REVIEW ARTICLE

Lung Ultrasound for the Regional Anesthesiologist and Acute Pain Specialist

Stephen C. Haskins, MD, Ban C. Tsui, MSc, MD,† Jemiel A. Nejim, MD,* Christopher L. Wu, MD,‡ and Jan Boublik, MD, PhD†*

Abstract: In this article, we discuss the emerging role of lung point-of-care ultrasonography for regional anesthesiologists and pain management specialists. Lung ultrasonography is a well-established clinical tool that is used on a routine basis in emergency rooms and critical care units internationally to evaluate patients with respiratory distress; however, its benefits to the regional anesthesiologist and pain specialist are not as well known and are practiced less frequently. This review article covers the clinical evidence in support of lung point-of-care ultrasonography as a rapid and superior tool to traditional imaging modalities such as chest radiography and fluoroscopy. As anesthesiologists routinely perform nerve blocks that put patients at potential risk of complications such as pneumothorax or diaphragmatic paresis, it is important to understand how to use lung ultrasonography to evaluate for these conditions, as well as to differentiate between other potential causes of respiratory distress, such as interstitial syndrome and pleural effusions. This article describes the normal and pathological findings that can be used to quickly and confidently evaluate a patient for these conditions.

(*Reg Anesth Pain Med* 2017;42: 289–298)

Regional anesthesiologists and pain management specialists routinely use ultrasound (US) to perform peripheral nerve blocks (PNBs), and as a result, US-guided regional anesthesia (UGRA) has essentially become the standard of care. As UGRA has become a fundamental skill for the regional anesthesiologist, US machines have become a ubiquitous tool in our practice. Because of our specialty's familiarity and routine use of US, there is momentum to expand this practice base and take advantage of the other countless applications for US. Although lung US (LUS) is not a common skill for the regional anesthesiologist, there is a long history dating back to its use to describe diaphragmatic paresis following interscalene block approximately 25 years ago.[1] In this first of several articles on the emerging role of point-of-care US, we will discuss the role of LUS for the regional anesthesiologist and acute pain management specialist performing PNBs.

Despite the known benefits of LUS and a well-established track record in the emergency medicine and critical care literature, there has been limited incorporation into our specialty. Lung US is an essential part of modern trauma assessment in the form of the extended-focused assessment with sonography in trauma examination (e-FAST),[2] which includes evaluating for pleural effusions as well as evaluating for a pneumothorax (PTX) in trauma patients. Critical care professionals have also embraced LUS for the initial and ongoing assessment of patients admitted to the intensive care unit in respiratory distress.[3] Clinical research has made a strong case for LUS, as it is clear that LUS has significant benefits when compared with conventional methods such as chest radiography, fluoroscopy, and computed tomography scans. These advantages include rapid assessment at the bedside to obtain high-yield information while limiting radiation exposure to the patient.

Major advances in LUS have resulted from the determination that artifacts, such as "lung rocket" reverberation artifacts that are troublesome when scanning solid or fluid-filled organs, are quite useful in LUS. The interpretation of these artifacts led to the development of standardized protocols to evaluate the lung, such as the BLUE (Bedside LUS in Emergency) protocol[4] and the FALLS (Fluid Administration Limited by Lung Sonography) protocol,[5] which led to widespread adaptation. These protocols provided a means to rapidly narrow the differential diagnosis of patients with acute respiratory failure. For example, the BLUE protocol describes specific profiles for pneumonia (PNA), congestive heart failure (CHF), chronic obstructive pulmonary disease (COPD), asthma, pulmonary embolism, and PTX. The profiles are highly sensitive and specific in all the conditions except PNA, in which it is only specific. The FALLS protocol is an adaption of the BLUE protocol to evaluate for acute circulatory failure that is outside the scope of this review.

Ultimately, the strongest argument for the regional anesthesiologist practicing LUS is the ability to differentiate between respiratory distress related to a complication of a PNB and another form of pulmonary pathology. There are several common nerve blocks performed near the pleura or vascular structures, such as paravertebral, intercostal, interscalene, supraclavicular, and infraclavicular blocks. In addition, transient phrenic nerve paralysis is a known common occurrence with interscalene and supraclavicular blocks.[1] Lung US allows the regional anesthesiologist to differentiate between complications, such as PTX,[6] hemothorax,[7] and phrenic nerve paralysis,[8] and other underlying pulmonary pathologies, such as interstitial syndrome and pleural effusions.[4] For example, delayed respiratory distress following a supraclavicular block could be related to a PTX, hemothorax,[9] or phrenic nerve paralysis.[1,8] The next portion of this article describes the normal and pathological findings needed to evaluate for these conditions rapidly.

Identifying the Pleura

The first step to assessing the lung is to identify the pleura confidently. When scanning, place the US probe on the anterior chest wall (Fig. 1A) perpendicular to the ribs in the sagittal (or longitudinal) plane. This probe placement facilitates identification of 2 ribs (noted by their dark rib shadowing) and highlights the pleura, a bright hyperechoic line deep to and wedged in between the ribs (Fig. 2A). The parietal chest wall also has several bright lines; however, the pleural line will be the brightest and will have a shimmery, shiny, hyperechoic appearance.

From the *Department of Anesthesiology, Hospital for Special Surgery, Weill Cornell Medical College, New York, NY; †Department of Anesthesiology, Stanford University School of Medicine, Stanford, CA; and ‡Department of Anesthesiology, Johns Hopkins University, Baltimore, MD.

Accepted for publication January 2, 2017.

Address correspondence to: Stephen C. Haskins, MD, Department of Anesthesiology, Hospital for Special Surgery, 535 E 70th St, New York, NY 10021 (e-mail: haskinss@hss.edu).

The authors declare no conflict of interest.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.rapm.org).

ISSN: 1098-7339
DOI: 10.1097/AAP.0000000000000583

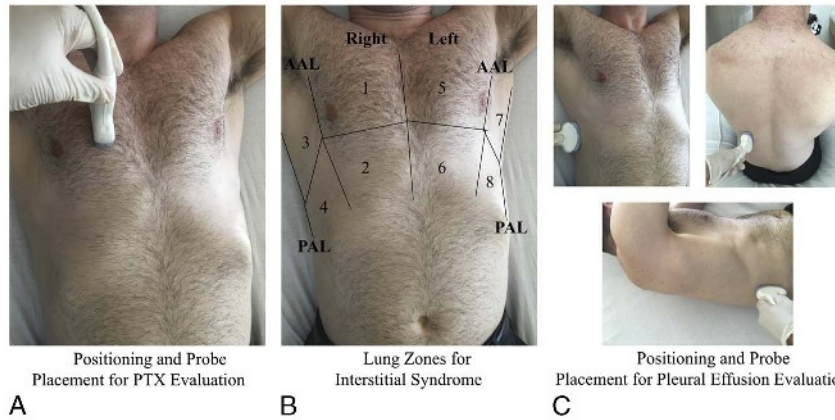

FIGURE 1. Patient position and probe placement. A, Evaluation for a PTX with optimal positioning (supine), probe selection (large footprint curvilinear), and probe placement (second to fourth intercostal space at the midclavicular line). Always ensure thorough evaluation for lung sliding. B, Thorough and systematic evaluation of interstitial processes including CHF, ARDS, and PNA require assessment of each of the 8 distinct lung zones. C, Evaluation for pleural effusion in multiple positions with the large footprint curvilinear probe. Sitting (bottom) and supine (upper left) and lateral (upper right) with slight elevation of the head of the bed. AAL indicates anterior axillary line; PAL, posterior axillary line.

