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REVIEW ARTICLE/BRIEF REVIEW

The sound of air: point-of-care lung ultrasound in perioperative medicine

Le bruit de l'air : échographie pulmonaire au point d'intervention en médecine périopératoire

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Abstract

Purpose *Lung ultrasound (LUS) has emerged as an effective and accurate goal-directed diagnostic tool that can be applied in real time for the bedside assessment of patients with respiratory symptoms and signs. Lung ultrasound has definite and easily recognized findings and has been shown to outperform physical examination and chest radiography for the diagnosis and monitoring of many pulmonary and pleural conditions. In this article, we review the principles of LUS image acquisition and interpretation, summarizing key terms and sonographic findings.*

Principal findings *Although LUS is easy to learn, adequate training and performance in an organized fashion are crucial to its clinical effectiveness and to prevent harm. Therefore, we review normal LUS findings and propose step-wise approaches to the most common LUS diagnoses, such as pneumothorax, pleural effusion, interstitial syndrome, and lung consolidation. We highlight potential pitfalls to avoid and review a recently published practical algorithm for LUS use in clinical practice.*

Conclusions *Because of the unique physical properties of the lungs, only a careful and systematic analysis of both artifacts and anatomical images allows accurate interpretation of sonographic findings. Future studies exploring the use of software for automatic interpretation, quantitative methods for the assessment of interstitial syndrome, and continuous monitoring devices may further simplify and expand the use of this technique at the bedside in acute medicine and the perioperative setting.*

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Résumé

Objectif *L'échographie pulmonaire s'est avérée un outil diagnostique efficace et précis qui peut être appliqué en temps réel au chevet des patients pour l'évaluation de signes et symptômes respiratoires. L'échographie pulmonaire permet des constatations claires et facilement reconnaissables qui surpassent les résultats de l'examen physique et de la radiographie du poumon pour le diagnostic et le suivi de nombreuses conditions pulmonaires et pleurales. Dans cet article, nous passons* *en revue les principes de l'acquisition et de l'interprétation de l'échographie pulmonaire, et résumons les principaux termes et constatations permises par l'échographie.*

Constatations principales *L'apprentissage de l'échographie pulmonaire est aisé, mais une formation adéquate et sa réalisation structurée sont les clés de l'efficacité clinique et de la prévention d'un préjudice pour le patient. Nous examinons donc les constatations d'une échographie normale et proposons une évaluation par étapes des diagnostics échographiques les plus fréquents, notamment le pneumothorax, l'épanchement pleural, le syndrome interstitiel et la consolidation pulmonaire. Nous soulignons les écueils éventuels à éviter et analysons un algorithme pratique récemment publié pour l'utilisation de l'échographie pulmonaire en pratique clinique.*

Conclusions *Compte tenu des caractéristiques physiques uniques des poumons, seule une analyse soigneuse et systématique des artefacts et des images anatomiques permet une interprétation exacte des constatations échographiques. De futures études explorant l'utilisation de logiciels pour une interprétation automatique, les méthodes quantitatives d'évaluation d'un syndrome interstitiel, ainsi que pour les dispositifs de surveillance continue pourront encore simplifier et étendre l'utilisation de cette technique au chevet des patients dans le cadre des soins aigus et périopératoires.*

Do we need lung ultrasound?

Since its original description 20 years ago,[1] lung ultrasound (LUS) has emerged as an indispensable goal-directed diagnostic tool that can be applied in real time at the bedside for the assessment of patients with respiratory symptoms and signs.[2,3] Advantages are striking, as LUS has been shown to be easy to learn, accurate, and reproducible because of definite and easily recognized findings.[3-5] In comparative studies, LUS has been shown to outperform physical examination and chest radiography for the diagnosis and monitoring of many pulmonary and pleural conditions.[3,6-14] Availability of new ultrasound devices, extremely portable but at the same time capable of excellent image quality, has further facilitated the use of LUS in non-traditional scenarios such as the operating room, emergency department, intensive care unit, pre-hospital setting, and other perioperative scenarios.

