Thoracic Ultrasound

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KEYWORDS

• Ultrasound • Thoracic • Pneumothorax • Pleural effusion
• Pneumonia • Blue • B-lines • Pleural line

Patients with thoracic emergencies can present a diagnostic dilemma to the emergency physician. Furthermore, there are often situations of severe respiratory distress in which an urgent diagnosis is required within minutes to direct potentially life-saving therapy. Traditionally, the emergency physician has relied on historical and physical examination findings to help in the initial differential diagnosis of dyspnea. These have often been found to be unreliable.[1–3] A bedside chest radiograph (CXR) can provide useful information but it has been shown to be inaccurate in many situations. Circumstances often arise in which one experienced physician evaluates the same patient as another physician and comes to diametrically different diagnoses; wet versus dry, pneumonia versus heart failure, pleural effusion versus pneumonia versus chronic obstructive pulmonary disease (COPD), and so forth. CT scan could resolve many of these issues but involves transporting potentially unstable patients out of the department, larger radiation doses (typically 200 times that of a CXR), the use of contrast, and cannot routinely be used in pregnancy. Clearly, there is a need for more exact tools.

Lung ultrasound is a new method of emergency patient assessment. So new in fact, that the latest editions of some North American emergency ultrasound textbooks do not even mention the lung as an organ that can be evaluated using ultrasound, except for passing discussions concerning the detection of traumatic pneumothorax.[4,5] The 2008 edition of *Harrison's Principles of Internal Medicine*[6] continues to state that ultrasound imaging is not useful for pulmonary parenchyma imaging. However, thanks to pioneering work of French intensivist Daniel Lichtenstein, and others, we now can confidently use ultrasound to evaluate patients with respiratory complaints.

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This article reviews the basic technical and anatomic principles of thoracic ultrasound, describes the important evidenced-based sonographic features found in a variety of pathologic conditions, and provides a framework of how to use thoracic ultrasound to aid in assessing a patient with severe dyspnea.

PRINCIPLES OF THORACIC ULTRASOUND

The basis and utility of thoracic ultrasound is attributed to several important principles first proposed by Lichtenstein[7]:

1. The intimate relationship between air and water in the lung causes a variety of artifacts seen by ultrasound. Because air (and, by extension, the lung) cannot be visualized by sonography, thoracic ultrasound is based primarily on the analysis of these artifacts.
2. Air and water have opposing gravitational dynamics. Consequently, a variety of pathologic conditions (pleural effusions, consolidations) is predominantly "water-rich" and, thus, considered "dependent disorders." These pathologies are generally found in the posterior aspects of a supine patient. On the other hand, there are several "air-rich" conditions (pneumothorax) that are considered "nondependent" disorders and, as a result, are predominantly found in the anterior aspects of a supine patient (**Fig. 1**).
3. All sonographic lung patterns arise from the "pleural line." The pleural line is a bright echogenic line approximately 0.5 to 1.0 cm below the ribs, corresponding to the apposition of the parietal and visceral pleura. Most acute lung disorders abut the lung surface, which explains the wide-ranging utility of thoracic ultrasound. The pathologic condition not attached to the pleural line is necessarily visualized by lung ultrasound (eg, tumor, other hilar processes).

PROBE SELECTION

There are several probe options when performing thoracic ultrasound, each with its inherent advantages and disadvantages. The curved array probe has the advantage of allowing rapid assessment of the lateral thoracic cavity for signs of pleural fluid in

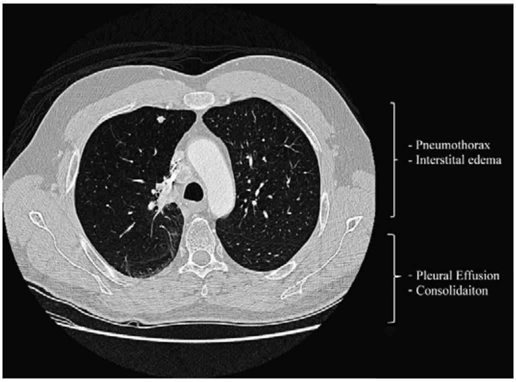

Fig. 1. Water-rich pathology such as pleural effusion and consolidation will tend to occur in the dependent (ie, posterior) regions of the supine patient. Pneumothorax and severe interstitial edema tend to occur in the anterior portions of the lung.

the supine patient. This is often the case in trauma (for example as part of the Extended Focused Assessment with Sonography for Trauma [EFAST] examination). However, due to its large footprint, only a small portion of the intercostal space (ICS) is accessible. Furthermore, the low frequency does not allow for detailed assessment of the main area of interest in thoracic ultrasound—the pleural line.

The high-frequency linear array probe allows for detailed examination of the pleura and provides rapid assessment of superficial lesions, such as pneumothorax. Its large footprint, however, hinders access to larger areas of lung tissue because of the interference of the ribs. Furthermore, the high-frequency sacrifices depth-of-penetration, preventing assessment of deeper structures such as atelectasis, consolidation, and large pleural effusions. Some investigators find the phased array cardiac probe convenient for simultaneous heart and lung examinations.[8] The relatively large dead-zone area in the near field may prevent clear assessment of superficial structures.

In the authors' opinion, the best probe to use for lung ultrasound is the 5 Mhz microconvex probe (**Fig. 2**). This probe design allows access to the ICS and facilitates examination of patients unable to cooperate by sitting. The probe can slide behind the patients back and aim up roughly perpendicular to the chest wall, even with the patient supine. Although sacrificing some resolution compared with the linear 10 Mhz probe, the microconvex has good depth of field, which is important for imaging deeper chest structures. All filters should be turned off to maximize real-time dynamic images. It is preferable not to smooth or suppress artifacts associated with lung movement or tissue impedance characteristics.

PATIENT POSITION AND LUNG FIELDS

Thoracic ultrasound can be performed either in the seated or, in sick patients unable to cooperate, in the supine position. The seated patient allows for the methodical assessment of all important lung fields: anterior, lateral, and posterior. It also allows the assessment of patients unable to lie supine (eg, severe COPD exacerbation, congestive heart failure [CHF]). When examining the supine patient who is unable to sit, each hemithorax should be divided into five zones; two anterior zones (separated by the third ICS), two lateral zones, and one posterior zone (**Fig. 3**).[9,10]

To begin the examination, the probe is placed between the ribs perpendicular to the chest wall, oriented in the longitudinal axis of the patient. The image generated will

Fig. 2. Microconvex probe.