LUS to Evaluate for PTX

All regional anesthesiologists must know the fundamental LUS skill of ruling out or diagnosing a PTX as a result of an inadvertent violation of the pleura following PNB. The use of LUS to evaluate for PTX is one of the most commonly studied, clinically relevant, and practically simple skills. Lung US is superior to chest radiography in both sensitivity and specificity (sensitivity, 88% vs 52%; specificity, 100% vs 99%).[10] The following section describes the relevant steps to evaluate for a PTX using LUS.

Patient Positioning and Probe Selection

When evaluating for a PTX, the optimal patient positioning is supine. This position allows air to rise into the anterior portion of the chest wall, typically between the second and fourth intercostal space at the midclavicular line (Fig. 1A). However, when dealing with a patient in respiratory distress, it might not be possible to lay the patient completely flat. In such case, a seated position can be utilized. Scanning around the clavicle to view the apex of the lung can be challenging, but as is the case with the supraclavicular block, the lung can be visualized around the first rib. Although a small PTX might be missed, a large PTX causing respiratory distress should be obvious.

Probe selection is also important when evaluating for a PTX. Although visualization of "lung sliding" can be seen with any US probe, a high-frequency linear probe is optimal because it will provide sharper temporal resolution of the pleural movement. An additional benefit is that this probe is commonly used by most regional anesthesiologists. The smaller curvilinear probe can also be used, which has the advantage of fitting neatly in between 2 rib spaces to facilitate identification of the pleura. However, the large footprint curvilinear probe (Fig. 1A) is often used in protocols such as the e-FAST examination to expedite evaluation of both shallow structures (such as the pleura) and deep structures (such as the diaphragm) with 1 probe. In this case, depth and gain adjustment are necessary.

Normal Lung Findings to Rule Out a PTX

Several fundamental normal US findings allow for a PTX to be ruled out, including lung sliding, lung pulse, B-lines, and the sea-shore sign with M-mode.

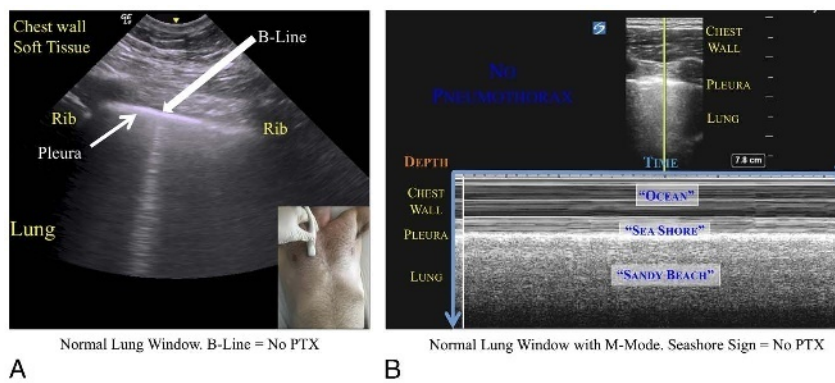

FIGURE 2. Normal lung imaging—2-dimensional and M-mode. A, The bright hyperechoic pleura is highlighted beneath 2 ribs (noted by their dark rib acoustic shadowing). The presence of the reverberation artifact. B-line indicates no PTX is present. B, The use of M-mode demonstrates the "seashore sign," which indicates no PTX.

Lung Sliding

The first and most important finding is lung sliding. Lung sliding occurs when a patient is breathing, and sonographically, the lung has a back-and-forth or "curtain" opening and closing movement. Lung sliding demonstrates the lung's dynamic visceral pleura (adherent to the lung parenchyma) sliding along the chest wall's static parietal pleura (Supplemental Digital Content 1, Lung Sliding, http://links.lww.com/AAP/A200). With a PTX, air separates the 2 pleural layers, and attenuation of the US waves prevents visualization of the dynamic visceral pleura causing lung sliding to be no longer visible. A relevant example demonstrating the effect of US attenuation with air is how a small volume of air injected into the field while performing a US-guided block obscures the sonoanatomy below the air. This same principle applies to a PTX. Therefore, the absence of lung sliding should significantly increase suspicion for a PTX.

Lung Pulse

Lung pulse is most often seen in apneic patients; however, for a regional anesthesiologist not routinely inducing general anesthesia, it would more commonly be seen during a respiratory pause at end-inspiration/expiration or in sections of the poorly aerated lung (ie, consolidations). Instead of seeing an active back-and-forth movement between the pleural layers, there is a passive vibration as a result of the cardiac cycle. This pulsatile movement is more prominent in the left hemithorax and corresponds with the heartbeat. Although similar in appearance to lung sliding, lung pulse can be seen only when lung sliding is absent. Visualization of lung pulse confirms that there is no air separating the parietal and visceral pleural layers, and therefore, it can be used to rule out a PTX (Supplemental Digital Content 2, Lung Pulse Video, http://links.lww.com/AAP/A201).

B-Lines

B-lines are bright, hyperechoic US reverberation artifacts that appear as "rockets" originating from the pleura line and traveling all the way to the edge of the screen (Figs. 2A and 3). The B-line artifact is the result of an interaction between the aerated lung and interstitial fluid and emerges from the visceral pleura. Because it originates from the visceral pleura, visualization means there is no air between the 2 pleural layers. Therefore, a single B-line can rule out a PTX. B-lines are normal in dependent areas of the lung (eg, the base of the lung), and it is normal to see up to 3 B-lines on the US screen (Fig. 3A). If more than 3 B-lines are present, this indicates increased interstitial fluid as seen in CHF, acute respiratory distress syndrome (ARDS), or acute lung injury (ALI) (Fig. 3B). A sufficiently aerated lung will appear gray, whereas a patient with an interstitial process will have a predominance of B-lines ("white-out").

