Pulmonary Ultrasound Examination for Edema, Effusion, and Thromboembolism

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ABSTRACT

Bedside, or point-of-care, ultrasound (US) has increasingly been used in various clinical settings to provide clinicians with rapid clinical information without the use of ionizing radiation. Lung US has been demonstrated as a valuable tool in the diagnosis and evaluation of pulmonary edema, pleural effusions, and pulmonary thromboembolism. Lung US enables the clinician to more quickly identify and initiate treatment for these potentially life-threatening conditions without the need for patient transportation to the radiology suite. Additionally, lung US can repeatedly be implemented to assess clinical changes without concern for repeated radiation exposure and is cost-effective given its ability to decrease the need for additional radiological and laboratory testing to confirm a suspected diagnosis. This review focuses on the application of lung US in the evaluation and management of pulmonary edema, pleural effusions, and pulmonary thromboembolism.

PULMONARY EDEMA

Introduction

Pulmonary edema is the phenomenon of fluid accumulation in the airspaces and parenchyma of the lung causing impairment of alveolar exchange capacity, ultimately leading to respiratory distress. For the past 2 decades, ultrasound (US) has been recognized as an important diagnostic tool for promptly and accurately recognizing pulmonary edema [1,2] because the interstitial and alveolar congestion present in pulmonary edema have direct, easily measurable ultrasonographic correlates. These correlates are known as "B-lines."

Typically, the lung is a poor transmitter of sound waves. When sound enters aerated lung parenchyma, it is scattered in all directions and little energy is reflected back to the transducer causing horizontal hyperintense lines seen at regular intervals below the pleura. These "A-lines" are reverberation artifacts caused by reflection between the skin and the pleural line, and their presence indicates aerated lung parenchyma and alveoli (see Fig. 1). The loss of A-lines suggests underlying increased density of lung from either interstitial fluid accumulation or consolidation [3]. B-lines are vertical hyperintense lines extending undiminished from the pleural line and which move with pleural sliding like spotlights. They are believed to be caused by the resonance phenomena of sound traveling through air-filled alveoli and edematous interlobular septa [4] (see Fig. 2). As extravascular lung water increases in the lungs, these lines become brighter and more numerous; ultimately, they coalesce [1].

Notably, these artifacts do not always apply specifically to pulmonary edema; rather they apply in varying degrees and, on the basis of clinical setting, to any state of parenchymal thickening in the lung, including pulmonary fibrosis, pneumonia, hemorrhage, etc. [5]. Typically focal processes such as pneumonia, contusion, atelectasis, and malignancy will be unilateral and therefore may be differentiated from more diffuse entities such as pulmonary edema. However, diffuse lung processes such as acute respiratory distress syndrome (ARDS) and pulmonary fibrosis are not well differentiated by B-lines alone. Whereas additional findings such as subpleural fluid collections and irregular pleural lines can help to distinguish pulmonary edema (thin regular pleural line) from an inflammatory process such as ARDS or fibrosis (subpleural fluid, irregular "lumpy bumpy" pleural lines), it is essential to appreciate the clinical context of the patient when performing and interpreting lung ultrasound for pulmonary edema [4].

Image Acquisition

There are several methods of scanning the lungs for signs of pulmonary edema that have been previously well described [3,6–8]. The indications for which scanning protocol is used depend on the urgency of the evaluation and in which clinical setting the examination is being performed. A 2-point positive approach can be used as a quick screen in the acutely dyspneic patient. Using a curvilinear or phased-array 2- to 5-MHz transducer on a supine or upright patient, the ultrasound should be placed between the third and fourth rib spaces in the mid-axillary line with the depth set to 18 cm. The probe marker should be toward the head, such that a longitudinal view is obtained. The presence of 3 or more B-lines is considered positive and a bilateral screen is suggestive of pulmonary edema in the acutely dyspneic patient [7]. A more complete lung evaluation suggested for emergency department patients that are not in extremis uses 8 quadrants as shown (Fig. 3). In this scanning protocol, 3 or more B-lines makes

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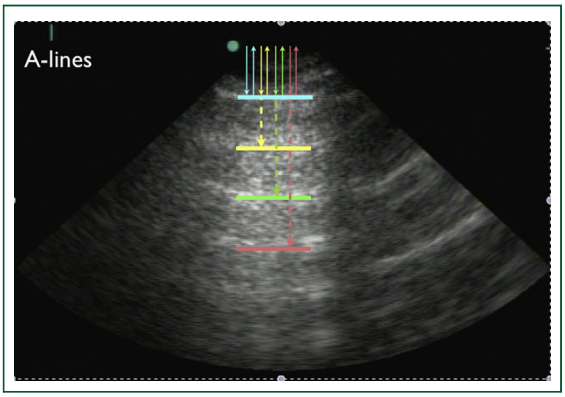

FIGURE 1. A lines—horizontal reverberation artifact caused by sound reflecting between the skin and pleura.

a quadrant positive and 2 quadrants per side must be positive to suggest pulmonary edema [8]. An even more complete evaluation uses 28 zones and has been used mostly to evaluate stable patients with congestive heart failure or as a research tool to more completely evaluate lung parenchyma [9]. This more complete scanning protocol has been shown to correlate with wedge pressure (i.e., more B-lines correlates with higher wedge pressure) [8,9] as well as to have prognostic significance (i.e., more B-lines correlates with higher 30-day mortality) [10].

Use in Clinical Setting

A number of studies have looked at the clinical efficacy of using lung US to diagnose and monitor pulmonary edema in an acute setting. The overall theme of much of the data is that lung ultrasound to evaluate for pulmonary edema in the appropriate context obviates the need for additional specialized laboratory or radiographic testing.

