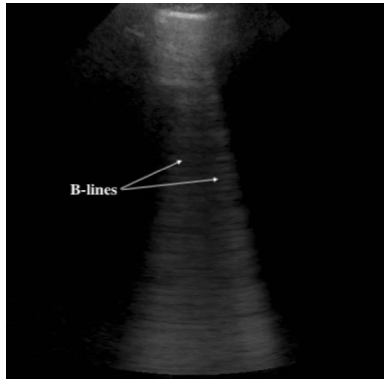
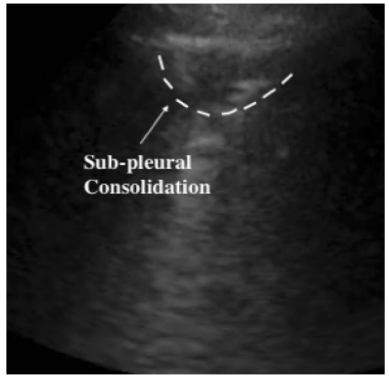
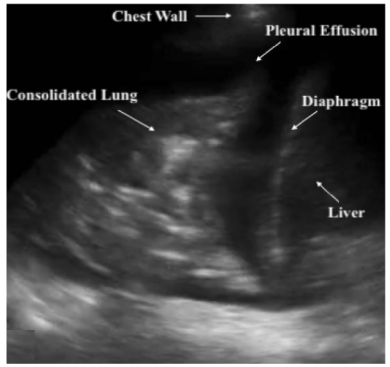
Sonographic sign	Description	Differential in acute respiratory failure	Clinical notes	Sonographic image
Pleural line [3]	Curvilinear hyperechoic line beneath the ribs representing the apposition of the visceral and parietal pleural	1. Normal Lung: (+) lung sliding or pulse 2. Pneumothorax: (−) lung sliding or pulse 3. ARDS or ILD: (+) fragmented, irregular, thickened pleura, (+) reduced lung sliding	1. Lung sliding: to-and-fro shimmering of the pleurae moving against each other with respiration 2. Lung pulse: movement of pleural surface with each systolic cardiac cycle rather than respiration 3. Lung sliding or pulse signify absence of air between the pleurae and confirm they are not fused, which can be seen in pneumonia or following pleurodesis	
A-Line [9, 10]	Horizontal hyperechoic lines equidistant from the pleural line	1. Normal lung 2. Pneumothorax: (−) lung sliding or pulse 3. Airways disease (asthma, COPD) 4. Pulmonary vascular disease (PE)	A-lines signify a high gas-to-volume ratio, and may be visualized in normal lung, hyperinflation, or in the presence of pneumothorax	
B-Line [8, 11–13]	Well-defined hyperechoic "comet-tails" extending from pleural line to the far-field and erasing intercepted A-lines	1. Cardiogenic pulmonary edema: (+) diffuse, (+) normal pleural line 2. ARDS or ILD: (+) diffuse, (+) irregular thickened fragmented pleura, (+) reduced lung sliding 3. Pneumonia: (+) focal, (+) scattered	1. B-lines result from widening of the interlobular septa from either fluid accumulation (by hydrostatic pressure or capillary permeability) or fibrosis 2. A mimic of B-lines is termed the "ring-down artifact" where hyperechoic lines do not extend to the edge of the screen; this artifact reflects subpleural fluid trapped in air 3. Up to two B-lines per field may be normal while three or more represent the "B-pattern," also known as the alveolar-interstitial syndrome	

Table 1 (continued)

Sonographic sign	Description	Differential in acute respiratory failure	Clinical notes	Sonographic image
Alveolar consolidation [9, 14, 15]	Tissue pattern from alveolar collapse with trapped fluid or air, loss of pleural line, presence of hypoechoic vascular structures, and an irregular serrated border Subpleural consolidations are juxtaposed to an irregular pleural line, representing the interface between partially aerated alveoli and collapsed or fluid-filled alveoli	1. Atelectasis: (+) static air-bronchogram 2. Pneumonia: (+) static or dynamic air-bronchogram 3. Pulmonary Infarction: (subpleural consolidation)	1. Air-bronchograms are linear, punctiform and hyperechogenic representing entrapped air within bronchi, and may be dynamic or static depending on the mobility of the air with respiration 2. A dynamic behavior is associated with infectious pneumonia as it suggests a sufficiently patent airway supplying the consolidated lung 3. A static behavior is associated with resorptive atelectasis as it suggests loss of lung volume due to hypoinflation, reflecting residual bronchial gas	
Pleural Effusion [9, 16]	Relatively anechoic space surrounded by diaphragm, chest wall, and lung	1. Transudates (heart failure, volume overload, and others) 2. Exudates (parapneumonic effusion, empyema, hemothorax, and others)	1. Echogenicity of fluid can suggest varying degrees of complexity: septations or loculations suggest parapneumonic effusion; dependent layering suggest hemothorax; an echogenic homogenous fluid suggests empyema 2. Sinusoidal movement of the visceral pleura compared to the fixed parietal pleura in M-mode suggests a free flowing effusion	