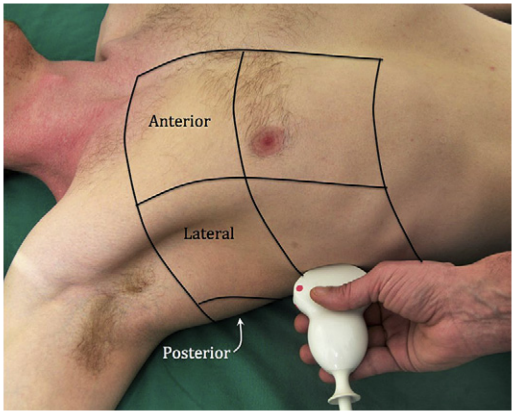

Fig. 3. In the supine patient, each hemithorax is divided into five zones; each should be interrogated by ultrasound depending on the indications.

show the upper rib on the left side of the screen and the lower rib at the right. The ribs cast a shadow framing the rest of the image. Approximately, 0.5 to 1.0 cm below and between the rib shadows will be the pleural line, a bright, slightly curved line. This is the key area of interest in almost all lung pathology of concern to the emergency physician and, as such, is the primary landmark to identify on the screen (**Fig. 4**).

In the normal lung, one will appreciate a shimmering or lung sliding representing the movement of the visceral on the parietal pleura during respiration. Note that, as one scans caudally down the chest wall, this should be more pronounced, whereas there is less lung movement or sliding near the apex of the lung.

Lung sliding is the first sonographic finding one should identify in the normal lung. Below the pleura, at regular intervals, are horizontal reverberation artifacts referred to as A lines (see **Fig. 4**).

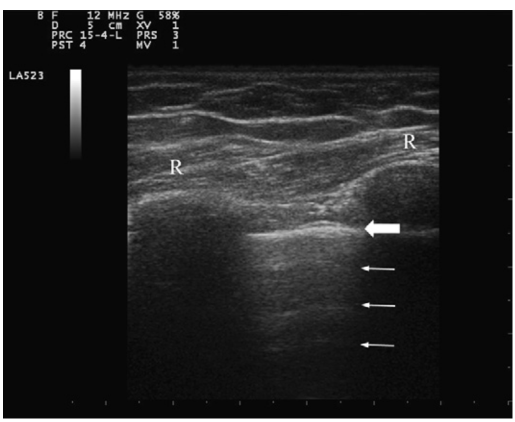

Fig. 4. Characteristic thoracic view showing adjacent ribs (R) with corresponding shadow artifact. Notice the white echogenic pleural line (*block arrow*), approximately 0.5 cm below the level of the ribs. A-line artifacts (*line arrows*) are seen at equidistant spaces below the pleural line.

Another artifact that may be seen both in normal and in diseased lung is the B-line (also known as a comet-tail artifact). Related to the sonographic interaction between small water-rich structures at the periphery of the lung surrounded by air, B lines have a very specific appearance that differentiates them from other, clinically unimportant artifacts. B lines are well-defined echogenic artifacts fanning out from the pleural line right down to the edge of the screen. They do not fade, they erase the A-lines, and they move in time with respiration (**Fig. 5**).

The number, location, and characterization of B-lines are important to differentiate normal lung from pathologic conditions. A solitary B-line is often a normal finding in any region of the lung and is found in the lower dependant areas of the lung in 28% of normal patients.[11] B-lines are not seen in all patients. The appearance of B-lines provides clinically important information with respect to pathologic diagnoses such as pneumothorax, pneumonia, and alveolar interstitial syndrome.

The physician should also be aware of the anatomic boundaries of the lung cavities and not mistake abdominal viscera or cardiac structures for pathologic condition. Anteriorly, the abdominal cavity usually starts at the fifth ICS and the pericardium and heart will be seen to the left of the sternum up to the midclavicular line. The liver and spleen are situated approximately at the sixth and fifth ICS, respectively, laterally and eighth ICS posteriorly. The diaphragm on both sides must always be identified to verify that intra-abdominal viscera are not being mistaken for an intrathoracic pathologic condition.

PATHOLOGIC STATES

Pneumothorax

Bedside radiography has a notoriously inconsistent accuracy in detecting pneumothorax, regardless of the cause, with sensitivities ranging between 50% and 90%.[12–16] Through the recognition of specific dynamic sonographic artifacts at the pleural line, bedside ultrasound can detect pneumothorax with the sensitivity similar to a CT scan.

There have been several studies years comparing the accuracy of ultrasound to CXR and/or CT scan for the diagnosis of pneumothorax.[16–24] Alrajhi and colleagues[25] recently published a systematic review of eight high-quality studies. Overall, in 1047 patients, ultrasound had a sensitivity of 90.0% (95% CI; 86.5–93.9) and a specificity of 98.2% (95% CI; 97.0–99.0). This translates into a positive likelihood ratio (LR^+)

Fig. 5. B-line, or comet-tail artifact, extending from the pleural line to the edge of the screen, erasing the A-line. Solitary B-lines have no pathologic significance.

of 50 and a negative likelihood ratio (LR^-) of 0.1. The comparative sensitivity and specificity of CXR in theses studies was 50.2% (95% CI; 43.5–57.0) and 99.4% (95% CI; 98.3–99.8), respectively. Among the 766 patients who had developed a traumatic pneumothorax, bedside ultrasound was 90.2% sensitive and 98.8% specific ($LR^+ = 75$; $LR^- = 0.1$). The time to perform the examination ranged between 2 and 7 minutes.

Because an air-containing pneumothorax is a nondependent entity, sonographic assessment of the lungs is initiated on the most anterior portion of the supine patient, usually at the third-fourth intercostal space, at the parasternal-midclavicular line (**Figs. 6** and **7**). It is sometimes necessary to scan more than one intercostal space to ensure that the most nondependent region is assessed. The landmark to identify is the pleural line. The diagnosis, or exclusion of pneumothorax, relies on a stepwise approach to assess the existence of various dynamic signs.