In a global health setting, laboratory tests or radiography are often unavailable, and when they are available, they require time and money to perform, making it difficult

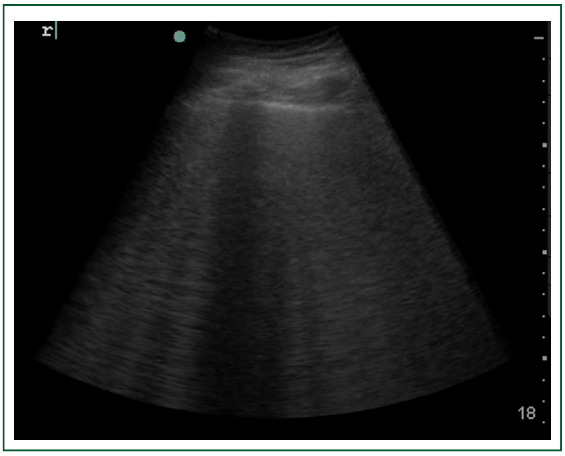

FIGURE 2. B lines—vertical artifact caused by increased extravascular lung water.

to obtain prompt results. N-terminus brain natriuretic peptide (BNP) is an accepted marker of atrial stretching reflecting increased left atrial pressures; multiple studies have noted its correlation with increased extravascular lung water [2,10,11]. However, a positive B-line lung US examination using the Volpicelli 8-zone technique was found to have a higher likelihood ratio for acute congestive heart failure over BNP (3.9 vs. 2.3), suggesting a higher sensitivity when compared to the lab result alone [2]. This relationship has been even more firmly established by the study showing the correlation between pulmonary wedge pressure and presence of B-lines ($r = 0.48$; $p < 0.01$) as mentioned [9].

In a standard pulmonary edema evaluation, chest radiography is routinely ordered to document extravascular fluid. However, several studies have shown US to be similarly sensitive (85% US vs. 93% chest X-ray) [6] in diagnosing pulmonary edema compared with standard chest radiography, with more recent data suggesting the sensitivity and specificity of lung US is superior to chest radiography (US 99% vs. chest X-ray 97% sensitivity; US 61% vs. chest X-ray 32% specificity) [12]. Indeed, several studies have shown that lung US is an excellent method of more quickly and more accurately differentiating pulmonary edema in the setting of congestive heart failure exacerbation from the complications of chronic obstructive pulmonary disease [13–15].

In addition to the diagnostic advantage lung US provides, it has also been shown to be useful in monitoring the efficacy of interventions to treat pulmonary edema. This is an advantage over chest radiography, as the lag between symptoms and radiographic correlates of extravascular lung water is known to be 24 to 48 h. Several studies have demonstrated this superiority by observing the resolution of B-lines during hemodialysis [16]or after administration of continuous positive airway pressure [17] (Fig. 4). This data shows that frequent reassessment with lung US can provide real-time feedback about the efficacy of interventions.

More recent studies combine cardiac and lung ultrasound to produce composite markers of volume status and cardiac function [18]. This data is emerging and is yet of unclear clinical utility.

Future research in lung US evaluation for pulmonary edema aims to find ways to better differentiate pulmonary edema from ARDS [4] and other processes causing interstitial alveolar syndrome to help even more precisely to diagnose lung disease states.

In conclusion, lung US in the evaluation of pulmonary edema has been found to be as good or superior to traditional evaluations with chest radiography and equivalent to testing for elevated BNP. Additionally, there is evidence to support its use in monitoring the efficacy of interventions used to treat pulmonary edema and individual patient responses to treatment. The role of lung US in conjunction with cardiac US for discriminating different types of interstitial alveolar syndrome are currently active areas of research.

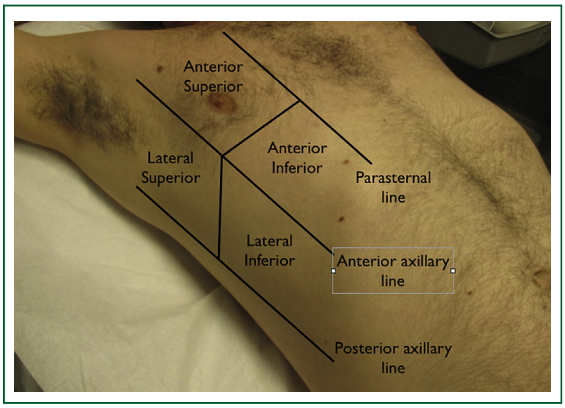

FIGURE 3. The 8 zones used to do a quick emergency department evaluation of the lung using ultrasound.

Artifacts and Pitfalls

- In an upright or slightly upright patient, superior lung fields may have no B-lines and be falsely reassuring as fluid accumulates preferentially to more-dependent areas first.
- Post-processing computations of some US machines may degrade or erase artifacts (B-lines); these post-processing algorithms may need to be turned off to make the best use of lung US.
- Pneumonia, interstitial fibrosis, ARDS, and atelectasis can all evoke B-lines. The patient's clinical context should still be taken into consideration when interpreting these artifacts. Numerous areas of the lung should also be sampled to differentiate a diffuse process (pulmonary edema) from a more focal process (pneumonia).
- B-lines in the dependent areas of a supine patient should also be evaluated with caution. Even healthy subjects may have posterior lateral lung fields with 3 or more B-lines if they have been supine for an extended period of time.

PLEURAL EFFUSION

Introduction

A pleural effusion is a collection of fluid in the potential space between the parietal and visceral pleura of the thoracic cavity. The clinical significance of a pleural effusion can range from minimal to immediately life threatening depending on the size of the pleural effusion, the comorbidities of the patient, and the physiologic reserve of the patient. Pleural effusions are also classified as either a transudate or exudate depending on the etiology and composition of the fluid. Transudative pleural effusions are most often caused by heart failure, atelectasis, or translocation of ascitic fluid across the diaphragm. Exudative pleural effusions can be caused by many different etiologies but are commonly related to a malignancy, infection, or an inflammatory process. Pleural fluid analysis focusing on cell count, pH, protein, lactate dehydrogenase, gram stain, culture, and glucose is the foundation for classifying a transudate versus an exudate [19,20].