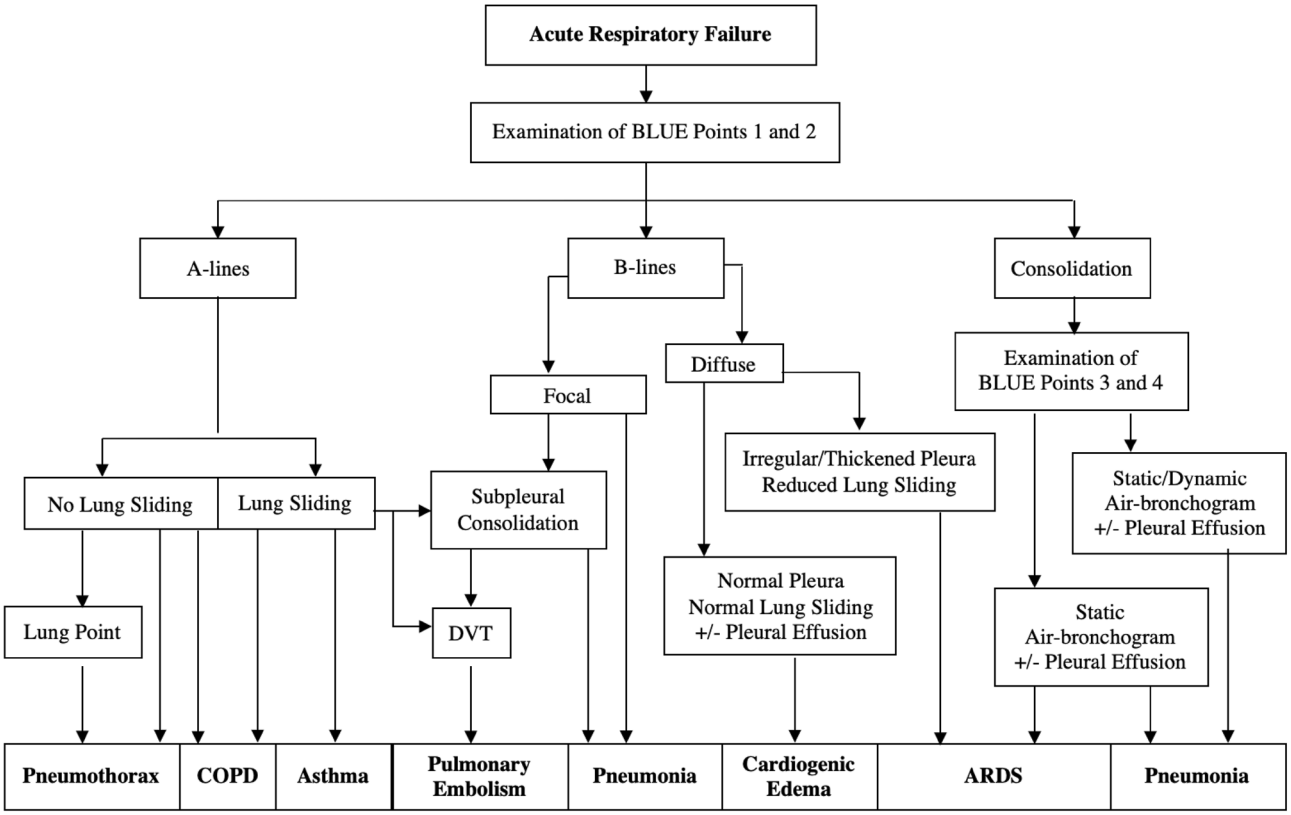


Fig. 2 Proposed algorithm for a systematic diagnostic approach to acute respiratory failure using lung ultrasound (*ARDS* acute respiratory distress syndrome, *COPD* chronic obstructive pulmonary disease, *DVT* deep vein thrombosis)

Table 2 Integration of the foundational sonographic signs for the accuracy of lung ultrasound in the diagnosis of thoracic conditions

	Foundational Sonographic signs	Sensitivity	Specificity	Clinical notes
Pneumothorax [20–23]	(−) Lung sliding (−) B-lines (+) A-lines (+) Lung point	US: 78–90% CR: 39–52%	US: > 98% CR: > 98%	Differential also includes pleural adhesion, emphysema; lung point is diagnostic of pneumothorax
Interstitial syndrome [28–31]	*CPE*: (+) B-lines [diffuse] (+) Normal pleural line (+) Lung sliding	US: 85–94% CR: 73%	US: 90–92% CR: 90%	Accuracy increases if combined with high pre-test probability of CPE
Pneumonia [35, 36, 70]	(+) B-lines [focal] (+) B-lines with (-) lung sliding (+) Alveolar consolidation (+) Static/dynamic Air-bronchogram	US: 94–97% CR: 77%	US: 90–96% CR: 91%	Combination of dynamic air-bronchogram with subpleural consolidation yields highest specificity
Pulmonary embolism [8, 43]	(+) Subpleural consolidation (+) A-lines with (+) DVT	US: 60.9% US: 81%	US: 95.9% US: 99%	If Wells > 4 or (+) D-dimer Compared to helical CT scan
Endotracheal intubation [46]	–	US: 98.7%	US: 97.1%	Ultrasound allows direct real-time visualization of ETT passing through vocal cords
Diaphragm dysfunction [63, 64]	Diaphragm excursion < 10-15 mm Diaphragm Thickening Fraction < 30%	US: 75–85%	US: 74–75%	Studies were heterogeneous in timing of diaphragm scanning and definition of extubation failure

ARDS acute respiratory distress syndrome, *CPE* cardiogenic pulmonary edema, *NCPE* non-cardiogenic pulmonary edema, *US* ultrasound, *CR* chest radiography, *CT* computed tomography, *ETT* endotracheal tube