Like other ultrasound applications, LUS performance and interpretation are operator dependent.[15] Adequate training and performance in an organized fashion are crucial to reduce operator dependency, ensure its clinical effectiveness, and prevent harm from misdiagnosis (falsely positive or negative).[4] In this article, we review the principles of LUS image acquisition and interpretation, summarizing key terms and sonographic findings and presenting step-wise approaches to frequent LUS diagnoses. We highlight potential pitfalls to avoid and review a recently published systematic algorithm for LUS use in clinical practice.

Physical principles of ultrasound

In the human body, ultrasound waves propagate in straight lines until they encounter a boundary between tissues of different acoustic impedance. At these boundaries, some waves are reflected back to the transducer (allowing image generation in relation to distance/time from the boundary and intensity of the reflection), while some travel further until they reach another tissue boundary and are reflected, or are completely absorbed by tissues. Two main interactions therefore affect ultrasound image generation: reflection and attenuation.

The intensity of *reflection* that occurs at a tissue interface (e.g., air-fluid; fluid-muscles; air-muscles) is directly proportional to the difference in acoustic impedance of the tissues. The degree of *attenuation* (i.e., gradual loss of intensity due to absorption and scattering) depends on the conducting medium, with the greatest attenuation occurring in air and bone. Thus, in normally aerated lung tissue, ultrasound waves are nearly completely reflected at the interface between the visceral pleura and lung tissue, with the few waves traversing the interface being absorbed almost immediately.

For decades, these physics principles discouraged attempts to use ultrasonography to study the lung. Nevertheless, in the past 20 years many have shown that ultrasound can be used for evaluation of the pulmonary parenchyma.[1,6-8,16,17]

Normal lung ultrasound findings

Because of the unique physical properties of the lungs, their sonographic examination requires systematic analysis of both non-anatomical (i.e., artifacts) and anatomical (e.g., visualization of the pleural space and lung parenchyma in the presence of effusion and consolidation) images.[3,4] In normal lungs, when an ultrasound transducer is placed sagittally on the chest wall over any intercostal space projecting over aerated lung (e.g., 2^{nd} to 7^{th}), the following structures and artifacts can be identified: 1) subcutaneous tissues and intercostal muscles (anatomical image); 2) superior and inferior ribs with posterior acoustic shadowing (artifact due to near complete reflection of the ultrasound beam at the calcified bone cortex); 3) a hyperechoic homogenous horizontal line at the interface between the pleura and aerated lung tissue, called the pleural line (artifact due to near complete reflection of the ultrasound beam at the aerated lung); 4) hyperechoic horizontal lines below the pleural line, regularly spaced at multiples of the distance between the probe and the pleural line, called A lines (reverberation artifacts generated from the strong reflectivity of the pleural line, with each ultrasound beam travelling several times between the probe and pleura). Moreover, in most lungs, short vertical artifacts (formerly called Z lines) originating from and moving with the pleural line can be identified. They are thought to represent areas of focal increased lung density (i.e., interlobular septa, microatelectasis) and considered pathologic only when visible on the whole image, from the pleural line to the end of the screen without fading, and present in large numbers.[18,19] Finally, two normal dynamic LUS findings can be recognized: lung sliding and lung pulse. These findings are generated by the movement of the lung surface (visceral pleura) with respect to the innermost chest wall (parietal pleura), with lung sliding representing air movement during respiration and lung pulse the transmission of cardiac contractions through the lung (Fig. 1; Video, available as Electronic Supplementary Material [ESM]; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

In the posterolateral and supradiaphragmatic regions of normal lung, when a low frequency transducer (typically 5-2 MHz) is placed at the 8th-9th /9th-10th intercostal spaces, mid-axillary line, in a cephalocaudal orientation and directed posteriorly, the following structures and artifacts can be identified: 1) subcutaneous tissues and intercostal muscles (anatomical image) and the pleural line (artifact as explained above); 2) a hyperechoic homogenous curved line between the lung and abdomen, representing the diaphragm (anatomical image); 3) abdominal organs: liver/spleen and potentially kidney (anatomical image); 4) the vertebral column with posterior acoustic shadowing (artifact as explained above). Note that the vertebral column is not visualized above the diaphragm because of