Traditionally physical examination findings and chest radiography have been used to identify the presence of pleural effusions. Additional details about a pleural effusion can be obtained using computed tomography (CT) scan; however, this is costly and exposes the patient to ionizing radiation. Lung US has been increasingly used to locate, quantify, and aid in the drainage of pleural effusions given the advantages of portability, expedience, and absence of ionizing radiation that US affords. Additionally, lung US has been found to have a higher sensitivity and specificity when compared to chest radiography for the identification of pleural effusions, especially in supine patients (sensitivity 93%, specificity 96%) [21], has comparable sensitivity for the detection of small pleural effusions (positive predictive value 92%) compared to lateral decubitus chest plain radiographs [22], is superior to plain radiographs in quantifying pleural effusions [23], and nonradiology physicians have been shown to be accurate in identifying the presence or absence of a pleural effusion with the use of US [24,25].

Image Acquisition

A curvilinear probe with low frequency, 3.5 to 5.0 MHz (which provides images at a greater depth compared with those from a linear probe with high frequency), should be used when evaluating for or examining a pleural effusion to ensure lung tissues and solid organs are identified. Given that pleural effusions are collections of fluid, they are subject to gravity and will be present in the pleural space between the parietal pleura abutting the diaphragm and the

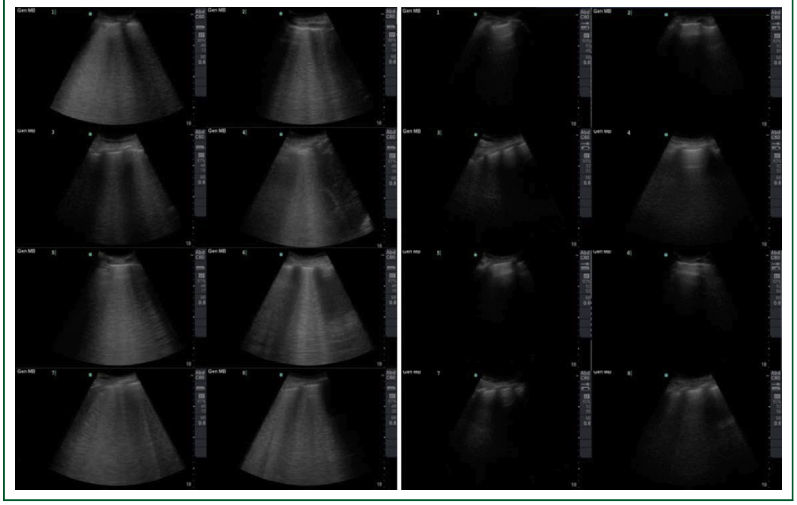

FIGURE 4. Real-time resolution of the positive scan on the left to the negative scan on the right. The B-lines resolved in minutes with just the administration of continuous positive airway pressure ventilation.

visceral pleura of the inferior lung tissue when a patient is semirecumbent.

With the patient laying supine, the probe should be placed parallel to the examination table (i.e., horizontal) in the mid- to posterior axillary line on either the right or left side of the patient (Fig. 5). Small fanning and rotary adjustments of the probe should be performed to optimize visualization of the hyperechoic curvilinear diaphragm and decrease the amount of rib shadowing. Once the diaphragm has been clearly identified, one should look superior to the diaphragm for the presence of a pleural effusion, which can appear as either an anechoic or hypoechoic region that may or may not contain loculations and septations (Fig. 6). Additional lung US signs suggestive of the presence of a pleural effusion include the presence of a "spine sign," which is the visibility of the thoracic spine above the diaphragm [25] (Fig. 7). The thoracic spine is seen here because the sound from the ultrasound is transmitted through the echolucent fluid and the thoracic spine can thus be visualized. Oftentimes, hyperechoic lung parenchyma can be seen floating within the anechoic effusion due to compression atelectasis giving the appearance of a "waving hand" (Fig. 7) [26]. The presence of multiple gyrating echogenicities with the appearance of "snow flurries" should raise suspicion for a possible hemothorax. In a patient without a pleural effusion, one should expect to visualize the normal presence of "mirroring artifact" of the liver or spleen superior to the diaphragm. Moreover, in a well-aerated lung, the air acts as a barrier to the sound and so the spine shadows stop at the diaphragm and are covered up with each inspiration as the diaphragm moves caudally (Fig. 8).

If the pleural effusion is large or if a thoracentesis will be performed, US can also be used to guide the procedure, and indeed, there is evidence that there are fewer complications with thoracentesis when US is used [26–29]. A spontaneously breathing patient should be placed in an upright-seated position with the probe placed in the mid-scapular line to assess for an anechoic or hypoechoic region (indicative of a pocket of fluid), separating the visceral and parietal pleura, which may be accessible by a needle during a thoracentesis. It is important to visualize the pocket during a respiratory cycle to ensure the diaphragm is visualized in both an inspiratory and expiratory phase so that the needle is inserted above the maximal diaphragmatic height. The needle should also be inserted to a depth less than the distance from the skin to the visceral pleura (as this can be seen on ultrasound).

The time required to obtain the necessary US images to assess for a pleural effusion should not be a limiting factor in performing a lung US as this examination has been found to take less than 3 min to complete [30].