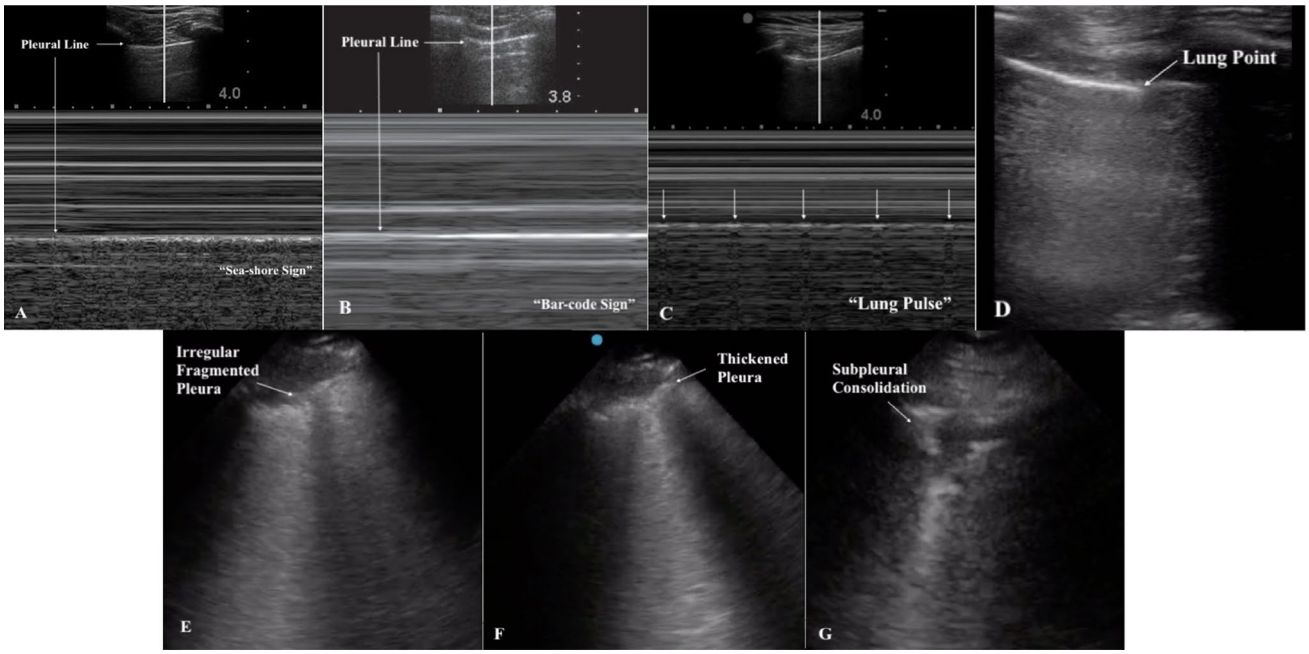


Fig. 3 M-mode for diagnosis of pneumothorax and pleuroparenchymal abnormalities in non-cardiogenic pulmonary edema. **a** Normal lung sliding: superficial tissues do not move with respiration and are represented as straight lines. The to-and-fro movement of lung sliding generates a granular artifact from the lung below the pleura, "the sea-shore sign"; **b** Absence of lung sliding without "lung pulse" presents with straight lines above and below the pleural line, "the bar-code sign". While sensitive for pneumothorax, this finding can be seen with hyperinflation or pleural adhesion; **c** Absence of lung sliding but with the presence of synchronous beating of the pleura from the heart demonstrates "lung pulse" which excludes pneumothorax; **d** "Lung point" confirms pneumothorax by identifying the contact point between the aerated lung where lung sliding is present and the air collection of the pneumothorax where lung sliding is absent. **e**, **f** Thickened and irregular pleural line can be identified; in real-time sonography, reduced lung sliding would be evident in image **e** and **f**; **g** Subpleural consolidation is visualized, representing the heterogeneous pleuroparenchymal involvement in non-cardiogenic pulmonary edema

a superior pooled sensitivity (78–90%) compared to chest X-ray (39–52%). Specificity (> 98%) was similar between both diagnostic modalities. Addition of M-mode was recently shown to increase diagnostic accuracy, especially in clinicians with less experience with LUS [24]. Compared to chest X-ray or computed tomography (CT), LUS offers the additional benefits of rapidity in diagnosis, portability, and absence of exposure to ionizing radiation, which may be particularly important in children or pregnant patients [25].

ARDS and Pulmonary Edema

B-lines arise from the pleural line, move in concert with lung sliding, and appear as well-defined hyperechoic "comet-tails," extending downwards and effacing A-lines (Table 1). This finding should not be confused with lines that do not extend to the edge of the screen, which are termed "ring-down artifact" and do not have the clinical significance of B-lines. B-lines result from widening of the pulmonary interlobular septa by either fluid accumulation (from hydrostatic pressure or capillary permeability), inflammation or fibrosis. When ultrasound waves meet the subpleural end of a thickened septum, an artifact composed of all reflections of the ultrasound beam is created [12]. Up to two B-lines may be seen in normal lung, while three or more per BLUE point is termed a "B-pattern," also known as "alveolar-interstitial syndrome" [9]. A B-pattern may serve to differentiate COPD exacerbation from CPE[13] or rule-out pneumothorax [14].

Despite the fact that alveolar-interstitial syndrome can describe a number of conditions that cause ARF, identifying pleural-line irregularity, reduced lung sliding, subpleural consolidations (Fig. 3e–g), or areas of sparing can all support a diagnosis of ARDS over CPE [26, 27], allowing clinicians to differentiate the etiology of B-lines in patients with ARF. Furthermore, interrogating the pleural line using M-mode has demonstrated that a fragmented, irregular pleural line is more commonly associated with ARDS, while a continuous pleural line is more likely seen in the setting of CPE [26].