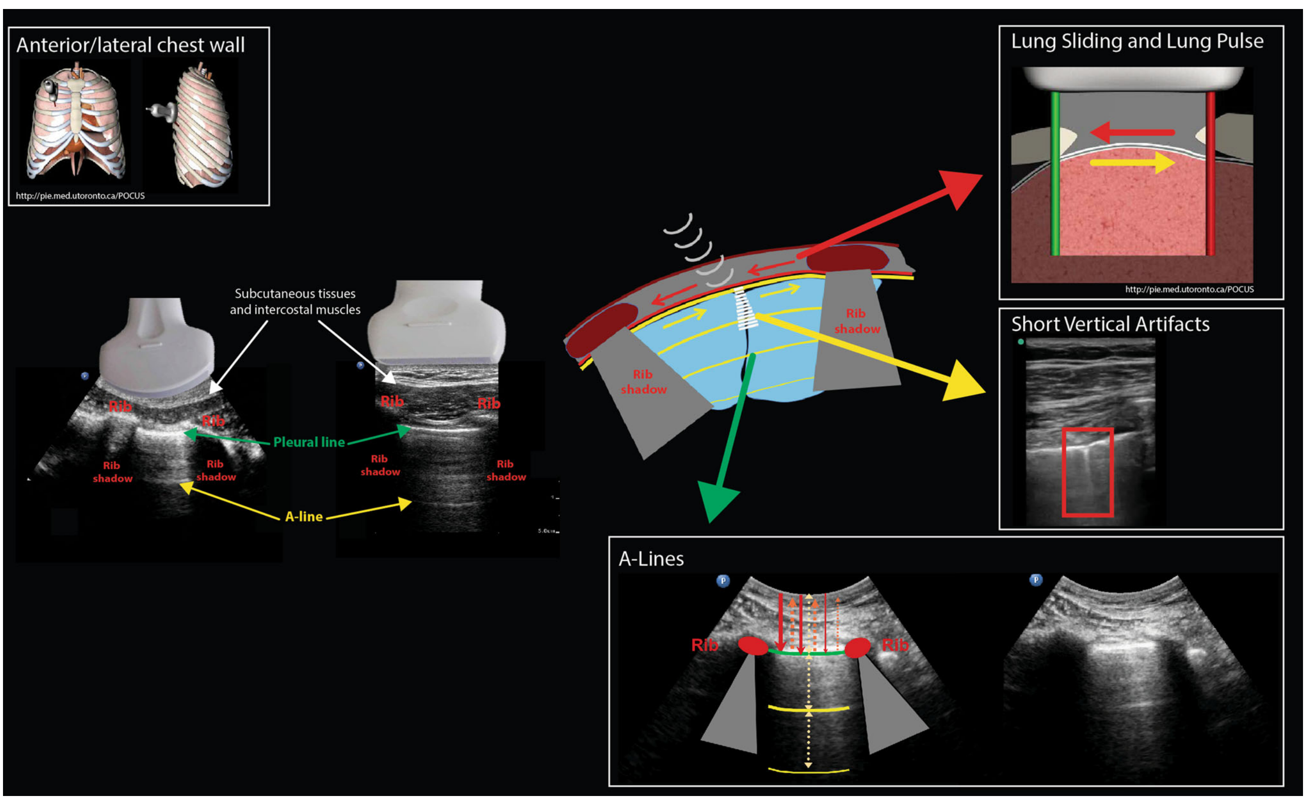


Fig. 1 Normal lung ultrasound findings: anterior and lateral chest. In normal lungs, when a transducer is placed sagittally on the chest wall over any intercostal space projecting over aerated lung (e.g., 2nd to 7th), the following structures and artifacts may be identified: 1) subcutaneous tissues and intercostal muscles; 2) ribs with posterior acoustic shadowing; 3) hyperechoic horizontal pleural line at the interface between pleura and aerated lung tissue; 4) hyperechoic horizontal A line artifacts below the pleural line at multiples of the distance between the probe and the pleural line; 5) short vertical artifacts (formerly called Z lines) originating from and moving with the pleural line; 6) two dynamic LUS findings: lung sliding and lung pulse, generated by the movement of the lung surface (visceral pleura) with respect to the innermost chest wall (parietal pleura). (Please refer to the article text for a detailed explanation of normal anterolateral lung ultrasound findings as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html). *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

the presence of air causing near complete reflection of the ultrasound beam. This is referred to as a negative *spine sign*. In addition, the *curtain sign* should be observed. At full inspiration, the descent of the lung and diaphragm obscures the liver/spleen previously seen to the right of the image and with expiration these organs reappear (Fig. 2; Video, available as ESM; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

Four of the most common and well-studied indications for LUS are the assessments of pneumothorax, pleural effusion, interstitial syndrome, and alveolar syndrome. We present step-wise approaches to these conditions below.