It is important to note that the presence of a large pleural effusion can be incidentally discovered while performing a cardiac US, specifically in the parasternal long view. If fluid is present posterior to the descending thoracic aorta (rather than anterior, which would be indicative of a pericardial effusion) then a complete lung US should be performed to further assess the pleural effusion (Fig. 9).

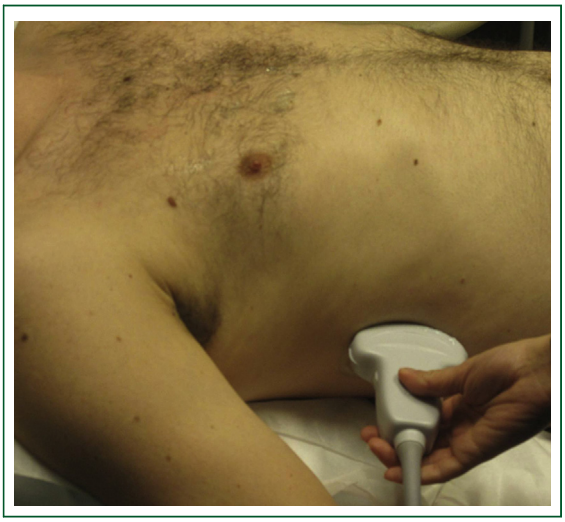

FIGURE 5. Probe position when evaluating for pleural effusion.

Use in Clinical Setting

Lung US is an effective clinical tool to evaluate for the presence of a pleural effusion, to aid in classification of the effusion, and to assist in performing a successful and safe thoracentesis should one be indicated. In the supine patient, it is difficult to tell on chest radiography between consolidation and an effusion, as both will appear to be white opacities. On lung US, however, this distinction is quite easy and can be done at the bedside.

When attempting to characterize the effusion, a sample of pleural fluid is the "gold standard" to diagnose a transudate versus an exudate. However, certain appearances of pleural effusions on lung US can help distinguish these 2

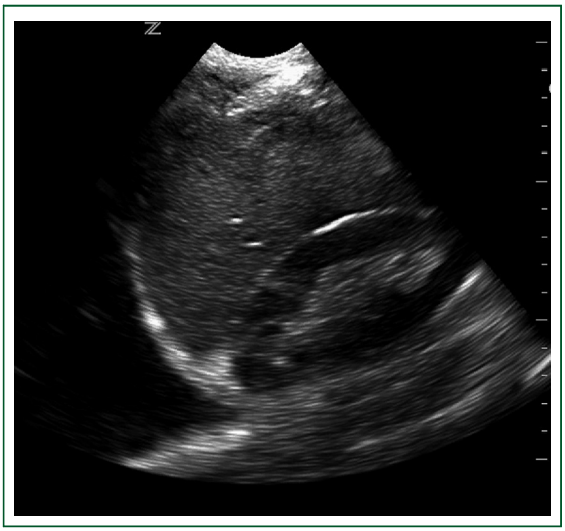

FIGURE 6. Pleural effusion with anechoic space above the diaphragm.

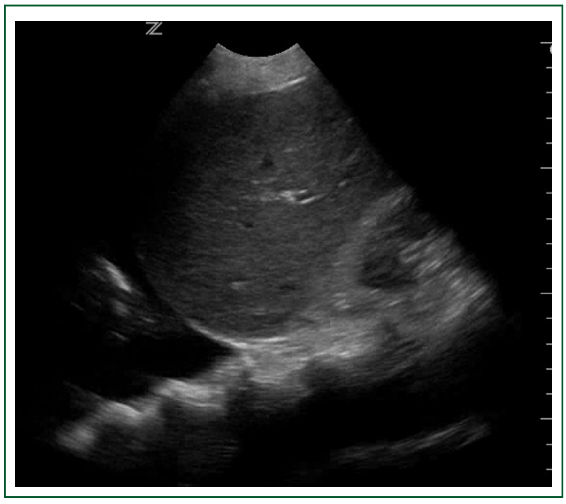

FIGURE 7. Spine sign with visible effusion. In addition, you can see the tip of the atelectatic lung floating in the pleural effusion.

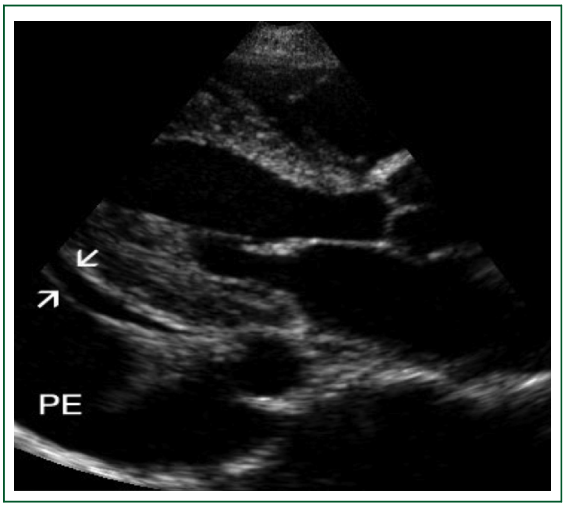

FIGURE 9. Pericardial versus pleural effusions in the parasternal long-axis view of the heart. PE, pleural effusion.

categorizations. The presence of an anechoic, or black, region superior to the diaphragm is indicative of a pleural effusion. An anechoic appearance can be seen in both transudates and exudates; therefore, this sonographic description of the fluid is not diagnostic. However, the presence of complex septated or echogenic fluid is suggestive of an exudate [31].