The most important initial sign to look for is lung sliding, which is the back-and-forth movement of the bright echogenic parietal and visceral pleura occurring during respiration, often resembling marching ants along the pleural line. The confirmation of lung sliding has a 100% negative predictive value for the absence of pneumothorax.[26] In cases where lung sliding may not be clearly appreciated, power Doppler may help in confirming movement of the pleural line.[27]

The use of M-mode can also objectify the presence or absence of lung sliding. In the normal lung, the familiar "sandy beach" or "sea-shore sign" appearance will confirm the presence of lung sliding (**Fig. 8**). In the context of a pneumothorax, the characteristic "bar code" or stratosphere sign is seen (**Fig. 9**).[7]

It is important to recognize that, although the presence of lung sliding effectively rules out pneumothorax, its absence does not necessarily rule it in, with the specificity of the absence of lung sliding ranging from 60% to 90%. Several clinical entities may also present with the absence of lung sliding (**Box 1**).

Therefore, to safely rule in a pneumothorax, the following sonographic signs must be relied on. B-lines are caused by the reflections of the ultrasound beam between the alveolar air and the fluid of the interlobular septa. Therefore, the appearance of a single B-line confirms the apposition of both pleural and effectively rules out a pneumothorax.[4]

Fig. 6. Initial placement of probe when assessing for pneumothorax.

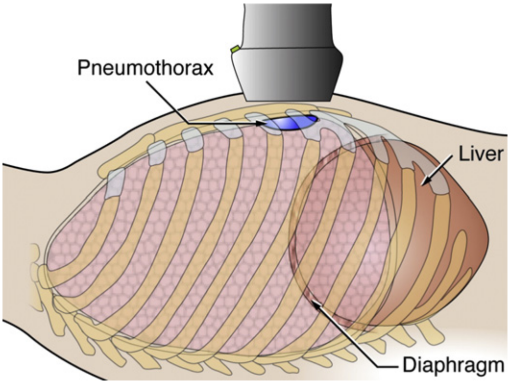

Fig. 7. Even small pneumothoraces can be identified anteriorly by lung ultrasound—a finding often missed in the supine CXR. (*Courtesy of* The EDE 2 Course, Sudbury, Ontario, Canada; with permission.)

The lung point refers to the point on the chest wall where the visceral pleura has separated from the parietal pleura and, therefore, defines where the pneumothorax begins. Visualization of the lung point is 100% specific for the diagnosis of pneumothorax.[28] Once the absence of lung sliding has been confirmed on the anterior chest wall, the physician should slide the probe laterally until the lung point comes into view with the reappearance of either lung sliding and/or B-lines (**Fig. 10**). This indicates the degree of extension of the pneumothorax.

Not only does the lung point confirm the presence of a pneumothorax, but its location may be able to predict its approximate size.[16,18,29] Although there has been not strict criteria comparing bedside ultrasound with CT scans regarding pneumothorax size, it is reasonable to suggest that the more lateral the lung point is found, the larger the extension of the pneumothorax. This information may be enough to drive treatment decision in most cases of pneumothorax.[30] A lateral lung point has been shown

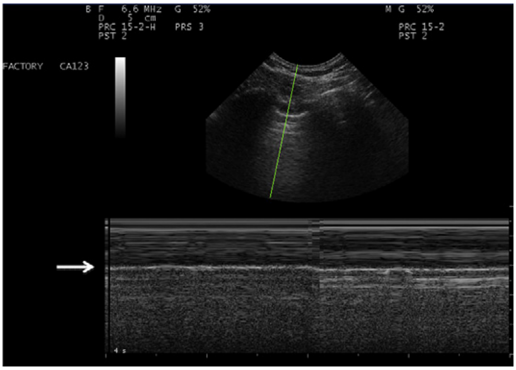

Fig. 8. M-mode appearance of normal lung sliding. Note that at the transition of the pleural line (*arrow*), the linear pattern (corresponding to the immobile muscle and subcutaneous tissue) is replaced by the grainy pattern (corresponding to the motion of lung tissue).

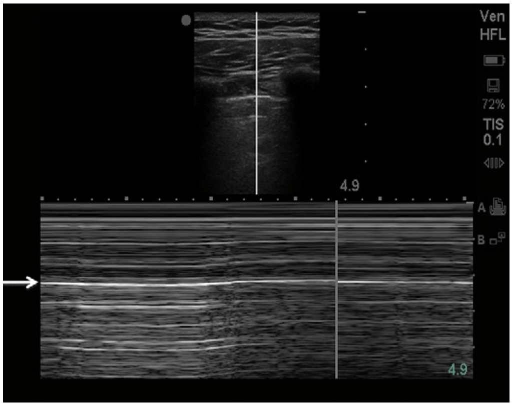

Fig. 9. M-mode appearance of absent lung sliding. The linear pattern remains distal to the pleural line (*arrow*), confirming lack of motion above and below the parietal pleura.

to correlate with a 90% need for chest tube drainage in the ICU, compared with 8% with an anterior lung point.[29] It should be noted that in the setting of a complete lung collapse there would be no lung point visualized. It should also be emphasized that in the setting of traumatic injury causing respiratory distress, impending cardiovascular collapse, or cardiac arrest the absence of both lung sliding and B-lines is enough to be necessitate immediate chest tube insertion. The extra time to identify the lung point is not advocated.

Occasionally, when lung sliding is absent, a vertical vibration at the pleural line is visualized and is noted to be in rhythm with the patient's heartbeat. This is known as the lung pulse and it can only occur if there is lung that extends to the pleural line allowing for the mechanical transmission of the heartbeat. Situations in which one might find absent lung sliding and the presence of the lung pulse include: apnea, pharmacologic paralysis, massive atelectasis, consolidation, and mainstem intubation.[30,31] Because air

Box 1
Differential diagnosis of absent lung sliding

Pneumothorax

Massive atelectasis or consolidation

Main stem intubation

Pulmonary contusion

Acute respiratory distress syndrome

Pleural adhesion or pleurodesis

Severe fibrosis

Phrenic nerve palsy

Apnea or cardiac arrest

Data from Volpicelli G. Sonographic diagnosis of pneumothorax. Intensive Care Med 2010;37(2):224–32; and Lichtenstein DA, Lascols N, Prin S, et al. The "lung pulse": an early ultrasound sign of complete atelectasis. Intensive Care Med 2003;29(12):2187–92.