Pneumothorax

How to… (Fig. 3 and Table; Video, available as ESM; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

Step 1

Patient position

Except for rare occasions (e.g., loculated pneumothorax), pleural air collects in the least dependent part of the thorax. Therefore, the supine position is ideal for pneumothorax detection, where the least dependent part of the thorax can be identified around the 2nd to 4th intercostal space between the parasternal and mid-clavicular lines, an area readily accessible for ultrasound imaging. If the semi-sitting position is used (e.g., patients in respiratory distress), the apical regions of the thorax become the least dependent. The presence of the clavicles makes this area less accessible for imaging, thus increasing the possibility of missing a small pneumothorax.[4,13,20-22]

Step 2

Probe selection

Visualization of the pleural line is key. Therefore, although the pleural line is seen with both low- and high-frequency probes, a high-frequency (typically 13-6 MHz) linear probe is preferred because of the higher resolution. Nevertheless, in complex scenarios where several differential diagnoses are considered and a "whole-body" examination is needed, the use of a low-frequency probe (convex or microconvex, with frequency ranging between 5 and 2 MHz) should be

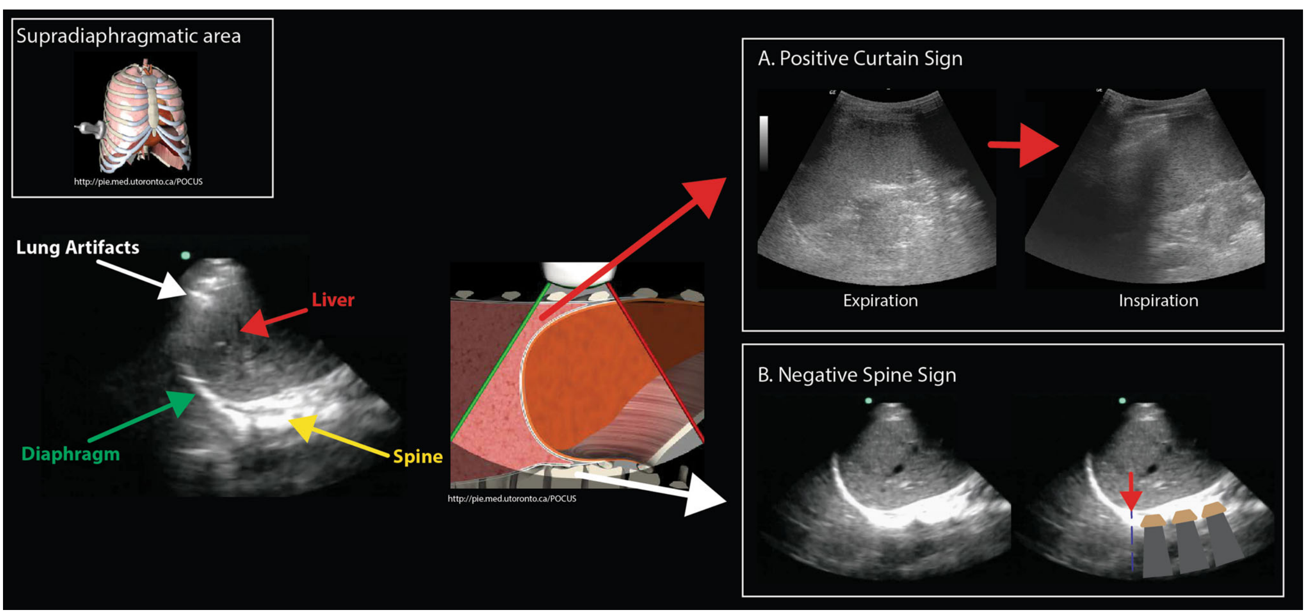


Fig. 2 Normal lung ultrasound findings: supradiaphragmatic area. In the posterolateral and supradiaphragmatic regions of normal lung, when a low-frequency transducer is placed at the 8th-9th /9th-10th intercostal spaces, in a cephalocaudal orientation and directed posteriorly, the following structures and artifacts can be identified: 1) hyperechoic homogenous curved line of the diaphragm between the lung artifacts cephalad and abdomen caudad; 2) abdominal organs: liver/spleen and potentially kidney; 3) vertebral column with posterior acoustic shadowing. 4) The *curtain sign* should be observed (top right panel A): at full inspiration, the descent of the lung and diaphragm obscures the liver/spleen previously seen to the right of the image and with expiration these organs reappear. 5) Also, a "negative" *spine sign* should be observed (bottom right panel B): in a normally aerated lung the vertebral column is not visualized above the diaphragm because of the presence of air causing near complete reflection of the ultrasound beam. (Please refer to the article text for a detailed explanation of normal supradiaphragmatic lung ultrasound findings as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html). *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