Thoracentesis has been demonstrated to be safer when done under US guidance. The optimal location to perform a thoracentesis is where the largest region of fluid is present, affording the least risk of puncturing a solid organ, lung tissue, or a neurovascular bundle. Using US guidance to select a puncture site for thoracentesis has been shown to be more effective than using the physical examination and decreases the risk of organ puncture [32]. Using US dynamically while performing a thoracentesis significantly increases the likelihood of successful pleural fluid aspiration and is favorable versus using US to mark an "X" on the skin followed by blind insertion [28,32,33]. Additionally, implementing US guidance while performing a thoracentesis has been shown to reduce the rate of iatrogenic pneumothorax, hemorrhage, and hospital costs [27,28,34]. Lung US also allows the user to identify any possible adhesions or loculations within the pleural effusion [26], which may influence the technical difficulty and increase the risk of procedural complications associated with performing a thoracentesis.

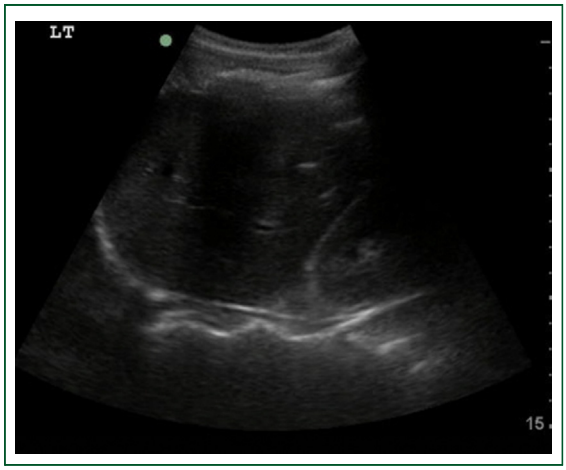

FIGURE 8. Normal examination—no pleural fluid is present. In addition, you can see here that the diaphragm and the spine meet at a point with the aerated lung blocking visibility of the thoracic spine.

Lung US has been shown to be accurate in estimating the volume of a pleural effusion [35]. Quantifying the volume of a pleural effusion can be achieved by placing the patient in a supine position, elevating the trunk to 15°, measuring the distance between the parietal and visceral pleura in the posterior axillary line in millimeters, and then multiplying this distance by 20 to obtain an estimated effusion volume in milliliters [33—35]. More complicated equations using a multiplanar approach have also been shown to be accurate in measuring pleural effusion volume as well [36,37]. Following completion of a thoracentesis, US can be used to quantify any remaining pleural effusion in the same manner in which the pleural effusion was measured prior to the thoracentesis.

Finally, the use of lung US in the intensive care unit setting for evaluation of pleural effusions has been shown to significantly decrease the number of chest plain radiographs and CT scans obtained [34]. Given the ability to implement at the bedside, and the lack of radiation, the lung US examination can be performed repeatedly to assess for changes in pleural effusions without concern for cumulative radiation exposure.

Artifacts and Pitfalls

- Failure to appreciate that the diaphragm and solid organs are dynamic structures that change position during inspiration and expiration when determining the puncture site for a thoracentesis.
- Failure to appreciate that minor changes in patient position can drastically affect the location and volume of a pleural effusion in a certain area of the pleural cavity.
- Failure to assess for and identify septated loculations and/or pulmonary adhesions, which increase the risk for procedural complications during a thoracentesis.
- Certain patient characteristics and clinical scenarios can make image acquisition of a pleural effusion using lung US more difficult. Subcutaneous emphysema can make lung US less accurate as the air in the subcutaneous tissues will scatter sound and thus prevent a full evaluation of the thoracic cavity. In addition, an obese habitus or the presence of any nonremovable tubes, lines, drains, bandages, or equipment overlying the chest surface will prevent good US images of the thoracic cavity. When good images are not obtainable, traditional radiologic evaluation is preferred

THROMBOEMBOLISM

Introduction

Thrombosis of the pulmonary vasculature or pulmonary embolism (PE) is among the more challenging diagnoses to make, as patients can have myriad presentations from mild pleurisy to cardiogenic shock and cardiac arrest [38]. The size of the PE, the location within the pulmonary vasculature, and the comorbidities of the patient can influence the signs and symptoms that a patient may experience.

Traditionally, the diagnosis of PE has been made with advanced radiology studies that require time, hemodynamic stability, transport to a radiology suite, intravenous contrast material, and exposure to ionizing radiation [39]. Whereas CT pulmonary angiography remains the preferred radiologic study for the diagnosis of PE [40,41], the lung, cardiac, and venous US findings in patients with PE can aid in clinical decision making—especially in patients who are hemodynamically unstable or in whom CT is contraindicated. US enables medical providers to rapidly obtain evidence that supports the diagnosis of PE and refutes other possible diagnoses, which subsequently facilitates initiation of early therapeutic measures including thrombolysis, anticoagulation, and specialty care consultation, which is especially important in patients who present with hemodynamic instability and are unable to tolerate transport to a radiology suite [42,43].

Image Acquisition

The US evaluation for PE involves a combination of 3 US examinations: cardiac; venous; and pulmonary. This multiorgan system approach has been shown to be more sensitive in the diagnosis of PE compared with a single organ system evaluation and may reduce the use of unnecessary CT angiography [44]. Cardiac US signs of PE include a dilated right ventricle, intraventricular septal bowing, right ventricular free wall hypokinesis with normal contractions at the apex (McConnell sign), inferior vena cava dilation without inspiratory collapse, and thrombus in transit [44–46]. Extremity US signs include evidence of a deep vein thrombosis, which confirms the presence of potential embolic thrombus [47]. Whereas the cardiac and extremity US examinations are most commonly used to assess for direct and indirect signs of a PE, the lung US examination provides the clinician with the opportunity to obtain additional clinical information during the evaluation of a patient with a suspected PE. A full discussion of the cardiac and venous ultrasound applications is beyond the scope of this paper; here the focus will be exclusively on the lung US examination and how it relates to the diagnosis of PE.