M-Mode—Seashore Sign

M-mode is an important modality for LUS, particularly for PTX assessment. M-mode is available on most modern point-of-care ultrasonography machines and represents a 1-dimensional "slice" of the 2-dimensional image. M-mode shows the depth of that "slice" of tissue in the *y* axis and plots how that "slice" moves over time in the *x* axis.

Similar to lung sliding, the "seashore sign" is a normal finding when assessing the lung with M-mode (Fig. 2B). When scanning through the chest wall, pleura, and lung parenchyma, the M-mode image appears like a seashore. In the near field (upper part of the image), minimal movement of the chest wall tissue appears as straight lines, which look like ocean waves. The bright pleura line dividing the chest wall and the lung parenchyma appears like a shoreline. The lung parenchyma, deep to the pleura, appears granular and sandy like a beach. Therefore, a lung without a PTX appears like a seashore with ocean waves crashing onto a sandy beach.

Abnormal Lung Findings to Diagnose a PTX

Lung Point

The most significant finding to diagnose a PTX is lung point. Visualization of lung point is approximately 100% diagnostic for PTX.[6,11] Lung point represents the edge of the PTX where, in the same view, one can visualize the normal interaction between the pleural layers and the presence of air between the layers. With US, this appears as a transition point between an absence of lung sliding and the presence of lung sliding that is due to expansion and contraction of the lung with the respiratory cycle (Fig. 4A). The optimal way to identify lung point is to scan the anterior chest wall on a supine patient. If there is an absence of normal lung signs (lung sliding, lung pulse, seashore sign), then slide the probe laterally and posteriorly along the chest wall to the "point" where lung sliding returns (Lung Point Video, Supplemental Digital Content 3, http://links.lww.com/AAP/A202).

M-Mode—Stratosphere or Barcode Sign

Lung point can also be seen on M-mode as a "stratosphere sign" or "barcode sign." When a PTX obliterates lung sliding, then the lung parenchyma mirrors the chest wall tissue in sonographic appearance. Therefore, the straight lines of the "ocean

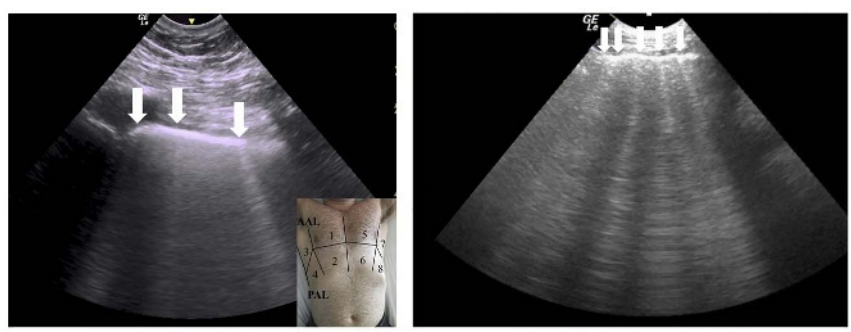

FIGURE 3. Interstitial syndrome. The presence of the "lung rocket" US artifact B-line can be a normal finding when 3 or less are visible on the screen. The presence of more than 3 B-lines suggests and interstitial process.

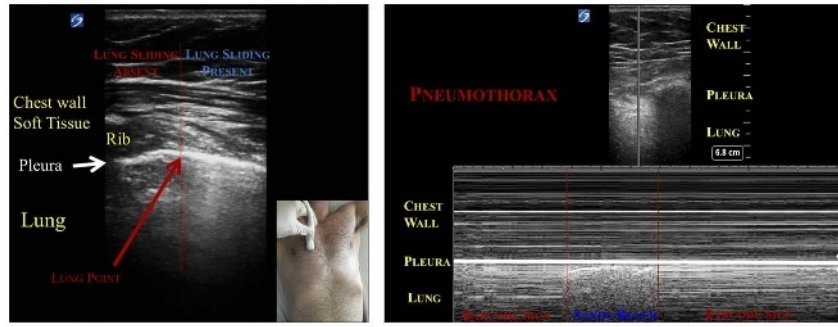

FIGURE 4. Pneumothorax—2-dimensional and M-mode. A, Using 2-dimensional imaging, lung point, as demonstrated by any alteration between the presence of lung sliding and absence of lung sliding on the screen, is diagnostic of a PTX. B, Lung point, as seen on M-mode, results in an alternation between the normal "seashore sign" and the pathological "barcode" or "stratosphere" sign.

waves" in the near field extend to the bottom of the screen and take on the appearance of a "barcode" (like that on the back of a book) or the "stratospheres" of our atmosphere. Lung point on M-mode is seen as an alteration between the "seashore sign" and "barcode sign" (Fig. 4B). Figure 5 describes a systematic algorithm to use when evaluating a patient in respiratory distress due to a suspected PTX.

Common Pitfalls—PTX

A massive PTX occupying the entire chest wall may not have a lung point, in which case the lack of normal US findings and high clinical suspicion should drive assessment and management.

Although lung point is diagnostic of a PTX, the stratosphere sign or barcode sign can be caused by improper positioning of the probe or inadequate depth; therefore, the barcode sign should not be considered diagnostic unless other normal US findings are also missing.

Patients with pleural adhesions (eg, following pleurodesis) will lack lung sliding.

LUS for Interstitial Syndrome

As regional anesthesiologists routinely manage patients with multiple cardiac and pulmonary comorbidities, it is essential to differentiate between the wide range of pathologies that can cause respiratory distress. A systematic evaluation of the lung not only takes into consideration pathology that is a result of our interventions (eg, PTX or diaphragmatic paresis), but it should also involve assessment for interstitial processes such as fluid overload resulting in pulmonary edema/CHF, PNA, or ARDS.