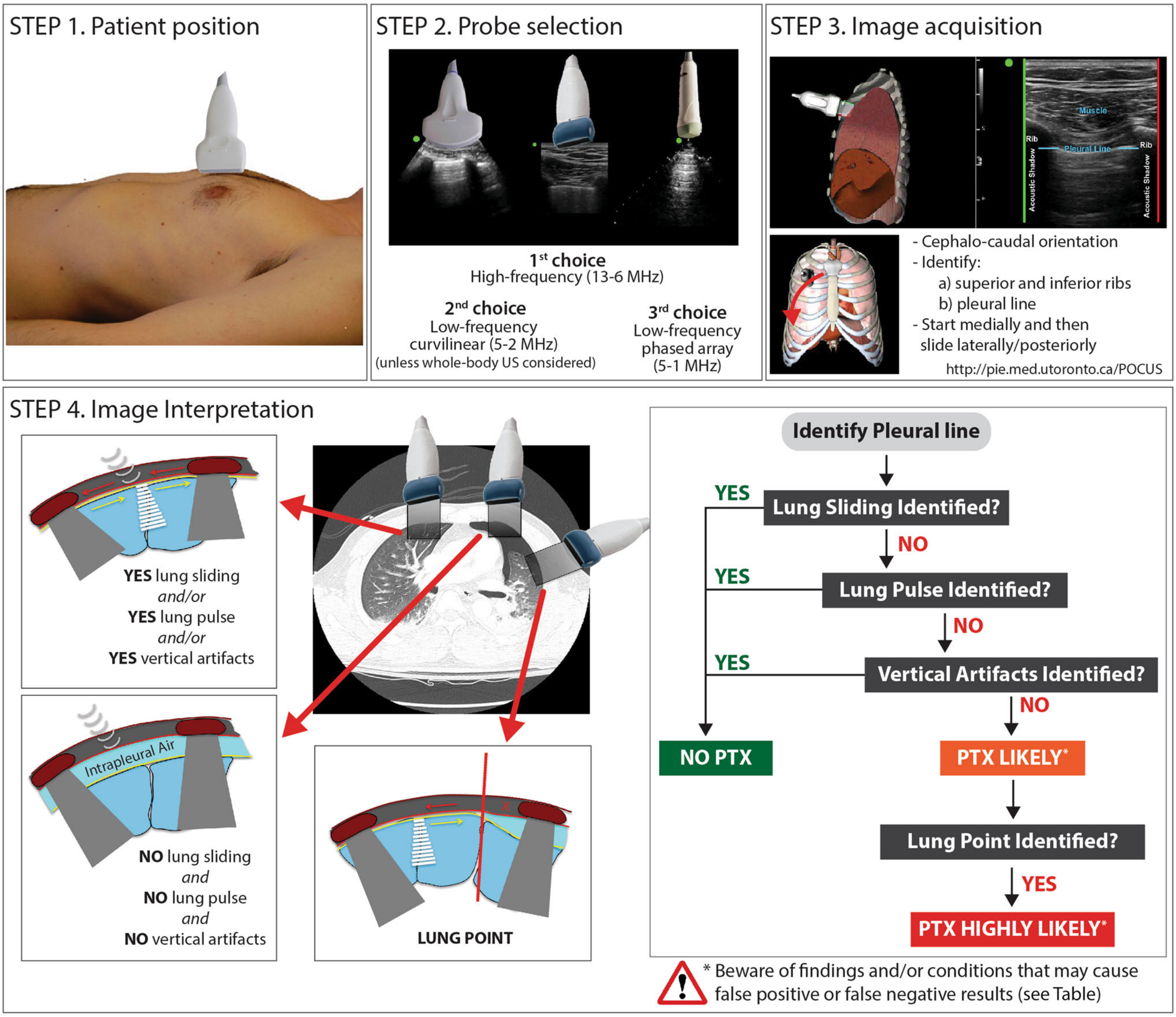


Fig. 3 Step-by-step approach to lung ultrasound for the diagnosis of pneumothorax. Please see the corresponding article text for detailed explanations of each step as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html. *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

considered as the first choice. Depth, focus, and gain should be adjusted to optimize pleural line visualization.

Step 3

Image acquisition

The probe should be placed on the anterior chest wall in a cephalocaudal orientation to allow visualization of at least two ribs with the pleural line between. This minimizes the risk of mistaking the rib border for a non-moving pleural line. The pleural line should be visualized at multiple interspaces (2^{nd} to 4^{th}) and from medial to lateral in the presumed least dependent zone of the thorax. Comparison with findings on the contralateral side may facilitate interpretation.

Step 4

Image interpretation

The three most useful findings when suspecting a pneumothorax are lung sliding, lung pulse, and vertical artifacts. In the case of a pneumothorax, the visceral pleura is separated from the parietal pleura by intra-pleural air; even a tiny amount of intra-pleural air is enough to reflect and attenuate all ultrasound waves at the level of the parietal pleura. Thus, all underlying lung movements (lung sliding and pulse) and vertical artifacts originating at the surface of the visceral pleura are not detectable. In the absence of both pleural movements and vertical artifacts, a pneumothorax is highly likely, though

Table Key findings and pitfalls in the performance and interpretation of lung ultrasound

	Main sonographic findings	Pitfalls	
PNEUMOTHORAX	Absence of lung sliding Absence of lung pulse Absence of vertical artifacts Presence of A lines ± Identification of lung point (only in non-complete PTX)	*False-negative results*	Failure to insonate least dependent zones of thorax Absence of lung point with complete PTX Misinterpretation of "E lines" (vertical artifacts originating in the subcutaneous tissues in the context of subcutaneous emphysema) for vertical artifacts originating from the pleural line Presence of lung sliding, pulse, and/or