Both linear high-frequency (4 to 8 MHz) and curvilinear or convex (3.5 to 5 MHz) US probes can be used during the lung examination to assess for signs of PE [48]. The linear probe offers a higher-quality image while sacrificing the ability to obtain images in the deeper tissues, whereas the curvilinear probe allows one to obtain images located deeper in the tissues while sacrificing image detail. Patient factors such as body habitus help determine the appropriate US probe to use. A complete examination requires evaluation of both the anterior and posterior chest. The anterior chest can be evaluated with the patient in the supine position, whereas the posterior chest can be examined with the patient in the left and right lateral decubitus positions or while sitting upright. If the patient is experiencing chest discomfort, then the examination should begin in that region of the chest followed by systematic placement of the probe in an oblique fashion in each intercostal space to best visualize the lung parenchyma in each of the following anatomical vertical landmark lines: mid-clavicular; anterior axillary; mid-axillary; posterior axillary; mid-scapular; and paravertebral [49].

The goal of lung US in the evaluation of PE is the detection of pulmonary infarcts that are a result of pulmonary artery vascular occlusion. These infarcts appear as pleural-based, homogenous, hypoechoic consolidations that are wedge-shaped (triangular) or round and can have either blurry edges or they can be well demarcated (Fig. 10) [48]. Lesions <5 mm in size are difficult to differentiate from pulmonary nodules and scars. Identification of 2 of these classic-appearing consolidations confirm the diagnosis of PE [27,50]. A hyperechoic signal in the center of infarcted lung parenchyma may be visible in older infarcts and is representative of a bronchiole [50,51]. Other lung US signs that may be visualized in the presence of a PE include absence of pulmonary arterial flow within the infarcted region when Doppler US is applied to the consolidation, fluid collections (pleural effusions) adjacent to a pleural infarction, and evidence of a congested thromboembolic vessel, which may be referred to as a "vascular sign" [48,49,51].

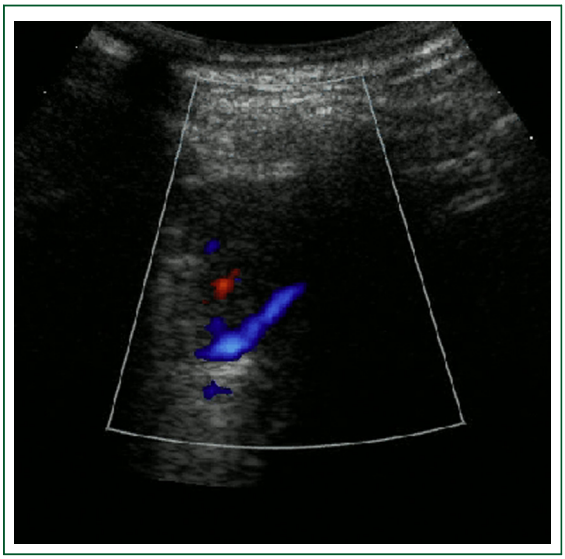

FIGURE 10. Pulmonary infarct.

The US appearance of PE can be differentiated from pneumonia in that a pneumonia typically appears as a heterogeneous hypoechoic region with variable shape and irregular borders, and it can contain multiple echogenic foci, which represent air bronchograms (Fig. 11), whereas a PE appears as a homogenous, triangular or round, hypoechoic region [49].

Image acquisition may limited or difficult to obtain in situations where the lesion of interest is not peripherally located in the pleura; there is air in the pleural space (pneumothorax); there is subcutaneous emphysema in the tissue overlying the pleural space; or if the lesion of interest is located behind a bony structure such as a rib [49].

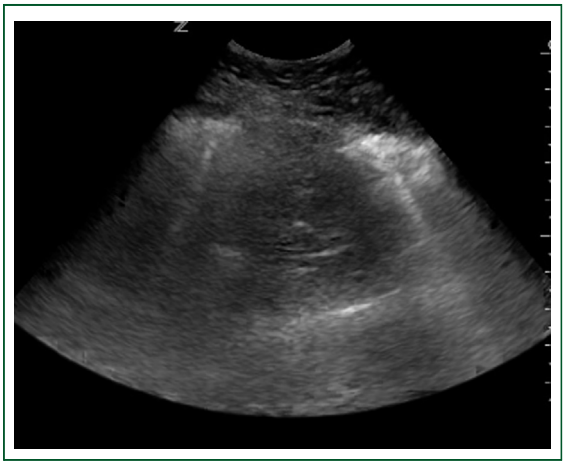

FIGURE 11. Consolidation representing pneumonia in the middle of the image. The consolidation is surrounded by interstitial fluid represented by B-lines and an irregular pleural line.

Use in Clinical Setting

It is crucial that providers appreciate that a negative lung US cannot be used to rule out the presence of a PE. Rather, it should be used as a tool that can be used at the bedside in an efficient, noninvasive, and cost-effective manner without the use of radiation to provide the clinician with additional information that may influence and expedite clinical decision making, including the decision to administer thrombolytic or anticoagulant therapy. Utilization of lung US is particularly valuable in resource-limited settings where CT pulmonary angiography is not readily available and in clinical scenarios where the patient is unable to undergo pulmonary angiography due to hemodynamic instability.

Prospective studies in the clinical setting have shown lung US to be an accurate and effective tool when used correctly in the evaluation for PE. These studies focused on patients suspected of having a PE and revealed the sensitivity, specificity, positive predictive value, negative predictive value, and diagnostic accuracy of lung US in the evaluation of PE to range from 74% to 90%, 60% to 95%, 77% to 95%, 72% to 80%, and 78% to 84%, respectively [48,50,52,53]. A systematic review and meta-analysis of the diagnostic accuracy of lung US for PE revealed a sensitivity of 87% and specificity of 82% [54].