Multiple investigations have outlined how to incorporate findings pertaining to the presence or absence of an interstitial pattern in patients with ARF. Two meta-analyses found that the interstitial syndrome may be used to diagnose

CPE with a sensitivity between 85–94% and a specificity of 92–93% in cohorts presenting with undifferentiated dyspnea [28, 29], while in patients at-risk for decompensated heart failure, an additional recent review found LUS to be more sensitive (88% versus 73%) with similar specificity (90%) compared to chest radiography for CPE [30]. Adding to this literature, a recent study found that for diagnosing CPE, combining LUS with a clinical assessment has a higher diagnostic accuracy than the combination of a clinical evaluation with chest radiography and NT-proBNP (AUC 0.95 vs 0.87) [31]. Conversely, the absence of an interstitial syndrome (A-line predominant pattern) may be useful to predict pulmonary artery occlusion pressure (PAOP) less than 18 mmHg with high specificity (93%) but limited sensitivity (50%) [12].

Pneumonia

Along with the integration of supporting clinical data, the findings of lung consolidation, patchy asymmetric B-lines, or dynamic air-bronchograms can aid in the rapid diagnosis of pneumonia. The term lung consolidation is not specific for an individual disease process, and may represent infectious or organizing pneumonia, pulmonary infarction or atelectasis among other potential diagnoses (Table 1) [14]. In the consolidated lung, alveoli may collapse or become fluid-filled. This process allows for ultrasound waves to better propagate through lung and visualize underlying consolidated tissue. Other features typical of consolidation include loss of pleural line, formation of a real-image (versus artifact), a tissue-like pattern with air-bronchograms, and an irregular serrated border ("shred sign", Table 1) [14]. Within consolidations, air-bronchograms can be identified by the presence of a linear punctiform hyperechogenicity representing entrapped air within bronchi, which may be dynamic or static depending on the mobility of the air with respiration. The dynamic behavior is a sign associated with infectious pneumonia as it suggests a sufficiently patent airway to the consolidated lung (Fig. 4b, c) [15, 32]. Dynamic air-bronchograms have been shown to yield a sensitivity and specificity of 61% and 94% for infectious pneumonia, with positive-predictive and negative-predictive values of 97% and 43%, respectively [15]. Conversely, loss of lung volume due to hypoinflation or extrinsic compression may be accompanied by static air-bronchograms: immobile hyperechogenic areas reflecting residual bronchial gas, typically associated with resorptive atelectasis (Fig. 4a) [15]. Specific for ventilator-associated pneumonia, findings of small subpleural consolidations and dynamic air-bronchograms have been shown to have the most diagnostic utility [33].

The sensitivity of LUS for detecting consolidations of any etiology has consistently been shown to be superior to chest radiography (91–100% versus 38–68%), although specificity between modalities has been found to be similar (78–100% versus 89–95%) [34–36]. Attempts to integrate LUS with clinical data have shown that a combination of LUS with gram-stain of endotracheal-aspirates to be superior to endotracheal aspirate combined with the clinical pulmonary infection score (CPIS). In this study, with LUS alone, the combination of dynamic air-bronchograms and subpleural consolidation yielded an 88% specificity for pneumonia, with a positive likelihood ratio of 2.9 [37]. Similarly, integration of procalcitonin testing with LUS has also shown promise to help diagnose ventilator-associated pneumonia [38].

Pulmonary Embolism

For the patient with suspected PE, LUS may limit the need for diagnostic CT pulmonary angiograms. Subpleural consolidations are indicative of pulmonary infarction in the context of PE, but are found in only 15–20% of patients [39–42].

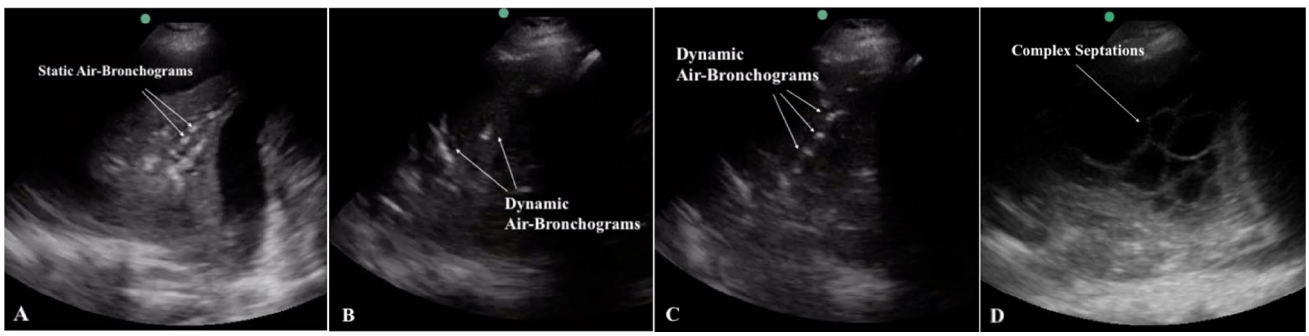


Fig. 4 Sonographic signs of Pneumonia and Pleural Diseases. **a** Punctate hyperechogenic spots (arrows) are visualized within consolidated lung that do not move with respiration identifying static air-bronchograms, suggestive of resorptive atelectasis though pneumonia is also possible; **b**, **c**) Dynamic air-bronchograms are identified by a linear hyperechoic line within consolidated lung which is highly specific for pneumonia; **d** Echogenic fluid with septated strands and consolidated lung suggest a complicated parapneumonic/inflammatory effusion with exudative adhesions