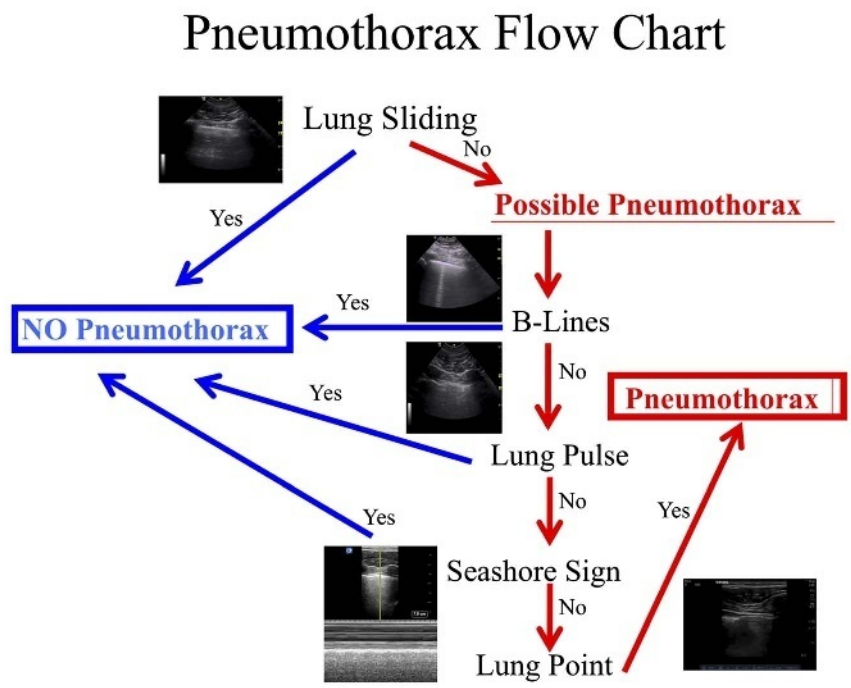

FIGURE 5. Pneumothorax flowchart. The presence of any of the following normal findings will rule out a PTX: lung sliding, B-lines, lung pulse, and seashore sign. First evaluate for lung sliding, then look for other US findings if lung sliding is not present. When all of the normal findings are missing, then the presence of a lung point will diagnose a PTX.

Patient Positioning and Probe Selection

Patient positioning is necessary to ensure a thorough assessment of all lobes of the lung, as well as differentiating between diffuse versus isolated processes. If possible, having a patient in the seated position allows for complete evaluation of the anterior, lateral, and posterior chest wall. However, when this is not possible, a supine position assessment of the anterior and lateral chest wall in the 8 distinct lung zones will suffice for most major pathologies (Fig. 1B). As is the case with evaluating for a PTX, visualization of B-lines can be seen with any US probe; however, a high-frequency linear probe provides sharper resolution of the B-lines and is readily available for most regional anesthesiologists.

Ultrasound Findings—Interstitial Syndrome

As mentioned earlier, the essential artifact to assess an interstitial process is the B-line (Figs. 2A and 3). B-lines are normal in dependent areas of the lungs such as the base (Fig. 3A); however, multiple B-lines are indicative of a pathological interstitial syndrome (Fig. 3B).[4] Interstitial syndrome is most commonly caused by pulmonary edema, which may be secondary to fluid overload, CHF, ALI, or ARDS. However, interstitial PNA, as well as lung fibrosis, must be considered, depending on the clinical scenario.[12] In general, the more B-lines in an intercostal window, the more severe the disease process.

When coming up with a differential diagnosis on a patient with prominent B-lines, use the following guidelines (Fig. 6):

1. Three or fewer B-lines: normal lung parenchyma.
2. Diffuse bilateral B-lines with more than 3 per intercostal window: indicative of an interstitial syndrome. Evaluate for lung sliding (note that the BLUE protocol recommends evaluating for lung sliding before evaluating for B-lines). If lung sliding is seen, pulmonary edema is most likely. If lung sliding is abolished, consider bilateral PNA or ARDS. Note the presence of B-lines rules out a PTX.
3. Localized or unilateral B-lines: evaluate for the presence of lung sliding. If present, consider a focal interstitial process, such as a lung contusion. If absent, consider PNA.
4. Differentiating between cardiovascular versus permeability-related edema. In general, a more thorough examination is necessary; however, there are some helpful tips. B-lines appear symmetrically in a lateral fashion in patients with cardiogenic edema and progress anteriorly as the disease becomes more severe. With ALI, B-lines appear in asymmetrical fashion in dependent areas of the lung posteriorly and caudally.

In summary, an important way to differentiate between interstitial syndromes is by assessing for either a focal or diffuse presence of B-lines and whether the B-lines are gravity dependent. Both ARDS and CHF are diffuse (present throughout both lungs) in nature; however, CHF is gravity dependent. This gravity-dependent nature is similar to hearing lung crackles at the base where the lungs are "wet" from congestion. Acute respiratory distress syndrome/ALI, on the other hand, has diffuse heterogeneous B-lines. In addition, ARDS/ALI and PNA often result in pleural inflammatory adherences, causing thickening of the pleural line and loss of lung sliding. Focal PNA can manifest B-lines in only 1 lobe where the inflammatory process is causing an interstitial manifestation. For example, a patient with aspiration PNA will have diffuse B-lines with a lack of lung sliding in the right upper lobe but may have clear left-sided lung parenchyma. See Table 1 for an example of how to use B-lines to differentiate between interstitial processes.

Common Pitfalls—Interstitial Syndrome

Dependent regions of the lung typically have a higher number of B-lines because of their alveolar/arterial pressure gradients. It is important to note patient positioning (seated, supine, or lateral) when scanning to assess for normal versus pathological presence of B-lines. Elderly patients have a higher number of B-lines present in normal lung tissue and are at risk of false-positive diagnosis for interstitial syndrome.[13] When scanning in the left lower chest (anterior axillary line) inferior to the diaphragm, the air-fluid interface present in the stomach and spleen may produce significant B-lines mimicking PNA.

LUS to Evaluate for Diaphragmatic Paresis

As a regional anesthesiologist, it is important to be able to assess for diaphragmatic function. The phrenic nerve, which controls diaphragmatic movement and contraction, can often be anesthetized following brachial plexus blocks (eg, interscalene block). Several imaging techniques have been used to monitor diaphragmatic function, including fluoroscopy, magnetic resonance imaging, plethysmography, and US.

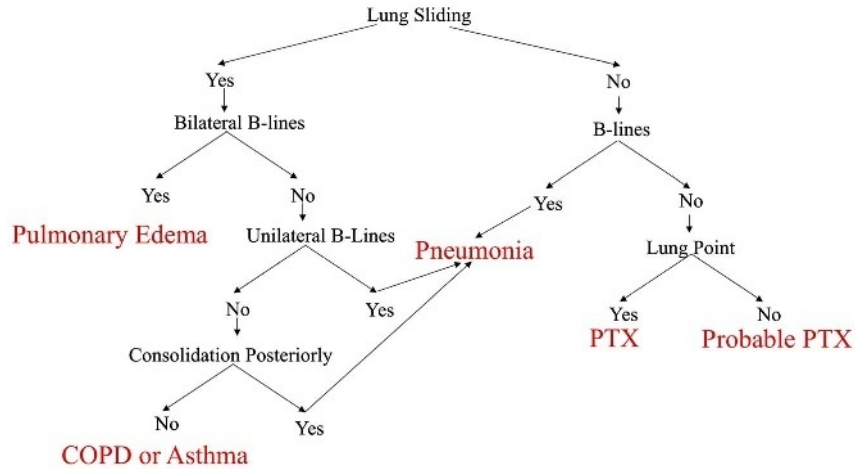

FIGURE 6. Bedside LUS in emergency protocol algorithm to differentiate between causes of respiratory distress including PTX, pulmonary edema, pneumonia, and asthma/COPD. COPD indicates chronic obstructive pulmonary disease.