vertical artifacts in the least dependent zones of thorax in the context of loculated PTX Small left PTX in the paracardiac area (misinterpretation of internal thoracic artery pulsation as a lung pulse) Misinterpretation of internal thoracic artery pulsation as a lung pulse On M-mode, misinterpretation of operator movement as lung sliding or pulse Failure to identify lung pulse in the context of severe bradycardia
		False-positive results	Absence of lung sliding in conditions where visceral pleura does not slide against parietal pleura (e.g., apnea, inflammatory adherences, over-inflation, severe bullous disease, decrease in lung compliance, pleural symphysis, endobronchial intubation) Absence of lung pulse when lung aeration is significantly increased (e.g., bullous disease, over-inflation/-distension) Absence of lung sliding, pulse, and vertical artifacts due to improper position of transducer over rib Misinterpretation of pericardial movement (paracardiac area), diaphragm (supradiaphragmatic area), adhesions, or transition point between normal lung and lung bulla as lung point
PLEURAL EFFUSION	Presence of anechoic (fluid) collection between the parietal and visceral pleura	*False-negative results*	Failure to insonate most dependent zone of thorax due to either inadequate depth or failure to visualize the spine when patients are in supine or semi-sitting position
	Absent (negative) curtain sign Positive spine sign		Failure to examine patients in the semi-sitting position (may miss small effusions)
	Hyperechoic regions of collapsed lung and possibly respiratory movements within these regions (i.e., sinusoid sign)		Failure to identify loculated collections Failure to differentiate complex hyperechoic collections (e.g., organized hematoma in the pleural cavity) from lung consolidation
	Transudates are mostly anechoic and exudates and hemorrhages often contain internal echoes within the anechoic effusion; however, significant overlap is present	*False-positive results*	Failure to differentiate between pleural fluid ABOVE the diaphragm and peritoneal fluid BELOW the diaphragm Absent curtain sign due to other conditions (e.g., hemidiaphragmatic paresis, consolidation without effusion)