Consequently, for the patient with undifferentiated dyspnea from PE, the sensitivity of LUS alone is low. In a cohort of 260 patients with undifferentiated dyspnea, combining LUS findings with compression ultrasound for lower-extremity deep venous thrombosis found a sensitivity and specificity of 81% and 99% for PE [8]. A recent study examined LUS and compression ultrasound with the additional integration of point-of-care echocardiography [43]. In patients with a Wells score > 4 or a positive D-dimer, the ultrasound exam was considered positive for PE if subpleural consolidation, right ventricular dilation, or deep vein thrombosis was detected. In a cohort of 357 patients with 110 confirmed PE, a composite of these ultrasound findings yielded a sensitivity and specificity of 90% and 86.2% [43].

Lung Ultrasound to Facilitate Clinical Decision-Making in Patients with Acute Respiratory Failure

In addition to diagnosing ARF, there is now evidence that LUS can guide decision-making during the ongoing management of critically ill patients with ARF, with respect to confirming endotracheal tube placement following intubation, aiding decision-making regarding volume status and fluid administration, in assisting PEEP titration, and in assessing diaphragm dysfunction as a barrier to successful liberation from mechanical ventilation.

Endotracheal Intubation

Although the gold standard for confirmation of endotracheal tube placement is quantitative capnography, LUS may provide supplemental utility [44]. By scanning the anterior neck in real time during or immediately after intubation, direct visualization of the endotracheal tube in the trachea can be achieved. Visualizing a "second trachea" on LUS represents an esophageal intubation and should immediately prompt providers to attempt reintubation [45]. A recent meta-analysis demonstrated the efficacy of this technique showing the sensitivity and specificity of ultrasound to confirm successful endotracheal intubation to be 98.7% and 97.1%, respectively [46].

Volume Status and Fluid Management

The ability of LUS to rapidly evaluate for the development or resolution of B-lines as a surrogate for extravascular lung water (EVLW) may guide fluid administration during the initial resuscitation period, and predict extubation success during ventilator weaning trials. In a cohort of critically ill patients, LUS has been shown to correlate better with EVLW than chest radiography, where transpulmonary thermodilution was the gold standard [47]. It has also been noted that early fluid administration in patients with ARDS and septic shock leads to worsening interstitial edema (as measured by the progressive development of B-lines) despite no change in oxygen measurements [48]. These findings suggest that LUS may be more sensitive in detecting pulmonary congestion than non-invasive monitoring for hypoxemia. While patient-oriented outcomes-research for use of LUS to guide fluid management is only recently gaining momentum [49, 50], protocolized administration of volume guidance by LUS has been proposed, whereby interval development of B-lines during resuscitation should caution clinicians to withhold further fluid administration [51]. With regards to risk-stratification prior to endotracheal extubation, the development of five or more B-lines on the anterior chest (BLUE points 1 and 2) during spontaneous breathing trials (SBT) has been found to be an excellent predictor of SBT failure [52]. While confirmatory studies are needed, the real-time detection of B-lines during ventilator weaning can aid intensivists in assessing candidacy for successful ventilator liberation among critically ill patients, namely those with congestive heart failure [52–55].

PEEP Titration and Alveolar Recruitment

The transition from lung consolidation to coalescent B-lines or progression of B-lines to A-lines with application of increasing PEEP is reflective of successful alveolar recruitment. In patients with ARDS, this has been demonstrated through aeration of previous consolidation in dependent lung regions during uptitration of PEEP compared to controls [56]. Similar studies noted significant correlations between pressure–volume curves and LUS aeration scores during PEEP-induced alveolar recruitment in patients with ARDS [57, 58]. Successful recruitment was demonstrated as resolution of anterolateral B-lines rather than aeration of dependent consolidations [56]. Following identification of anterolateral B-lines or consolidation, a step-wise increase in PEEP with real-time visualization by LUS may identify the plateau pressure at which point improved lung aeration by alveolar recruitment has been achieved. As alveolar recruitment improves respiratory compliance, using LUS with gradual PEEP titration may guide clinicians aiming to achieve lower driving pressures, which has been associated with survival in ARDS [58, 59].

Diaphragmatic Assessment and Ventilator Weaning

Ultrasound can identify diaphragm excursion or thickening fraction to assess for diaphragmatic dysfunction [60, 61]. Excursion is assessed using M-mode by measuring diaphragmatic displacement between end-inspiration and expiration. Thickening fraction is calculated as the difference

between the thickness of the diaphragm at end-inspiration and expiration divided by expiration × 100. While the sonographic definition of diaphragmatic dysfunction is variable, a recent investigation noted these measurements to significantly correlate with endotracheal pressure during phrenic nerve stimulation, suggesting they strongly associate with diaphragm strength [62]. Despite this, measurements of diaphragmatic dysfunction to predict successful extubation have led to conflicting results [63–66].

Using proposed cut-off ranges of > 10-15 mm for diaphragmatic-excursion and > 20–30% for thickening fraction to predict extubation success, two recent meta-analyses found a pooled sensitivity and specificity of 75–85% and 74–75% [63, 64]. The studies however were heterogeneous in timing of diaphragm measurements (spontaneous breathing or otherwise) and definitions of extubation failure. In a recent prospective multicenter study of 191 mechanically ventilated patients at high risk for extubation failure, ultrasound was used to assess for diaphragmatic dysfunction (defined by excursion < 10 mm or thickening fraction < 30%) immediately following a successful SBT, and found no difference in either parameter to predict successful extubation [65]. The authors suggest diaphragmatic dysfunction may be useful in identifying mechanisms of SBT failure; however, following a successful SBT, diaphragm assessment may not add to clinical decision-making regarding whether to proceed with ventilator liberation [65].