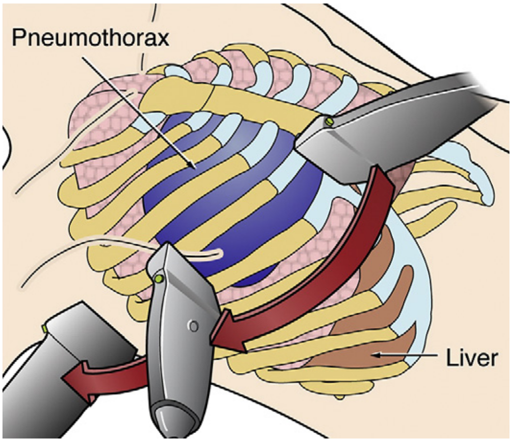

Fig. 10. The approximate size of the pneumothorax can be predicted by sliding the probe laterally until the lung point is visualized. (*Courtesy of* The EDE 2 Course, Sudbury, Ontario, Canada; with permission.)

(ie, of a pneumothorax) cannot transmit the movements of the heartbeat to the parietal pleura, visualization of the lung pulse rules out pneumothorax.

Putting together the various dynamic sonographic signs required to either rule out or rule in pneumothorax, a flow chart can provide the necessary steps to take to make an accurate diagnosis (**Fig. 11**).

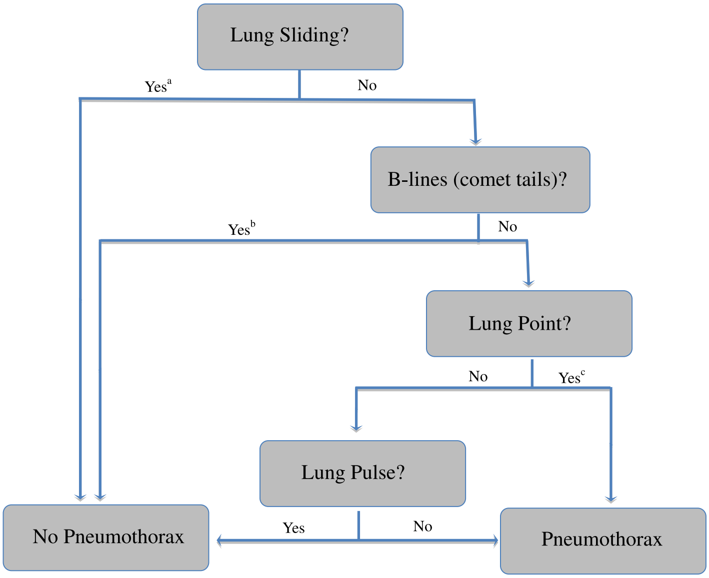

Fig. 11. Proposed flow chart for the sonographic assessment of pneumothorax. The presence of lung sliding ([a]) rules out pneumothorax with a PPV of 100%.[26] The presence of any comet tail ([b]) or B-line rules out pneumothorax with a sensitivity of 100%.[4] The presence of a lung point ([c]) confirms pneumothorax with 100% specificity.[28] (*Adapted from* Volpicelli G. Sonographic diagnosis of pneumothorax. Intensive Care Med 2010;37(2):224–32; with permission.)

Alveolar Interstitial Syndrome

First described in the mid 1990s, alveolar interstitial syndrome (AIS) constitutes a group of diseases that is caused by an increase in lung fluid and/or a reduction in its air content. The result of this engorgement or thickening of the interlobular septa causes a particular artifact that is seen arising from the pleural line. The major causes of AIS are summarized in **Box 2**. By far, the most common cause of acute AIS presenting to the emergency department (ED) is cardiogenic pulmonary edema. The sonographic appearance of AIS is a vertical artifact, called a B-line. When compared with CT scan images, B-lines correspond to edema of the interlobular septa.[11] As described above, B lines are well-defined vertical artifacts generated from the pleural line, reaching the edge of the screen. They do not fade, they erase the A-lines, and they will move synchronously with lung sliding. It is believed that B-lines are caused by multiple reflections of the ultrasound beam between the air-rich and water-rich structures, such as the alveoli and the edematous interlobular septa, generating the resonance phenomenon.[32]

The number, location, and characterization of B-lines are important to note. An isolated B-line (often defined as located >7 mm from an adjacent B-line) is a normal finding. In fact, B-lines are found in the lower dependant areas of the lung in up to 28% of normal patients.[11,33] Lichtenstein and colleagues[34] also suggest that B-lines extend up the back of bedridden patients so frequently that their absence suggests severe dehydration.

To be considered an abnormal finding, some investigators suggest that there must be at least three B-lines on a single scan using a microconvex probe or at least six B-lines using a linear probe.[33]

When diffuse B-lines are visualized, this gives the appearance of lung rockets (or B+ pattern), and suggests a diagnosis of AIS (**Fig. 12**).[10,11]

There is some controversy when diagnosing cardiogenic pulmonary edema using lung ultrasound. Lichtenstein and colleagues[11] and Lichtenstein and Meziére[35] originally categorized a positive scan when diffuse B-lines are found on both sides of the anterior chest (referred to as the B-Profile). In this scenario, bilateral diffuse B-lines had a specificity of 95% and a sensitivity of 97% for the diagnosis of pulmonary edema. It is suggested, however, that this may be true of only severe cases. Others have suggested that in milder cases multiple bilateral B-lines need only be visualized at several intercostal spaces along the anterolateral or lateral surfaces of the chest.[10,36] Using these criteria, diffuse B lines had a sensitivity of 85.7% and a specificity of 97.7% for AIS. This translates into an LR^+ of 37.3 and an LR^- of 0.15.