TABLE 1. Differential Diagnosis of Interstitial Syndrome Based on the Presence of B-Lines

	B-Lines Present	Lung Sliding	Location	Notes
Pneumonia	Yes	May be abolished	Focal	Absence of lung sliding with anterior B-lines is very sensitive and specific for anterior PNA
				Posterior PNA is more difficult to diagnose
CHF	Yes	Present	Diffuse	B-lines appear late in mild exacerbations
				As disease state worsens, B-lines progress anteriorly
ARDS/ALI	Yes	Present	Diffuse	B-lines are heterogeneously distributed
				They are mostly in the posterior lung
				Effusions and consolidations are typical for ARDS
Pulmonary fibrosis	Yes	May be abolished	Diffuse, varied	Examine for abnormalities in pleural sliding
				Unlike ARDS and CHF, the number of B-lines does not correlate with severity of disease

Ultrasound is considered one of the most attractive options, regarding imaging techniques, as it can provide a noninvasive way to assess diaphragmatic function and is more accurate than other portable modalities, such as fluoroscopy.[14–18] Through various B- and M-mode US techniques,[16,19] diaphragmatic activity and lung motion can be visualized in a real-time, portable, and bedside manner. Traditionally, one of the most commonly used US scanning methods has relied on the ability to identify and image the right and left hemidiaphragm through the acoustic windows of the liver and spleen, respectively, and then record diaphragmatic movement in M-mode (Fig. 7). However, this method has questionable clinical utility as it is often difficult and time consuming to obtain an adequate acoustic view in a relatively deep plane, especially on the splenic (left) side. Recently, other studies have demonstrated that diaphragmatic function can be alternatively assessed by observing diaphragm muscle thickening during the respiratory cycle via intercostal windows (8th and 10th spaces) at the zone of apposition.[16,19] The zone of apposition is defined as the area of the diaphragm that is nestled closely to the inner aspect of the lower rib cage where the diaphragm also begins to peel away from the rib cage.

Comparison of the changes in the diaphragm thickening ratio [(thickness at inspiration − thickness at expiration) / thickness at expiration] reveals changes in muscle contraction effort (28%–96% changes in healthy patients vs −35% to 5% change in those with diaphragmatic paresis).[20,21] Despite the fact that the diaphragm can be readily observed via the use of superficial intercostal views using a high-frequency probe, this is rarely practiced by anesthesiologists because of their unfamiliarity with the method and the challenge of quickly recalling how to locate the scanning position. Recently, the simple mnemonic "ABCDE" has been suggested in aiding one to recall and locate the scanning rate for evaluating the diaphragm via these intercostal windows (Fig. 8). This mnemonic method simply uses step-by-step landmarking of readily recognizable features such as lung sliding, to facilitate the identifying diaphragmatic muscle and reach typical scanning site.[22]

Although the use of intercostal windows has been well described and avoids the challenges associated with utilizing

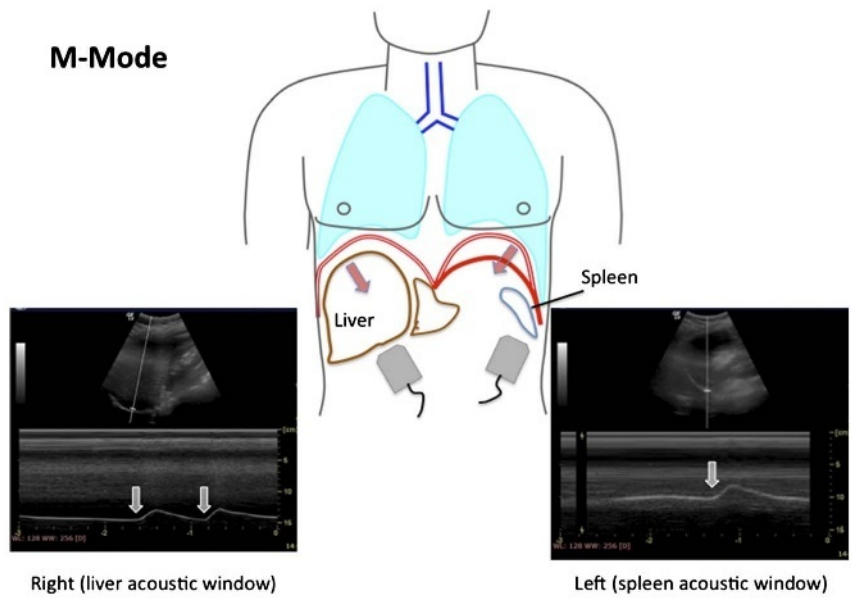

FIGURE 7. M-mode US image of the diaphragm using the conventional method with the sniff test. Schematic of the technique demonstrated by probe placement (middle). Diaphragm typically appears as a thin white line via acoustic windows of the liver (right) and spleen (left). Red arrows indicate the downward and inward deflection of the diaphragm muscle upon sniffing. White arrows indicate the starting of the sniff test on M-mode and a brief descent (ie, toward the probe) of the diaphragm when the patient sniffs reflected by an upward spike in M-mode.

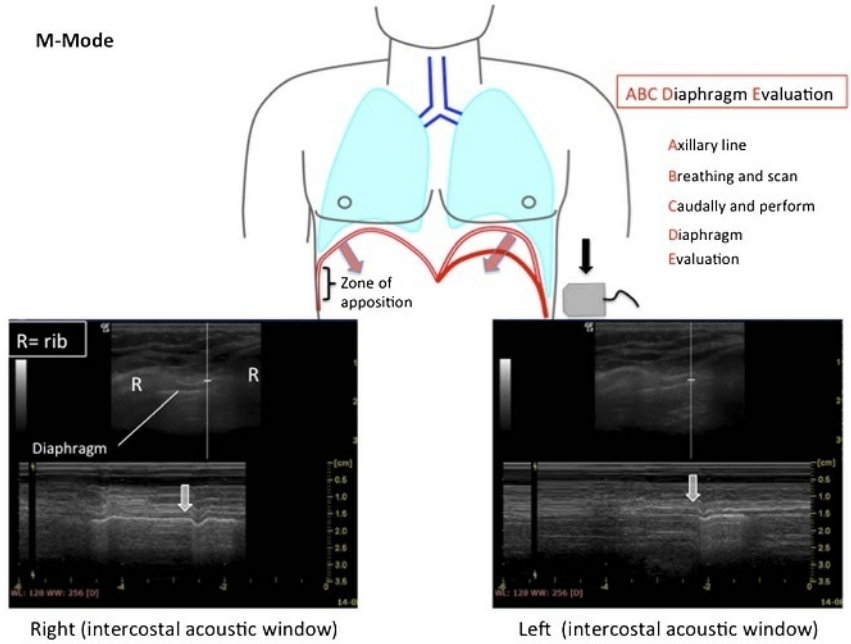

FIGURE 8. M-mode US image of the diaphragm using the ABCDE method. Schematic of the technique demonstrated by probe placement and movement (middle). D indicates diaphragm; IM, intercostal muscle. Arrows indicate the border of the diaphragm. Diaphragm musculature can be readily seen via intercostal windows for both right and left. White arrows indicate the starting of the sniff test and a brief descent (ie, away from the probe) of the diaphragm when the patient sniffs reflected by a downward spike in M- mode.