Incorporation of lung US into the armamentarium of diagnostic tools for evaluation of PE has minimal risk to the patient and has the potential benefit to quickly detect the presence of a PE, thus expediting treatment.

Artifacts and Pitfalls

- Failing to consider the use of bedside lung US in a patient suspected of having a PE.
- Using a negative lung US to "rule out" PE in a patient.
- Failing to include a lung US examination in addition to cardiac and extremity US examinations during the bedside US evaluation for PE and thus losing the added specificity of the composite US findings.
- To date, lung US has not been used to help make the decision to administer thrombolysis—this risk analysis mostly uses cardiac signs of right ventricle strain and markers such as troponin and BNP that indicate myocardial stretch and damage. However, by demonstrating a pulmonary infarct, perhaps a graded system using US to assess the size of the infarct could be incorporated into the risk benefit analysis of thrombolysis.

REFERENCES

1. Lichtenstein D, Mézière G, Biderman P, Gepner A, Barré O. The comet-tail artifact: an ultrasound sign of alveolar-interstitial syndrome. Am J Respir Crit Care Med 1997;156:1640–6.
2. Liteplo AS, Marill KA, Villen T, et al. Emergency thoracic ultrasound in the differentiation of the etiology of shortness of breath (ETUDES): sonographic B-lines and N-terminal pro-brain-type natriuretic peptide in diagnosing congestive heart failure. Acad Emerg Med 2009;16:201–10.