In the bedside assessment of a patient with CHF, it has been shown that the number of B-lines is directly related to the severity of cardiogenic pulmonary edema when compared with CXR findings and pulmonary wedge pressure.[37–40] The number of

Box 2
Differential diagnosis of AIS

Acute

Pulmonary edema

Acute respiratory distress syndrome

Interstitial pneumonia

Chronic

Pulmonary Fibrosis

Fig. 12. Multiple B-lines, greater than three in a single scan, each less than 7 mm apart from adjacent one (*double arrow*), suggestive of AIS.

B-lines is also directly correlated with B-type natriuretic peptide levels, which may aid in the diagnosis of cardiogenic pulmonary edema.[41,42] In addition, the appearance of B-lines may precede any abnormalities on CXR, which may aid in the determining the aggressiveness of fluid resuscitation in critically ill.[43]

In addition to its utility in diagnosing pulmonary edema, lung ultrasound can also be used to monitor the effects of treatment. Several studies have demonstrated that B-lines clear rapidly after medical treatment as well as dialysis.[44–46] Because this effect has been shown to occur in real time, lung ultrasound has a significant advantage over CXR to evaluate the response to therapy.

Over the past 15 years, the use of lung ultrasound at the bedside to assess for the presence of B-lines has become has become universally accepted in both the critical care as well as ED setting. Recently, the ability to use this technique has been endorsed by various scientific bodies such as the American College of Chest Physicians and La Societe de Reanimation de Langue Française, in their joint Statement on competence in critical care ultrasonography, as well as the Heart Failure Association of the European Society of Cardiology.[47,48]

Pleural Effusion

The ability to diagnose pleural effusion by ultrasound has existed for almost 50 years. Despite this, its routine use at the ED bedside remains low. Ultrasound is, in fact, the diagnostic modality of choice in cases of suspected pleural effusion and hemothorax and is considered the standard of care in the safe localization, characterization, and aspiration of pleural fluid. Several studies have confirmed the relative ease in acquiring the skill to perform thoracic ultrasound for the detection of a pleural effusion.[49–51]

Ultrasound is exquisitely sensitive for the presence of pleural effusions even when the CXR is normal (may miss up to 500 cc).[52] Lung ultrasound can detect as little as 20 cc of pleural fluid,[53] whereas an upright posteroanterior CXR requires 100 to 200 mL of fluid before blunting of the costophrenic angle can be seen.[54] The supine CXR, in trauma situations or in the setting of a critically ill patient, is even less accurate.

There are two possible methods to ascertain the presence of a pleural effusion. When used as an extension of the FAST examination, simply sliding the probe from the right upper quadrant or left upper quadrant areas of the abdomen cephalad, past the identified diaphragm, allows access to the lungs. The presence of a pleural effusion is confirmed by the anechoic appearance in the postero-lateral recesses of the thoracic cavity (**Fig. 13**).

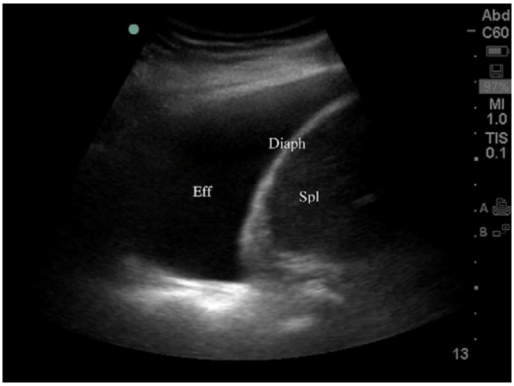

Fig. 13. Moderate left-sided pleural effusion. Diaph, diaphragm; Eff, pleural effusion; Spl, spleen.

A second method, as described by Lichtenstein,[55] is to simply place the probe directly along the posterolateral aspect of the thorax. Other than the obvious anechoic fluid appearance distal to the ribs, two additional signs that confirm the presence of a pleural effusion are described. The static sharp sign (or quad sign) refers to the four boundaries that delineate the appearance on the screen: the superior and inferior rib shadows on either side of the screen, the superficial parietal pleura, and the deep boundary, usually the lung. The dynamic sinusoid sign refers to the sinusoidal pattern of the effusion seen on M-Mode corresponding to the centrifugal movement of the visceral pleura during respiration (**Fig. 14**). This sinusoidal movement of fluid also confirms the low viscosity of the effusion (eg, transudate). The presence of these two signs has a specificity of 96% in identifying effusion and it should prevent the physician from misidentifying, for example, a large hiatus hernia or a breast implant as effusion.[56]

Trauma-related hemothorax is a condition that requires urgent bedside diagnosis. The accuracy of the supine CXR is quite low, leading to possible delayed or unnecessary chest tube insertions. Bedside trauma ultrasound has now expanded its role to include the lung (ie, EFAST). The sensitivity of ultrasound to diagnose a hemothorax ranges between 92% and 96% and has a specificity of over 99%.[57–59]

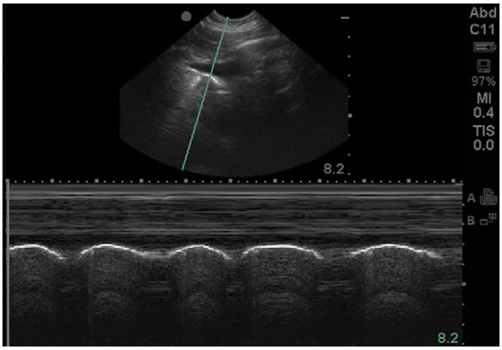

Fig. 14. Sinusoid sign.

Recently, Grimberg and colleagues[60] performed a systematic review comprising 924 patients who underwent lung ultrasound to diagnose pleural effusion. In the four studies included, CT scan and/or chest tube drainage was used as the gold standard.[3,57,59,61] They reveal that lung ultrasound has a sensitivity of 93% (95% CI; 89%–96%) and a specificity of 96% (95% CI; 95%–98%). This translates into an LR^+ of 23.25 and an LR^- of 0.07. These same four studies revealed that the sensitivity of the comparative CXR ranged between 24% and 100%.