the hepatic or splenic acoustic window methods (such as poor reproduction and dependence on operator experience), it is important to point out that there are no published data or evidence comparing the effectiveness of the 2 approaches.[23] Thus, further well-designed clinical studies will be needed to determine the superiority and clinical merit of these techniques.

In the following sections of this article, we briefly highlight 2 separate approaches to viewing the diaphragm using different acoustic windows. However, we refer the reader to more in-depth articles[16,19,23] to obtain a further understanding of the complex 3-dimensional anatomy of the diaphragmatic curvature and its movement, as well as to appreciate how to effectively place and manipulate the probe and interpret the images and movements.

Patient Positioning and Probe Selection

Using Hepatic or Splenic Acoustic Windows

A low-frequency probe (eg, cardiac or abdominal of 2–5 MHz) is placed between the midclavicular and anterior axillary lines in the subcostal region. Through either the hepatic or splenic acoustic window, a hyperechoic line of the diaphragm can be seen moving toward and away from the probe, in B-mode, during respiration.

Using Intercostal Windows

A high-frequency probe (eg, >10 MHz) is placed at the midaxillary line between the 8th and 10th intercostal spaces (ie, just below the costophrenic sinus) at the zone of apposition. One can use the mnemonic "ABCDE" to aid in locating this site by placing a high-frequency linear probe at the anterior ***a***xillary line, watching for ***b***reathing, then moving the probe ***c***audally to identify the ***d***iaphragm for ***e***valuation. By placing the probe at the anterior axillary line just below the nipple level, one can easily observe sliding of the lungs and pleura through the intercostal muscle between the ribs during the respiratory cycle. As the probe is moved in a caudal direction along the axillary line, the diaphragm becomes easily visualized when it is no longer obscured by the pleura between the 8th and 10th intercostal spaces. As pointed out in this ABCDE technical article, however, there is no evidence that degree of lung sliding has any relationship to spontaneous diaphragmatic function and contraction.[24–26]

Ultrasound Findings—Diaphragmatic Function

When using the hepatic or splenic acoustic windows, the diaphragmatic function can be assessed by measuring diaphragmatic inspiratory excursion (reference range, 1.34 ± 0.18 cm) in M-mode.[27] In a patient with unilateral diaphragmatic paresis, a contralateral mediastinal shift during inspiration leads to a paradoxical upward motion of the diaphragm. This motion can be elicited by a quick nasal inspiration with a closed mouth (ie, sniff test) under US M-mode assessment.[28]

Through the intercostal windows, the change in diaphragmatic muscle thickness during respiration is used as the measure of diaphragmatic function when assessing the diaphragm. Also, similar to its use in association with the hepatic and splenic windows, performing a sniff test can easily provide further assessment of diaphragmatic movement.[29] With the probe directed cephalad, one will detect a brief descent of the diaphragm when the patient sniffs (reflected by a downward spike in M-mode) if the diaphragm is functioning normally. Because the technique allows direct visualization of the muscular portion of the diaphragm via a relatively superficial intercostal window, it eliminates most of the impact that body habitus has on the difficulty of imaging, allowing it to be used equally as effectively in obese adults and small pediatric patients. In pediatric practice, the scanning view provided by a standard linear probe is often large enough to view multiple rib levels while enabling both lung sliding and diaphragmatic movement to be observed simultaneously and clearly in a single image.[30]

Common Pitfalls—Diaphragmatic Paresis

In the sitting position, patients with significant pleural effusions can have paradoxical diaphragmatic motion, suggesting paresis that will revert to normal motion when supine.

LUS for Pleural Effusions

A regional anesthesiologist must be able to systematically and thoroughly approach respiratory distress in patients following PNB. Although extremely rare, there has been a clinical case report of massive hemothorax following supraclavicular block.[9] In addition to causing respiratory compromise, a large pulmonary effusion can have a significant impact on hemodynamics and cardiac output. For the regional anesthesiologist assessing a hemodynamically unstable patient, evaluation for pleural effusions in addition to potential cardiac compromise is essential. More importantly, given the comorbidities of our aging patient population at risk of CHF, assessing for effusions can direct management and decision making in the perioperative setting.

Evaluation of pleural effusions using LUS is superior to traditional modalities such as chest radiography and tomography because it is more sensitive in detection of volume[31] and septations within pleural effusions.[32] Compared with chest radiography and even computed tomography scan, US allows for delineation between effusions and lung consolidations and is more accurate at detecting pleural effusions when compared with bedside chest radiography (93% vs 47%).[33,34] Ultrasound visualization of adjacent structures during invasive procedures such as thoracentesis has been shown to decrease complications including PTX when compared with clinically guided thoracentesis.[35]

Patient Positioning and Probe Selection

For pleural effusion assessment, optimal patient positioning and probe selection are important. In regard to patient positioning, pleural effusions—unless loculated—accumulate in the dependent areas of the lung; therefore, sitting up is optimal for scanning for fluid above the diaphragm (Fig. 1C). A supine position causes pleural fluid to collect posteriorly, which is difficult to assess with the US as the bed prevents accurate posterior scanning. However, in an intensive care unit, sitting may not be feasible, because the patient may be attached to multiple devices or unable to sit up because of either respiratory or hemodynamic disturbance. If possible, turn the patient to a lateral decubitus position coupled with slight head elevation and scan in the posterior axillary line (Fig. 1C).

Probe selection is also important for the evaluation of pleural effusions. One should use a low-frequency transducer, between 3.5 and 5 MHz. The cardiac phased-array and the large footprint curvilinear probes work well for scanning with the smaller footprint of the cardiac probe, facilitating scanning between the intercostal spaces. The high-frequency linear probe should be avoided by novice scanners as the depth and acoustic window make an evaluation of diaphragm and pleura challenging and may result in false negatives. The small acoustic window of the small footprint probe also makes the evaluation for effusions more challenging.