No single application of LUS has been found to predict extubation failure. That being said, integration of the above findings along with point-of-care echocardiography may be integrated together at the bedside to guide decisions regarding the appropriateness of ventilator liberation for patients with ARF [67].

Limitations of Lung Ultrasound

Like any application of point-of-care ultrasound, LUS is operator-dependent, and requires training and practice before proficiency can be achieved. International consensus statements have suggested hands-on and didactic learning with standardized competency assessments and continued quality assurance [68, 69]. When a patient presents with ARF, clinicians must be able to not only acquire and interpret images but also appropriately integrate ultrasound findings with the clinical scenario. LUS is a testing modality rather than a therapy, and thus proper administration of treatment are essential for LUS to benefit patients. Investigations defining the influence of LUS on clinical decision-making and patient outcomes, rather than purely diagnostic accuracy, remain an area for future investigation.

While the studies we have reviewed consistently report favorably on the accuracy of LUS to diagnose and aid in management of patients with ARF, many studies were performed by expert sonographers. Clinicians can only duplicate the results of these studies if they can achieve comparable competency. Additionally, some investigations may be prone to bias brought on by lack of complete blinding of the ultrasonographer at the bedside. This may result in integration of other clinical data along with the prevalence of disease in the study cohort. Furthermore, as was seen for the use of diaphragmatic dysfunction to predict extubation failure, rigorous investigations may indeed show that, in some clinical situations, LUS may not prove to be beneficial.

Conclusion

The current era has seen LUS emerge as a well-validated modality for the diagnosis and therapeutic management of patients with ARF. LUS can be applied at the bedside in an immediate and repeated manner to help critically ill patients. While a powerful tool, the importance of provider input for integrating sonographic findings within clinical context is critical for the effective and judicious use of LUS. We believe LUS is an indispensable tool for diagnosing and managing respiratory conditions, and should be a core competency for critical care providers caring for patients with ARF.

Compliance with Ethical Standards

Conflict of interest All authors declare that they have no conflict of interest.

References

1. Weinberger S, Drazen JM (2005) Diagnostic procedures in respiratory diseases. Harrison's principles of internal medicine. McGraw-Hill, New York, pp 1505–1508
2. Lichtenstein D, Meziere G (1998) A lung ultrasound sign allowing bedside distinction between pulmonary edema and COPD: the comet-tail artifact. Intensive Care Med 24:1331–1334
3. Lichtenstein D (2010) Whole body ultrasound in the critically-ill. Springer, Berlin Heidelberg
4. Fein D (2015) Lung and pleural ultrasound technique. Point-of-Care ultrasound. Elsevier, Philadelphia, pp 51–58
5. Blaivas M, Lyon M, Duggal S (2005) A prospective comparison of supine chest radiography and bedside ultrasound for the diagnosis of traumatic pneumothorax. Acad Emerg Med 12:844–849
6. Cortellaro F, Colombo S, Coen D, Duca PG (2012) Lung ultrasound is an accurate diagnostic tool for the diagnosis of pneumonia in the emergency department. Emerg Med J 29:19–23
7. Jambrik Z, Monti S, Coppola V et al (2004) Usefulness of ultrasound lung comets as a nonradiologic sign of extravascular lung water. Am J Cardiol 93:1265–1270