Although not replacing the need for a diagnostic thoracentesis, the composition of the effusion can also be predicted with the use of ultrasound.[62] Transudates will be almost completely black in most cases, whereas an exudate will be more echogenic. A hemothorax and empyema have often been described as having a "snow flurry" appearance. An empyema can also reveal complex loculations and bright echogenic traces comparable to "Swiss cheese."[63] The presence of septations can also be assessed by ultrasound, sometimes with higher accuracy than CT scan.[64]

With the presence of a pleural effusion acting as an acoustic window, the lung will have an appearance of a bright line moving back and forth with respiration. If the pleural effusion is abundant enough to be compressive, the lung is seen consolidated and floating in the pleura effusion.

Examining the use of ultrasound in the ED to diagnose nontraumatic pleural effusion, it has been shown to be a rapid test to perform (<2 minutes) and that it changes management in 41% of symptomatic patients.[65] To determine whether bedside ultrasound to diagnose pleural effusion decreases the need for radiography and chest CT scans. Peris and colleagues[66] examined 376 mechanically ventilated patients admitted to the ICU. The use of daily bedside ultrasound led to a 26% reduction in CXRs and a 47% decrease in CT scans.

Pneumonia

Pneumonia causes significant morbidity and mortality, with an estimated 15% mortality rate in those admitted to hospital. Early diagnosis is essential for rapid initiation of therapy. The accuracy of CXR has shown to be extremely variable and is especially low in dehydrated, immunocompromised, and elderly patients. Campbell and colleagues[67] found that in 671 cases where an emergency physician diagnosed pneumonia on radiograph, the radiologist agreed in only 57% of cases. Furthermore, postero-anterior and lateral CXR's are often difficult to obtain in many patients, especially the critically ill and the elderly. Anteroposterior CXRs performed portably often fail to show an infiltrate. Over the past 15 to 20 years, lung ultrasound has developed as an important modality for the bedside diagnosis of pneumonia both in the ED and ICU setting.

The sonographic characteristic of an alveolar consolidation is one of a hypoechoic structure, whose appearance is "liver-like" (ie, hepatisation), with irregular deep boundaries. The superficial boundary corresponds to the level of the pleural line; the deep boundary is in direct connection with either the aerated lung giving an irregular, shredded boundary (the shred sign) (**Fig. 15**) or a corresponding pleural effusion.

In more than one-third of cases, pneumonia is accompanied by a pleural effusion.[68,69] The absence of the "sinusoid sign" helps distinguish alveolar consolidation from an associated pleural effusion. The presence of these signs has 90% sensitivity and 98% specificity for the diagnosis of alveolar consolidation.[9]

In most cases, the consolidation will also show corresponding hyperechoic punctiform images signifying air bronchograms arborizing within (**Fig. 16**). Centrifugal movement of these air bronchograms during respirations, referred to as "dynamic air bronchograms," confirms the presence of a consolidation and differentiates this

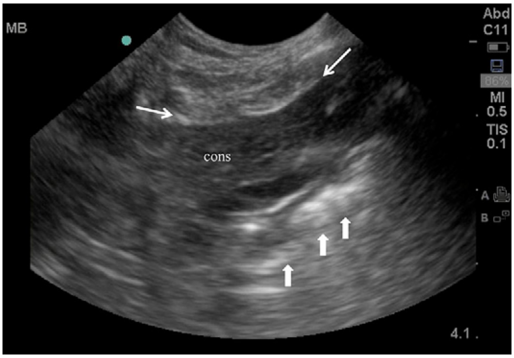

Fig. 15. Left lower lobe pneumonia showing hepatization of consolidation (cons), shred sign at the deep boundary of the consolidation (*block arrows*), and apposition of consolidation along the pleural line (*arrows*).

from atelectasis (static air bronchograms) with a specificity of over 94%.[70] The presences of B-lines can aid in the diagnosis of pneumonia. Often, the consolidation area is surrounded by multiple localized B lines, consistent with alveolar interstitial syndrome. Finally, it has been shown that diffuse B-lines found on a single lung is highly predictive of interstitial pneumonia with a specificity of 99%.[35] The sensitivity, however, remains quite low (14.5%) and should not be used to rule out pneumonia.

Because pulmonary consolidation consists mostly of fluid, with little air, these lesions are found mostly in the lateral and posterior aspects of the lung. When sonographic signs of pneumonia appear anteriorly, they often represent whole lung involvement.[9]

In several case control and retrospective studies, lung ultrasound was found to accurately detect the characteristic findings of a consolidation.[71,72] In a nonblinded study of 342 patients admitted with pneumonia, ultrasound was able to detect 92% of the consolidations.[69] In a prospective study of ICU patients, ultrasound was found to have a sensitivity of 90% and a specificity of 98% in diagnosing consolidation when compared with CT scan.[9]

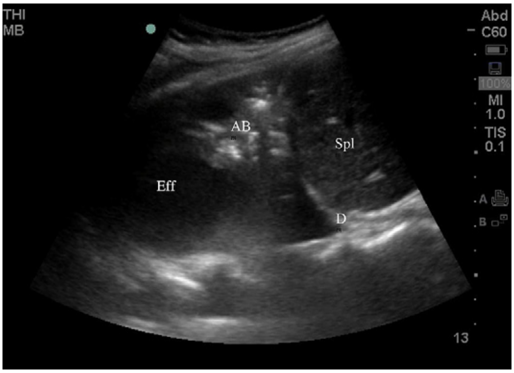

Fig. 16. Left, lower lobe consolidate showing air bronchograms (AB), and pleural effusion (Eff). D, diaphragm; Spl, Spleen.

Two ED-based prospective studies found that lung ultrasound has a high concordance rate with CXR to diagnose pneumonia and often demonstrated higher sensitivities than CXR when compared with CT scan findings. In 49 adult patients with suspected pneumonia, Parlamento and colleagues[73] revealed that lung ultrasound was diagnostic in 97% of cases. In eight cases where ultrasound and CXR were discordant, CT scan confirmed the sonographic findings. More recently, 120 patients with suspected pneumonia were evaluated in the ED.[74] Using the CT scan result and discharge diagnosis, ultrasound was found to have a sensitivity and specificity of 98% and 95%, respectively. The CXR in this study had a sensitivity of only 67%. When assessing the ultrasound's ability to diagnose pneumonia in ED patients presenting with dyspnea of unknown cause, ultrasound was found to be more reliable than CXR when using CT scan as the gold standard.[75]

Although these early ED and ICU-based studies provide strong evidence for the use of lung ultrasound to diagnose pneumonia, these studies were performed by a limited number of expert physician ultrasonographers. The generalizability of these results requires further confirmation.