3. Lichtenstein D. General Ultrasound in the Critically Ill. Berlin: Springer; 2005.
4. Copetti R, Soldati G, Copetti P. Chest sonography: a useful tool to differentiate acute cardiogenic pulmonary edema from acute respiratory distress syndrome. Cardiovasc Ultrasound 2008;6:16.
5. Smargiassi A, Inchingolo R, Soldati G, et al. The role of chest ultrasonography in the management of respiratory diseases: document II. Multidiscip Respir Med 2013;8:55.
6. Volpicelli G, Mussa A, Garofalo G, et al. Bedside lung ultrasound in the assessment of alveolar-interstitial syndrome. Am J Emerg Med 2006;24:689–96.
7. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest 2008; 134:117–25.
8. Agricola E, Bove T, Oppizzi M, et al. "Ultrasound comet-tail images": a marker of pulmonary edema: a comparative study with wedge pressure and extravascular lung water. Chest 2005;127:1690–5.
9. Volpicelli G, Caramello V, Cardinale L, Mussa A, Bar F, Frascisco MF. Bedside ultrasound of the lung for the monitoring of acute decompensated heart failure. Am J Emerg Med 2008;26:585–91.
10. Frassi F, Gargani L, Tesorio P, Raciti M, Mottola G, Picano E. Prognostic value of extravascular lung water assessed with ultrasound lung comets by chest sonography in patients with dyspnea and/or chest pain. J Card Fail 2007;13:830–5.
11. Davis M, Espiner E, Richards G, et al. Plasma brain natriuretic peptide in assessment of acute dyspnoea. Lancet 1994;343:440–4.
12. Martindale JL, Noble VE, Liteplo A. Diagnosing pulmonary edema: lung ultrasound versus chest radiography. Eur J Emerg Med 2013;20: 356–60.
13. Cardinale L, Volpicelli G, Binello F, et al. Clinical application of lung ultrasound in patients with acute dyspnea: differential diagnosis between cardiogenic and pulmonary causes. Radiol Med 2009;114: 1053–64.
14. Lichtenstein D, Mezière G. A lung ultrasound sign allowing bedside distinction between pulmonary edema and COPD: the comet-tail artifact. Intensive Care Med 1998;24:1331–4.
15. Silva S, Biendel C, Ruiz J, et al. Usefulness of cardiothoracic chest ultrasound in the management of acute respiratory failure in critical care practice. Chest 2013;144:859–65.
16. Noble VE, Murray AF, Capp R, Sylvia-Reardon MH, Steele DJ, Liteplo A. Ultrasound assessment for extravascular lung water in patients undergoing hemodialysis: time course for resolution. Chest 2009;135:1433–9.
17. Liteplo AS, Murray AF, Kimberly HH, Noble VE. Real-time resolution of sonographic B-lines in a patient with pulmonary edema on continuous positive airway pressure. Am J Emerg Med 2010;28:541.e5–8.
18. Anderson KL, Jenq KY, Fields JM, Panebianco NL, Dean AJ. Diagnosing heart failure among acutely dyspneic patients with cardiac, inferior vena cava, and lung ultrasonography. Am J Emerg Med 2013;31: 1208–14.
19. Hooper C, Lee YC, Maskell N. BTS Pleural Guideline Group. Investigation of a unilateral pleural effusion in adults: British Thoracic Society Pleural Disease Guideline 2010. Thorax 2010;65(Suppl 2):ii4–17.
20. Light RW. Clinical practice: pleural effusion. N Engl J Med 2002;346: 1971–7.
21. Grimberg A, Shigueoka DC, Atallah AN, Ajzen S, Iared W. Diagnostic accuracy of sonography for pleural effusion: systematic review. Sao Paulo Med J 2010;128:90–5.
22. Kocijancic I, Vidmar K, Ivanovi-Herceg Z. Chest sonography versus lateral decubitus radiography in the diagnosis of small pleural effusions. J Clin Ultrasound 2003;31:69–74.
23. Eibenberger KL, Dock WI, Ammann ME, Dorffner R, Hörmann MF, Grabenwöger F. Quantification of pleural effusions: sonography versus radiography. Radiology 1994;191:681–4.
24. Rahman NM, Singanayagam A, Davies HE, et al. Diagnostic accuracy, safety and utilisation of respiratory physician-delivered thoracic ultrasound. Thorax 2010;65:449–53.
25. Rozycki GS, Pennington SD, Feliciano DV. Surgeon-performed ultrasound in the critical care setting: its use as an extension of the physical examination to detect pleural effusion. J Trauma 2001;50: 636–42.
26. Tirado A, Wu T, Noble VE, et al. Ultrasound-guided procedures in the emergency department-diagnostic and therapeutic asset. Emerg Med Clin North Am 2013;31:117–49.
27. Reissig A, Copetti R, Kroegel C. Current role of emergency ultrasound of the chest. Crit Care Med 2011;39:839–45.
28. Duncan DR, Morgenthaler TI, Ryu JH, Daniels CE. Reducing iatrogenic risk in thoracentesis: establishing best practice via experiential training in a zero-risk environment. Chest 2009;135:1315–20.
29. Patel PA, Ernst FR, Gunnarsson CL. Ultrasonography guidance reduces complications and costs associated with thoracentesis procedures. J Clin Ultrasound 2012;40:135–41.
30. Tayal VS, Nicks BA, Norton HJ. Emergency ultrasound evaluation of symptomatic nontraumatic pleural effusions. Am J Emerg Med 2006; 24:782–6.
31. Yang PC, Luh KT, Chang DB, Wu HD, Yu CJ, Kuo SH. Value of sonography in determining the nature of pleural effusion: analysis of 320 cases. AJR Am J Roentgenol 1992;159:29–33.
32. Diacon AH, Brutsche MH, Solèr M. Accuracy of pleural puncture sites: a prospective comparison of clinical examination with ultrasound. Chest 2003;123:436–41.
33. Havelock T, Teoh R, Laws D, et al., for the BTS Pleural Disease Guideline Group. Pleural procedures and thoracic ultrasound: British Thoracic Society Pleural Disease Guideline 2010. Thorax 2010;65-(Suppl 2):ii61–76.
34. Peris A, Tutino L, Zagli G, et al. The use of point-of-care bedside lung ultrasound significantly reduces the number of radiographs and computed tomography scans in critically ill patients. Anesth Analg 2010;111:687–92.
35. Vignon P, Chastagner C, Berkane V, et al. Quantitative assessment of pleural effusion in critically ill patients by means of ultrasonography. Crit Care Med 2005;33:1757–63.
36. Balik M, Plasil P, Waldauf P, et al. Ultrasound estimation of volume of pleural fluid in mechanically ventilated patients. Intensive Care Med 2006;32:318–21.
37. Remérand F, Dellamonica J, Mao Z, et al. Multiplane ultrasound approach to quantify pleural effusion at the bedside. Intensive Care Med 2010;36:656–64.
38. Goldhaber SZ. Pulmonary embolism. Lancet 2004;363:1295–305.
39. Huppmann MV, Johnson WB, Javitt MC. Radiation risks from exposure to chest computed tomography. Semin Ultrasound CT MR 2010;31:14–28.
40. Pena E, Dennie C. Acute and chronic pulmonary embolism: an in-depth review for radiologists through the use of frequently asked questions. Semin Ultrasound CT MR 2012;33:500–21.
41. Lake DR, Kavanagh JJ, Ravenel JG, Schoepf UJ, Costello P. Computed tomography and pulmonary embolus: a review. Semin Ultrasound CT MR 2005;26:270–80.
42. Borloz MP, Frohna WJ, Phillips CA, Antonis MS. Emergency department focused bedside echocardiography in massive pulmonary embolism. J Emerg Med 2011;41:658–60.
43. Chung-Esaki H, Knight R, Noble J, Wang R, Coralic Z. Detection of acute pulmonary embolism by bedside ultrasound in a patient presenting in PEA arrest: a case report. Case Rep Emerg Med 2012;2012: 794019.
44. Nazerian P, Vanni S, Volpicelli G, et al. Accuracy of point-of-care multiorgan ultrasonography for the diagnosis of pulmonary embolism. Chest 2013 Oct 3 [E-pub ahead of print].
45. Goldhaber SZ. Echocardiography in the management of pulmonary embolism. Ann Intern Med 2002;136:691–700.
46. Hou X, Liu W, Zhang Z, Li Z. Free-floating right atrial thrombus with acute pulmonary embolism. Thorax 2009;64:736.
47. Elias A, Colombier D, Victor G, et al. Diagnostic performance of complete lower limb venous ultrasound in patients with clinically suspected acute pulmonary embolism. Thromb Haemost 2004;91: 187–95.
48. Reissig A, Kroegel C. Transthoracic ultrasound of lung and pleura in the diagnosis of pulmonary embolism: a novel non-invasive bedside approach. Respiration 2003;70:441–52.

49. Comert SS, Caglayan B, Akturk U, et al. The role of thoracic ultrasonography in the diagnosis of pulmonary embolism. Ann Thorac Med 2013;8:99–104.

50. Mathis G, Blank W, Reissig A, et al. Thoracic ultrasound for diagnosing pulmonary embolism: a prospective multicenter study of 352 patients. Chest 2005;128:1531–8.

51. Mathis G, Dirschmid K. Pulmonary infarction: sonographic appearance with pathologic correlation. Eur J Radiol 1993;17:170–4.

52. Porcel JM, Light RW. Pleural effusions due to pulmonary embolism. Curr Opin Pulm Med 2008;14:337–42.

53. Reissig A, Heyne JP, Kroegel C. Sonography of lung and pleura in pulmonary embolism: sonomorphologic characterization and comparison with spiral CT scanning. Chest 2001;120:1977–83.

54. Squizzato A, Rancan E, Dentali F, et al. Diagnostic accuracy of lung ultrasound for pulmonary embolism: a systematic review and meta-analysis. J Thromb Haemost 2013;11:1269–78.