8. Lichtenstein DA, Meziere GA (2008) Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest 134:117–125
9. Mojoli F, Bouhemad B, Mongodi S, Lichtenstein D (2019) Lung ultrasound for critically-ill patients. Am J Respir Crit Care Med 199:701–714
10. Goodgame. Imaging Artifacts (2015) Point-of-care ultrasound. Elsevier, Philadelphia, pp 38–45
11. Lichtenstein D, Meziere G, Biderman P, Gepner A, Barre O (1997) The comet-tail artifact. An ultrasound sign of alveolar-interstitial syndrome. Am J Respir Crit Care Med 156:1640–1646
12. Lichtenstein DA, Meziere GA, Lagoueyte JF, Biderman P, Goldstein I, Gepner A (2009) A-lines and B-lines: lung ultrasound as a bedside tool for predicting pulmonary artery occlusion pressure in the critically-ill. Chest 136:1014–1020
13. Lichtenstein D, Meziere G, Biderman P, Gepner A (1999) The comet-tail artifact: an ultrasound sign ruling out pneumothorax. Intensive Care Med 25:383–388
14. Lee P (2015) Lung ultrasound interpretation. Point-of-care ultrasound. Elsevier, Philadelphia, pp 59–69
15. Lichtenstein D, Meziere G, Seitz J (2009) The dynamic air-bromchogram. A lung ultrasound sign of alveolar consolidation ruling out atelectasis. Chest 135:1421–1425
16. Balik M (2006) Ultrasound estimation of volume of pleural fluid in mechanically ventilated patients. Intensive Care Med 32:318–321
17. Lichtenstein DA (2019) Current misconceptions in lung ultrasound: a short guide for experts. Chest 156:21–25
18. Volpicelli G, Elbarbary M, Blaivas M et al (2012) International evidence-based recommendations for point-of-care lung ultrasound. Intensive Care Med 38:577–591
19. Hew M, Tay TR (2016) The efficacy of bedside chest ultrasound: from accuracy to outcomes. Eur Respir Rev 25:230–246
20. Ding W, Shen Y, Yang J, He X, Zhang M (2011) Diagnosis of pneumothorax by radiography and ultrasonography: a meta-analysis. Chest 140:859–866
21. Alrajhi K, Woo MY, Vaillancourt C (2012) Test characteristics of ultrasonography for the detection of pneumothorax: a systematic review and meta-analysis. Chest 141:703–708
22. Alrajab S, Youssef AM, Akkus NI, Caldito G (2013) Pleural ultrasonography versus chest radiography for the diagnosis of pneumothorax: review of the literature and meta-analysis. Crit Care 17:R208
23. Ebrahimi A, Yousefifard M, Mohammad Kazemi H et al (2014) Diagnostic accuracy of chest ultrasonography versus chest radiography for identification of pneumothorax: a systematic review and meta-analysis. Tanaffos 13:29–40
24. Avila J, Smith B, Mead T, Jurma D, Dawson M, Mallin M, Dugan A (2018) Does the addition of M-mode to B-mode ultrasound increase the accuracy of identification of lung sliding in traumatic pneumothoraces? J Ultrasound Med 37:2681–2687
25. El Zahran T, El Sayed MJ (2018) Prehospital ultrasound in trauma: a review of current and potential future clinical applications. J Emerg Trauma Shock 11:4–9
26. Copetti R, Soldati G, Copetti P (2008) Chest sonography: a useful tool to differentiate acute cardiogenic pulmonary edema from acute respiratory distress syndrome. Cardiovasc Ultrasound 6:16
27. Singh AK, Mayo PH, Koenig S, Talwar A, Narasimhan M (2018) The use of M-mode ultrasonography to differentiate the causes of B lines. Chest 153:689–696
28. Al Deeb M, Barbic S, Featherstone R, Dankoff J, Barbic D (2014) Point-of-care ultrasonography for the diagnosis of acute cardiogenic pulmonary edema in patients presenting with acute dyspnea: a systematic review and meta-analysis. Acad Emerg Med 21:843–852
29. Martindale JL, Wakai A, Collins SP et al (2016) Diagnosing acute heart failure in the emergency department: a systematic review and meta-analysis. Acad Emerg Med 23:223–242
30. Maw AM, Hassanin A, Ho PM et al (2019) Diagnostic accuracy of point-of-care lung ultrasonography and chest radiography in adults with symptoms suggestive of acute decompensated heart failure: a systematic review and meta-analysis. JAMA Netw Open 2:e190703
31. Pivetta E, Goffi A, Nazerian P, Castagno D et al (2019) Study group on lung ultrasound from the molinette and Careggi Hospitals. Lung ultrasound integrated with clinical assessment for the diagnosis of acute decompensated heart failure in the emergency department: a randomized controlled trial. Eur J Heart Fail 21:754–766
32. Lichtenstein D, Mezière G, Seitz J (2002) The dynamic air-bronchogram: an ultrasound sign of nonretractile alveolar consolidation. Réanimation 11:98
33. Staub LJ, Biscaro RR, Maurici R (2018) Accuracy and applications of lung ultrasound to diagnose ventilator-associated pneumonia: a systematic review. J Intensive Care Med 33:447–455
34. Hew M, Corcoran JP, Harriss EK, Rahman NM, Mallett S (2015) The diagnostic accuracy of chest ultrasound for CT-detected radiographic consolidation in hospitalised adults with acute respiratory failure: a systematic review. BMJ Open 5:e007838
35. Hu QJ, Shen YC, Jia LQ et al (2014) Diagnostic performance of lung ultrasound in the diagnosis of pneumonia: a bivariate meta-analysis. Int J Clin Exp Med 7:115–121
36. Chavez MA, Shams N, Ellington LE et al (2014) Lung ultrasound for the diagnosis of pneumonia in adults: a systematic review and meta-analysis. Respir Res 15:50
37. Mongodi S, Via G, Girard M et al (2016) Lung ultrasound for early diagnosis of ventilator-associated pneumonia. Chest 149:969–980
38. Zhou J, Song J, Gong S, Hu W, Wang M, Xiao A, Zhang C, Dong Z (2019) Lung ultrasound combined with procalcitonin for a diagnosis of ventilator- associated pneumonia. Respir Care 64(5):519–527
39. Cha SI, Shin KM, Lee J et al (2012) Clinical relevance of pulmonary infarction in patients with pulmonary embolism. Thromb Res 130:e1–5
40. Kirchner J, Obermann A, Stuckradt S et al (2015) Lung infarction following pulmonary embolism: a comparative study on clinical conditions and CT findings to identify predisposing factors. Rofo 187:440–444
41. Miniati M, Bottai M, Ciccotosto C, Roberto L, Monti S (2015) Predictors of pulmonary infarction. Medicine (Baltimore) 94:e1488
42. Islam M, Filopei J, Frank M et al (2018) Pulmonary infarction secondary to pulmonary embolism: an evolving paradigm. Respirology. https://doi.org/10.1111/resp.13299
43. Nazerian P, Vanni S, Volpicelli G et al (2014) Accuracy of point-of-care multiorgan ultrasonography for the diagnosis of pulmonary embolism. Chest 145:950–957
44. Takeda T, Tanigawa K, Tanaka H, Hayashi Y, Goto E, Tanaka K (2003) The assessment of three methods to verify tracheal tube placement in the emergency setting. Resuscitation 56:153–157
45. Gottlieb M, Nakitende D, Sundaram T, Serici A, Shah S, Bailitz J (2018) Comparison of static versus dynamic ultrasound for the detection of endotracheal intubation. West J Emerg Med 19:412–416
46. Chou EH, Dickman E, Tsou PY et al (2015) Ultrasonography for confirmation of endotracheal tube placement: a systematic review and meta-analysis. Resuscitation 90:97–103
47. Rusu D, Siriopol I et al (2019) Lung ultrasound guided fluid management protocol for the critically-ill patient: study protocol for a multi-center randomized controlled trial. Trials 20:236