Pulmonary Embolism

The use of lung ultrasound for the diagnosis of pulmonary embolism (PE) is a relatively new concept compared with the other indications. The most common positive sonographic finding in PE is a wedge-shaped hypoechoic lesion that extends to the pleural surface.[76] These have been referred to as C-lines by Lichtenstein.[77] Most lesions will be localized in the area of the pleuritic chest pain and adopt a triangular shape. A localized fluid collection may eventually develop adjacent to the affected lung. The pleural line may then become convex, bulge outward, and appear less echogenic and fragmented.[76,78] A localized subpleural effusion is seen in about 40% of patients with confirmed PE. Basal pleural effusions are seen in 50% to 60% of cases.

The literature examining the sensitivity of lung ultrasound to diagnose PE is sparse and limited by significant referral bias. Furthermore, the criteria used to diagnose PE are not standard. Mathis[78] used the following criteria: PE was *likely* when two or more characteristic triangular or rounded pleura-based lesions were demonstrated; PE was *probable* when one typical lesion with a corresponding low-grade pleural effusion; PE was *possible* if nonspecific subpleural lesions less than 5 mm in size or a single pleural effusion alone; and PE was *unlikely* if the lung ultrasound was normal. Using the first two criteria as diagnostic for PE, lung ultrasound showed a sensitivity of 74% and a specificity of 95%.

Lichtenstein simplified the sonographic criteria to diagnose PE. According to his Bedside Lung Ultrasound in Emergency (BLUE) protocol, in the severely dyspneic patient not in shock, a normal lung ultrasound (presence of A-lines throughout) plus signs of deep vein thrombosis (DVT) is 81% sensitive and 99% specific for PE.[35] This translates to a LR^+ of 81 and a LR^- of 0.19.

There are several limitations of lung ultrasound to diagnose PE. Only two-thirds of the lung area is accessible to ultrasound examination because the remainder is covered by bony structures. However, almost 80% of lesions are located in the lower lobes, which are accessible to examination.[79] Only thromboembolic lesions extending to the pleura can be detected. It has been demonstrated that central and peripheral lesions occur concurrently in 80% of cases.[76,78] As is the case with lung ultrasound for the diagnosis of pneumonia, studies on PE are limited to an exclusive group of expert sonographers and as such, its reproducibility and generalizability remains to be seen.

It should be added that in addition to performing lung ultrasound, the ability of the emergency physician to perform a bedside cardiac echocardiogram as well as compression ultrasound (looking for DVT) greatly improves the diagnostic power of ultrasound.

In a patient presenting with symptoms suggestive of PE, 50% have a documented DVT with no appreciable evidence on physical examination.[80] Lichtenstein and Meziére[35] reported that, in the BLUE protocol of patients with severe dyspnea, 85% of patients with a diagnoses of PE had a documented DVT.

In a patient with shock and severe shortness of breath, a normal lung ultrasound (or presence of C-lines) and signs of right ventricular overload on echocardiography rules in massive PE; therefore, intravenous thrombolytics or thrombectomy should be considered. A normal cardiac examination of the right heart rules out massive PE only in hemodynamically unstable patients.[81]

The most common differential diagnoses of such hypoechoic peripheral lesions include pneumonia, malignancy (primary or metastatic), and pleurisy. The description of these lesions is beyond the scope of the article.

PUTTING IT TOGETHER: THE DYSPNEIC PATIENT

The severely dyspneic patient often presents a challenge to the emergency physician as well as to associated consultants—often resulting in dichotomous impressions.

One of the most difficult challenges lies in differentiating patients with cardiogenic respiratory failure (ie, pulmonary edema) with those caused by primary lung disease (ie, COPD, asthma, PE). All too often, the CXR in the supine or poorly cooperative patient results in uninterruptable or nondiagnostic impressions that possibly lead to delays in treatment or in the wrong treatment being started.

Several studies have looked at the ability of bedside ultrasound to help differentiate the cause of respiratory symptoms when presenting to the ED or once admitted to an ICU. With the high sensitivity of lung ultrasound in recognizing alveolar interstitial syndrome described above, the diagnoses of CHF and COPD can be easily differentiated. For example, when originally describing the existence of B-lines, Lichtenstein and Mezière[82] concluded that the appearance of diffuse, bilateral B-line artifacts was 100% sensitive and 92% specific in diagnosing pulmonary edema versus COPD. As part of a landmark BLUE protocol study, lung ultrasound was found to distinguish patients with COPD and CHF with similarly high precision.[35]

Two recent ED-based studies were published evaluating the use of lung ultrasound in assessing the cause of patients presenting with dyspnea. Volpicelli and colleagues[10] performed lung ultrasound on 300 consecutive patients within 48 hours of arrival to the ED. They reported a sensitivity and specificity of 85.7% and 97.7%, respectively, of diffuse B-lines to diagnose AIS. More recently, Cibinel and colleagues[83] performed bedside lung ultrasound on 56 patients presenting to the ED with dyspnea. Ultrasound was performed by the emergency physician during the patient's initial assessment. The presence of diffuse B-lines was highly predictive for cardiogenic pulmonary edema, with a sensitivity and specificity of 93.6 and 84%, respectively (LR^+ of 5.6, LR^- of 0.08).

In 2008, Lichtenstein and Mezière[35] published the BLUE protocol, with the goal of determining the cause of a patient's respiratory failure. Just as the Rapid Ultrasound in SHock (RUSH) protocol revolutionized the assessment of the undifferentiated shock patient,[84] the BLUE protocol aimed to improve the speed and accuracy of the bedside diagnosis of patients with severe breathlessness. The study, which was performed on patients on admission to ICU, is pertinent to the emergency assessment of patients with respiratory failure. For a detailed description of the protocol, the reader is encouraged to refer to Ref.[35]

The results of the BLUE protocol are summarized in **Table 1**. The examination of the lower extremities for evidence of DVT is a crucial aspect of the protocol for the diagnosis of PE. Furthermore, PE cannot be ruled out using the BLUE protocol and should be treated on speculation, if the pretest probability is not extremely low, until a definitive test can be performed. However, if another diagnosis such as CHF or pneumothorax can be established with confidence, this lowers the pretest probability of PE below the test threshold because none of the patients with diffuse bilateral B-lines or with absent lung sliding had a PE. A complete pneumothorax (no lung point) needs to be confirmed on CXR.