Ultrasound Findings—Pleural Effusion

The presence of pleural fluid may be the result of a transudate, exudate, or hemothorax. Ultimately, thoracentesis is necessary for a definitive answer; however, the following characteristics are required to define a pleural effusion:

1. There must be a black (anechoic) space within the thoracic cavity visualized between the inside of the chest wall, the surface of the lung, and the diaphragm (Fig. 9B).
2. If heterogeneous (white granular) echogenic material is present, then it is a complex (nonseptated) effusion. If white fibrin strands are floating inside the effusion, that is considered a complex septated effusion. A wedge-shaped hypoechoic lesion with an air bronchogram in the lung parenchyma suggests a consolidation.[7] In general, the complex presentations are more likely to suggest an exudative effusion. Of note, a new effusion as a result of a hemothorax should not have a complex presentation.
3. The effusion should move with the respiratory cycle, the diaphragm, and the lung.

When evaluating a patient that is hemodynamically unstable, a helpful resource is the FATE (Focus Assessed Transthoracic Echocardiography) protocol,[36] which combines an echocardiographic assessment of obvious cardiac pathology, quantitative valvular and biventricular function, wall thickness, and chamber dimensions, as well as assessment of the pleura on both sides. Placed in a clinical context, this allows for dynamic evaluation of the potential effect pleural fluid can have on hemodynamics (Pleural Effusion Videos, Supplemental Digital Content 4 and 5, http://links.lww.com/AAP/A203, and http://links.lww.com/AAP/A204).

Common Pitfalls—Pleural Effusion

Mirror artifacts (a reflection of a false image most commonly seen when scanning through a hyperechoic structure such as the

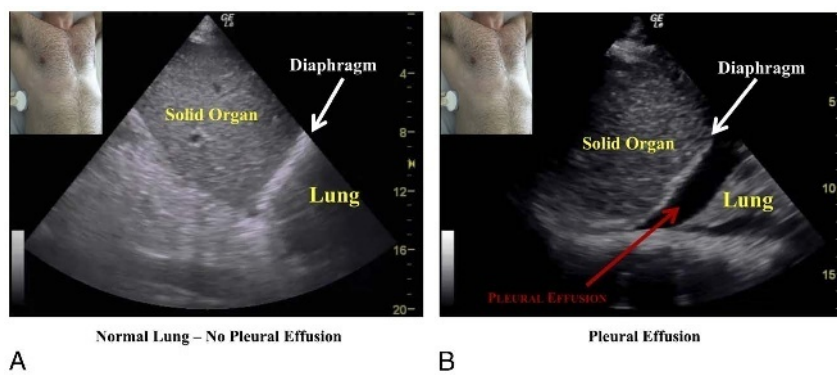

FIGURE 9. Pleural effusions. Pleural effusions are gravity dependent and appear at the base of the lung. First, identify a solid organ (the liver on the right and spleen on the left) with the bright hyperechoic diaphragm noted in the cephalad direction. A, In the absence of an effusion, the lung appears gray and granular. B, With a pleural effusion, the lung will be visible and surrounded by a black anechoic fluid collection.

diaphragm) can result in the liver/spleen tissue appearing in the lung field and mimicking a consolidation. It is essential to visualize hypoechoic fluid surrounding the lung tissue before increasing suspicion for an effusion.

Putting It All Together

When a regional anesthesiologist is evaluating a patient in respiratory distress following a PNB, a rapid and systematic approach to rule out obvious and high-risk pathology should be taken. Pneumothorax should be high on the differential diagnosis following PNB near the pleura. Assessing the patient in supine positioning whenever possible (Fig. 1A) will allow visualization of normal LUS signs to rule out a PTX (Fig. 2) or lung point to diagnose a PTX (Fig. 4). Simultaneous evaluation for interstitial syndrome can also be done in this position, and a predominance of B-lines in the anterior thoracic cavity (Fig. 3) will both rule out a PTX and indicate an interstitial process as the source of the respiratory distress. Once an interstitial process is of primary concern, then a thorough assessment of each lung zone (Fig. 1B) will differentiate between a diffuse process (such as ARDS or CHF) or a focal process (such as PNA).

In the setting of an interscalene or supraclavicular block, following evaluation for a PTX and interstitial syndrome, unilateral diaphragmatic paresis should be assessed (Figs. 7 and 8). While scanning at the base of the lung to assess diaphragmatic function, the regionalist can also scan cephalad to the diaphragm to evaluate for a pleural effusion (Fig. 9). Note that positioning for an effusion may require a slight incline in the bed or a sitting position (Fig. 1C).

CONCLUSIONS

Lung US is a powerful perioperative tool to rule out or diagnose potential complications caused by PNBs, as well as determine differential diagnoses for patients with acute respiratory distress. Because LUS is rapid and noninvasive and causes no harmful radiation to patients, there is little downside to its utilization to evaluate for potential pathology such as PTX, pleural effusions, interstitial syndrome, and assessment of hemidiaphragmatic paresis. Appropriate patient positioning, probe selection, and a systematic approach are essential to ensure accurate assessment of pathology. As is always the case with patient care, it is essential for all clinicians to recognize that US is only 1 piece of the clinical puzzle when it comes to assessing a patient in respiratory distress. The entire clinical context should be considered before any action, and no decisions should be made based solely on a US image. Instead, management decisions should be made based on the severity of disease and impact on the respiratory status and hemodynamics. For example, diagnosis of small PTX or pleural effusion without hemodynamic changes does not indicate immediate decompression or drainage.

As US machines continue to become more compact, portable, and affordable, there is an increasing role for US assessment of patients with respiratory distress. Lung US is an essential skill for regional anesthesiologists and acute pain management specialists who routinely practice UGRA, providing them with the ability to assess patients with respiratory distress that may be the direct result of a known complication from our regional blocks. As LUS becomes more standard, future applications for the anesthesiologist will undoubtedly evolve and thereby drive future relevant technological advances. In the meantime, these fundamental skills will significantly enhance perioperative patient assessment and management by the regional anesthesiologist and acute pain management specialist.