Table continued

	Main sonographic findings	Pitfalls	
INTERSTITIAL SYNDROME	Absence of A lines Presence of ≥ 3 B lines/intercostal space B line definition: discrete, laser-like, vertical, hyperechoic artifact that arises from the pleural line, extends to the bottom of the screen without fading, and moves synchronously with lung sliding [3] *B line density*: absolute number of B lines correlates with severity/loss of lung aeration: B1 pattern: moderate loss of aeration, associated with presence of ≥ 3 well-defined spaced B lines/ intercostal space	*False-negative results*	High positive end-expiratory pressure Absence of B lines due to improper position of transducer over rib Absence of B lines due to improper angulation of transducer: transducer must be perpendicular to the pleural line for visualization of artifacts (with any scan either A or B lines should be visualized) Misinterpretation of B lines as non-pathologic short vertical artifacts due to inadequate depth or inadequate far field gain Failure to systematically explore the entire chest and to identify focal areas of interstitial syndrome
	B2 pattern: severe loss of aeration, associated with multiple coalescent B lines/intercostal space[17,44] *Other associated findings:* B line distribution Gravity-dependent *vs* -independent pattern Changes in lung sliding and pulse Pleural line and subpleural abnormalities	*False-positive results*	Misinterpretation of short vertical artifacts as marker of increased lung density Misinterpretation of B lines in dependent areas as sign of lung pathology Elderly patients (higher number of B lines without pathology) Misinterpretation of "E lines" (vertical artifacts originating in the subcutaneous tissues in the context of subcutaneous emphysema) for vertical artifacts originating from the pleural line
ALVEOLAR SYNDROME	Poorly echogenic or tissue-like image (hepatisation), originating from the pleural line Interior border of consolidated lung tissue abutting aerated lung appears shredded and irregular (shred sign) Presence of fluid or air bronchograms	*False-negative results*	Failure to systematically explore the entire chest and to identify focal areas of alveolar syndrome Failure to use alternative diagnostic modalities in patients with a high pre-test probability and negative LUS scan (LUS will not identify consolidations that do not abut the pleural line)
	Other associated findings: Shape Margin Distribution Vascularization pattern on Doppler imaging Only conditions that reach the pleural line can be identified on LUS	*False-positive results*	Misinterpretation of liver mirror artifact as marker of increased lung density

LUS = lung ultrasound; PTX = pneumothorax

not definite. Certain conditions (e.g., severe chronic obstructive pulmonary disease, lung overdistension) can generate similar findings and potentially cause false-positive results. Other conditions generate one of the findings, but not the others. For example, apnea, airway obstruction, and endobronchial intubation all result in absent lung sliding. Nevertheless, since the pleural layers are still in physical contact, lung pulse and vertical artifacts are still present.[23] Unsurprisingly, the absence of lung sliding alone has very poor specificity for pneumothorax, with a positive predictive value of only 22%. Therefore, the three findings (lung pulse, sliding, and vertical artifacts) are more important to "rule out" than "rule in" a pneumothorax.[7] The presence of any one of them can exclude a pneumothorax in a particular area of insonation. On the other hand, a "positive" finding with a high specificity for confirming a pneumothorax is the lung point.[24] A lung point can be visualized in a non-complete pneumothorax when the beam insonates the transition between the intra-pleural air and expanded lung adhering to the parietal pleura without interposed air. The ultrasound image displays the absence of lung sliding, pulse, and vertical artifacts on one side of the image and the presence of any/all of these findings on the other side