It should be noted that neither the emergency nor the ICU physicians had access to the information in the study and that 26% of the diagnoses made in the ED were incorrect compared with the discharge diagnosis. The incorrect diagnoses chiefly included under-calling pneumonia, missing PE, and over-calling and under-calling CHF. The overall accuracy of the BLUE protocol was 90.5% for reaching the correct diagnosis.

This study was performed by the world's experts in lung ultrasound on the sickest patients presenting to the ED with respiratory failure. It is not yet known how the BLUE protocol will perform in other settings, in different spectrums of illness, and by other physicians. There have not been any validation studies at the time of this writing.

PEDIATRIC LUNG ULTRASOUND

The use of bedside ultrasound in the pediatric population is slowly increasing in the ED and intensive care environments. Studies have been focused mainly on the use of ultrasound in obtaining vascular access in children.[85–88] There remain several obstacles to its widespread use because there are no well-founded indications specifically for children. Much of its current use in pediatrics has simply been extended from well-established indications in the adult population (eg, assessment of free fluid following

Table 1
Results of the BLUE protocol

	Sensitivity (%)	Specificity (%)	Positive LR	Negative LR
Cardiogenic pulmonary edema[a]	97	95	19.4	0.03
COPD or asthma[b]	89	97	29.6	0.11
Pulmonary embolism[c]	81	99	81[g]	0.19
Pneumothorax[d]	88	100	∞	0.12
Pneumonia[e]	14	100	∞	0.86
Pneumonia[f]	21	99	21.0	0.80

[a] Diffuse bilateral anterior B-lines.
[b] Predominant anterior A-lines, lung sliding, and no posterior or lateral abnormalities; or with absent lung sliding without lung point.
[c] Predominant anterior A-lines with signs of DVT.
[d] No anterior lung sliding, no anterior B-lines and present lung point.
[e] Predominant anterior B-lines on one side, predominant anterior A-lines on the other.
[f] Anterior alveolar consolidation (C profile).
[g] A specificity of 100% indicates a theoretical positive likelihood ratio (LR) of infinity.

Data from Lichtenstein DA, Meziére GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest 2008;134(1):117–25.

trauma, first trimester pregnancy, and limited echocardiography) but without the same number of dedicated studies in children.[89] The use of abdominal ultrasound in pediatric abdominal trauma remains controversial because studies have revealed varied results. In the literature, promising research has emerged on the role of inferior vena cava diameter and collapsibility to predict dehydration in children,[90,91] several orthopedic pathologies such as the diagnosis of clavicle fractures,[92] and the presence of hip joint effusions.[93–95]

The literature on lung ultrasound in the pediatric population is also sparse. Similar to other indications, the sensitivity of ultrasound for the diagnosis of conditions such as pneumothorax, pleural effusion, interstitial edema, and pneumonia is extrapolated mostly from findings in adults. The belief is that the same lung artifacts observed in the adult lung are seen equally in the pediatric lung. In fact, Lichtenstein[96] reported from a 3-year experience in the neonatal ICU that all basic signs (eg, A-lines, B-lines, lung sliding, sinusoid sign, shred sign) were present and found to be identical in critically ill newborns. Neonatal studies do suggest that lung ultrasound is a valuable tool for the diagnosis of transient tachypnea of the newborn[97] as well as respiratory distress syndrome.[98]

Examining the role of lung ultrasound to diagnose pediatric lung infections, Copetti and colleagues[99] examined 79 children between 6 months and 16 years of age presenting with clinical signs suggesting pneumonia. Among the 79 patients, 60 had lung ultrasound findings consistent with pneumonia, 10 of which also had a pleural effusion. Interestingly, while CXR "confirmed" the diagnosis of pneumonia in 53 of the 60 cases, there were four patients with a negative CXR and positive ultrasound who underwent CT scan imaging. In all four cases, CT scans confirmed the sonographic pneumonia diagnosis. These results reinforce the low sensitivity of CXR to diagnose pneumonia reported in the adult literature. Iuri and colleagues[100] also examined the role of lung ultrasound in 28 children presenting with a clinical suspicion of pneumonia. All 22 patients with subpleural consolidation found on CXR were also confirmed by ultrasound. Seven cases of perihilar consolidation were not detected by ultrasound. Lung ultrasound did seem to detect more pleural effusions (15) than CXR (8).

In a recent study comparing CXR and lung ultrasound in bronchiolitis, Caiulo and colleagues[101] performed a case control study of 52 children between 1 and 16 months of age. In their control group, lung ultrasound revealed 0 out of 52 consolidations, all had normal pleural lines, and 5 out of 52 revealed isolated B-lines (a normal finding). In contrast, 44 out of 52 infants with bronchiolitis had subpleural lung consolidation (only 16 out of 52 were found on CXR), 34 out of 52 had the presence of diffuse B-lines, and one infant had a small pneumothorax (not found on CXR). These initial findings suggest that bedside ultrasound is able to identify lung abnormalities not seen on CXR. The area of pediatric lung ultrasound shows much promise but requires much more vigorous studies.

SUMMARY

Bedside lung ultrasound has revolutionized the way emergency physicians and intensivists assess and reassess patients with a variety of respiratory conditions. It has been said that lung ultrasound has become the "stethoscope" of the twenty-first century.

This article is intended to provide an up-to-date review of the critical role of lung ultrasound for diagnosing pneumothorax, pleural effusion, PE, cardiogenic pulmonary edema, COPD, and pneumonia, all with accuracies far beyond what the physical examination and CXR can provide. Lung ultrasound is a rapid, safe tool that aids in diagnosis as well as monitors the effect of therapy.

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