REFERENCES

1. Urmey WF, McDonald M. Hemidiaphragmatic paresis during interscalene brachial plexus block: effects on pulmonary function and chest wall mechanics. *Anesth Analg*. 1992;74:352–357.
2. Montoya J, Stawicki SP, Evans DC, et al. From FAST to E-FAST: an overview of the evolution of ultrasound-based traumatic injury assessment. *Eur J Trauma Emerg Surg*. 2016;42:119–126.
3. Volpicelli G, Elbarbary M, Blaivas M, et al. International evidence-based recommendations for point-of-care lung ultrasound. *Intensive Care Med*. 2012;38:577–591.
4. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. *Chest*. 2008; 134:117–125.
5. Lichtenstein D. Fluid administration limited by lung sonography: the place of lung ultrasound in assessment of acute circulatory failure (the FALLS-protocol). *Expert Rev Respir Med*. 2012;6:155–162.
6. Volpicelli G. Sonographic diagnosis of pneumothorax. *Intensive Care Med*. 2011;37:224–232.
7. Prina E, Torres A, Carvalho CR. LUS in the evaluation of pleural effusion. *J Bras Pneumol*. 2014;40:1–5.
8. Lloyd T, Tang YM, Benson MD, et al. Diaphragmatic paralysis: the use of M mode ultrasound for diagnosis in adults. *Spinal Cord*. 2006;44: 505–508.
9. Singh SK, Katyal S, Kumar A, Kumar P. Massive hemothorax: a rare complication after supraclavicular brachial plexus block. *Anesth Essays Res*. 2014;8:410–412.
10. Ding W, Shen Y, Yang J, He X, Zhang M. Diagnosis of pneumothorax by radiography and ultrasonography: a meta-analysis. *Chest*. 2011;140: 859–866.
11. Lichtenstein D, Mezière G, Biderman P, Gepner A. The "lung point": an ultrasound sign specific to pneumothorax. *Intensive Care Med*. 2000; 26:1434–1440.
12. Hasan AA, Makhlouf HA. B-lines: Transthoracic chest ultrasound signs useful in assessment of interstitial lung diseases. *Ann Thorac Med*. 2014;9: 99–103.
13. Ciccarese F, Chiesa AM, Feletti F, et al. The senile lung as a possible source of pitfalls on chest ultrasonography and computed tomography. *Respiration*. 2015;90:56–62.
14. Houston JG, Fleet M, Cowan MD, McMillan NC. Comparison of ultrasound with fluoroscopy in the assessment of suspected hemidiaphragmatic movement abnormality. *Clin Radiol*. 1995; 50:95–98.
15. Houston JG, Morris AD, Howie CA, Reid JL, McMillan N. Technical report: quantitative assessment of diaphragmatic movement—a reproducible method using ultrasound. *Clin Radiol*. 1992;46:405–407.
16. Matamis D, Soilemezi E, Tsagourias M, et al. Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. *Intensive Care Med*. 2013;39:801–810.
17. Testa A, Soldati G, Giannuzzi R, et al. Ultrasound M-mode assessment of diaphragmatic kinetics by anterior transverse scanning in healthy subjects. *Ultrasound Med Biol*. 2011;37:44–52.
18. Sarwal A, Walker FO, Cartwright MS. Neuromuscular ultrasound for evaluation of the diaphragm. *Muscle Nerve*. 2013;47:319–329.
19. Zambon M, Cabrini L, Beccaria P, Zangrillo A, Colombo S. Ultrasound in critically ill patients: focus on diaphragm. *Intensive Care Med*. 2013; 39:986.
20. Vivier E, Mekontso Dessap A, Dimassi S, et al. Diaphragm ultrasonography to estimate the work of breathing during non-invasive ventilation. *Intensive Care Med*. 2012;38:796–803.
21. Gottesman E, McCool FD. Ultrasound evaluation of the paralyzed diaphragm. *Am J Respir Crit Care Med*. 1997;155:1570–1574.

22. Tsui JJ, Tsui BC. A novel systematic ABC approach to diaphragmatic evaluation (ABCDE). *Can J Anaesth*. 2016;63:636–637.

23. Zambon M, Greco M, Bocchino S, Cabrini L, Beccaria PF, Zangrillo A. Assessment of diaphragmatic dysfunction in the critically ill patient with ultrasound: a systematic review. *Intensive Care Med*. 2017;43:29–38.

24. Halliday S, Horne S, Tsui BC. Diaphragm thickness and its relationship to lung sliding using the ABC approach to diaphragmatic evaluation: a feasibility study in patients undergoing ultrasound-guided brachial plexus blocks. Spring 2016 abstract titles: ASRA 41st Annual Regional Anesthesiology and Acute Pain Medicine Meeting March 31–April 2, 2016, New Orleans, LA. *Reg Anesth Pain Med*. 2016;41:632652.

25. Mead J. Functional significance of the area of apposition of diaphragm to rib cage [proceedings]. *Am Rev Respir Dis*. 1979;119:31–32.

26. Reber A, Nylund U, Hedenstierna G. Position and shape of the diaphragm: implications for atelectasis formation. *Anaesthesia*. 1998; 53:1054–1061.

27. Boussuges A, Gole Y, Blanc P. Diaphragmatic motion studied by m-mode ultrasonography: methods, reproducibility, and normal values. *Chest*. 2009; 135:391–400.

28. Gerscovich EO, Cronan M, McGahan JP, Jain K, Jones CD, McDonald C. Ultrasonographic evaluation of diaphragmatic motion. *J Ultrasound Med*. 2001;20:597–604.

29. Naik LY, Sondekoppam RV, Jenkin Tsui J, Tsui BC. An ultrasound-guided ABCDE approach with a sniff test to evaluate diaphragmatic function without acoustic windows. *Can J Anaesth*. 2016;63:1199–1200.

30. Tsui BC, Tsui J. ABC diaphragmatic evaluation for neonates. *Paediatr Anaesth*. 2016;26:768–769.

31. Remérand F, Dellamonica J, Mao Z, et al. Multiplane ultrasound approach to quantify pleural effusion at the bedside. *Intensive Care Med*. 2010;36: 656–664.

32. Esmadi M, Lone N, Ahmad DS, Onofrio J, Brush RG. Multiloculated pleural effusion detected by ultrasound only in a critically-ill patient. *Am J Case Rep*. 2013;14:63–66.

33. Yu CJ, Yang PC, Wu HD, Chang DB, Kuo SH, Luh KT. Ultrasound study in unilateral hemithorax opacification. Image comparison with computed tomography. *Am Rev Respir Dis*. 1993;147:430–434.

34. Lichtenstein D, Goldstein I, Mourgeon E, Cluzel P, Grenier P, Rouby JJ. Comparative diagnostic performances of auscultation, chest radiography, and lung ultrasonography in acute respiratory distress syndrome. *Anesthesiology*. 2004;100:9–15.

35. Mercaldi CJ, Lanes SF. Ultrasound guidance decreases complications and improves the cost of care among patients undergoing thoracentesis and paracentesis. *Chest*. 2013;143:532–538.

36. Holm JH, Frederiksen CA, Juhl-Olsen P, Sloth E. Perioperative use of focus assessed transthoracic echocardiography (FATE). *Anesth Analg*. 2012;115:1029–1032.