48. Caltabeloti F, Monsel A, Arbelot C et al (2014) Early fluid loading in acute respiratory distress syndrome with septic shock deteriorates lung aeration without impairing arterial oxygenation: a lung ultrasound observational study. Crit Care 18:R91
49. Noble VE, Murray AF, Capp R, Sylvia-Reardon MH, Steele DJR, Liteplo A (2009) Ultrasound assessment for extravascular lung water in patients undergoing hemodialysis. Time course for resolution. Chest 135(6):1433–1439
50. Frasure SE, Matilsky DK, Siadecki SD, Platz E, Saul T, Lewiss RE (2015) Impact of patient positioning on lung ultrasound findings in acute heart failure. Eur Heart J Acute Cardiovasc Care 4(4):326–332
51. Lichtenstein D (2012) Fluid administration limited by lung sonography: the place of lung ultrasound in assessment of acute circulatory failure (the FALLS-protocol). Expert Rev Respir Med 6(2):155–162
52. Ferre A, Guillot M et al (2019) Lung ultrasound allows the diagnosis of weaning-induced pulmonary edema. Intensive Care Med 45(5):601–608
53. Antonio A, Teixeira C, Castro P, Savi A, Maccari J, Oliveira R, Knorst M (2017) Behavior of lung ultrasound findings during spontaneous breathing trial. Rev Bras Ter Intensiva 29(3):279–286
54. Silva S, Aissa D, Cocquet P, Hoarau L, Ruiz J (2017) Combined thoracic ultrasound assessment during a successful weaning trial predicts postextubation distress. Anesthesiology 127(4):666–674
55. Soummer A, Perbet S, Brisson H et al (2012) Ultrasound assessment of lung aeration loss during a successful weaning trial predicts postextubation distress. Crit Care Med 40:2064–2072
56. Stefanidis K, Dimopoulos S et al (2011) Lung sonography and recruitment in patients with early acute respiratory distress syndrome: a pilot study. Crit Care 15:185
57. Bouhemad B, Brisson H, Le-Guen M, Arbelot C, Lu Q, Rouby JJ (2011) Bedside ultrasound assessment of positive end-expiratory pressure-induced lung recruitment. Am J Respir Crit Care Med 183:341–347
58. Tusman G, Acosta CM, Costantini M (2016) Ultrasonography for the assessment of lung recruitment maneuvers. Crit Ultrasound J 8:8
59. Amato M, Meade M et al (2015) Driving pressure and survival in acute respirtory distress syndrome. N Engl J Med 372:747–755
60. Gerscovich EO, Cronan M, McGahan JP, Jain K, Jones CD, McDonald C (2001) Ultrasonographic evaluation of diaphragmatic motion. J Ultrasound Med 20:597–604
61. Cohn D, Benditt JO, Eveloff S, McCool FD (1997) Diaphragm thickening during inspiration. J Appl Physiol 83:291–296
62. Dube BP, Dres M, Mayaux J, Demiri S, Similowski T, Demoule A (2017) Ultrasound evaluation of diaphragm function in mechanically ventilated patients: comparison to phrenic stimulation and prognostic implications. Thorax 72:811–818
63. Llamas-Alvarez AM, Tenza-Lozano EM, Latour-Perez J (2017) Diaphragm and lung ultrasound to predict weaning outcome: systematic review and meta-analysis. Chest 152:1140–1150
64. Qian Z, Yang M, Li L, Chen Y (2018) Ultrasound assessment of diaphragmatic dysfunction as a predictor of weaning outcome from mechanical ventilation: a systematic review and meta-analysis. BMJ Open 8:e021189
65. Vivier E, Muller M, Putegnat JB et al (2019) Inability of diaphragm ultrasound to predict extubation failure: a multicenter study. Chest 155:1131–1139
66. Demoule A, Molinari N, Jung B et al (2016) Patterns of diaphragm function in critically-ill patients receiving prolonged mechanical ventilation: a prospective longitudinal study. Ann Intensive Care 6:75
67. Mayo P, Volpicelli G, Lerolle N, Schreiber A, Doelken P, Vieillard-Baron A (2016) Ultrasonography evaluation during the weaning process: the heart, the diaphragm, the pleura and the lung. Intensive Care Med 42:1107–1117
68. Mayo PH, Beaulieu Y, Doelken P et al (2009) American college of chest physicians/la société de réanimation de langue française statement on competence in critical care ultrasonography. Chest 135:1050–1060
69. Cholley BP, Mayo PH, Poelaert J et al (2011) International expert statement on training standards for critical care ultrasonography. Intensive Care Med 37:1077–1083
70. Ye X, Xiao H, Chen B, Zhang S (2015) Accuracy of lung ultrasonography versus chest radiography for the diagnosis of adult community-acquired pneumonia: review of the literature and meta-analysis. PLoS ONE 10:e0130066