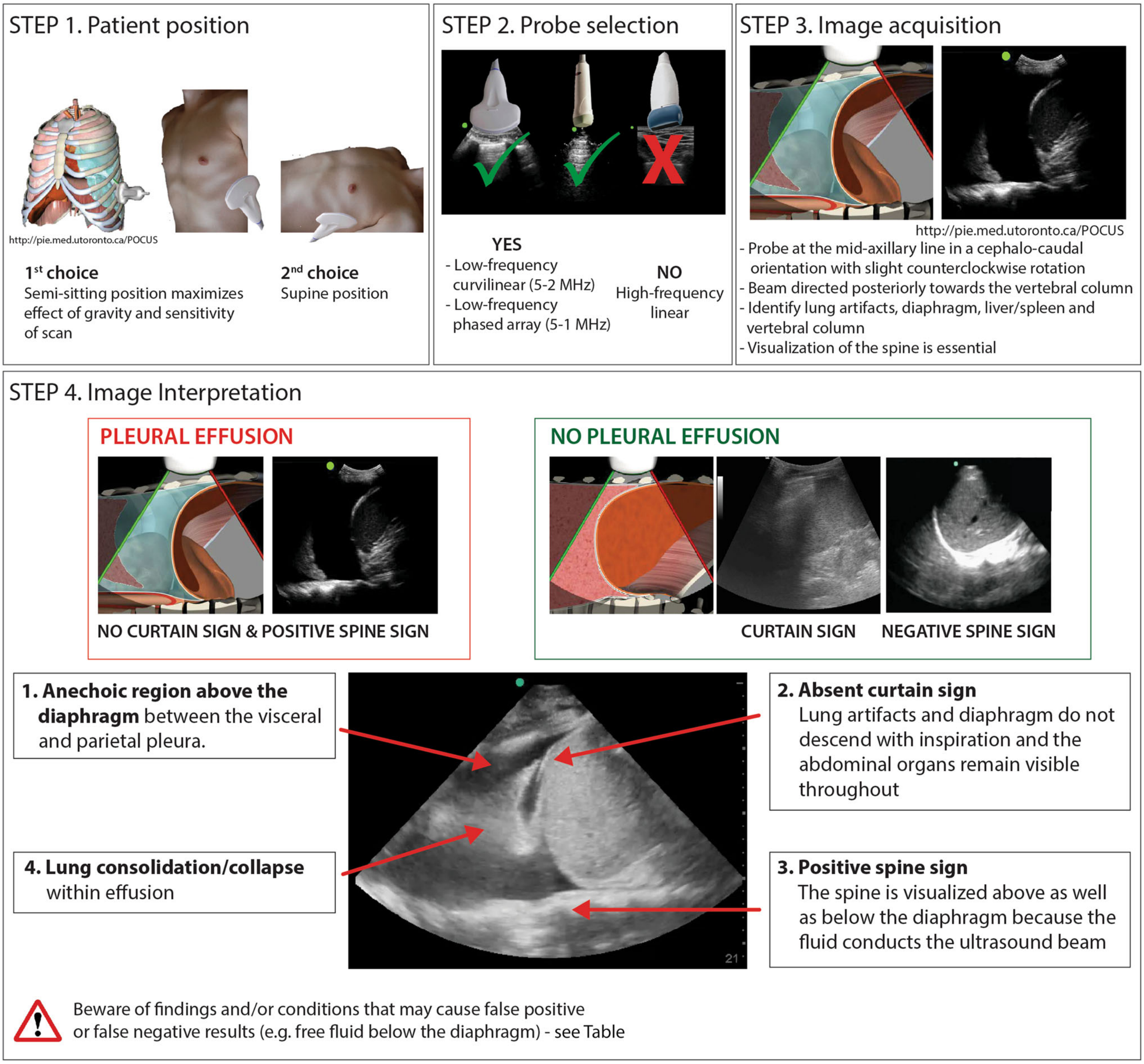


Fig. 4 Step-by-step approach to lung ultrasound for the diagnosis of pleural effusion. Please see the corresponding article text for detailed explanations of each step as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html. *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

(Fig. 3 and Video, available as ESM). In a supine patient with suspected pneumothorax, the lung point is identified by rotating the probe transversely over an intercostal space and sliding laterally and posteriorly. If a lung point is not found, one possibility is circumferential detachment of the lung (i.e., complete pneumothorax), a clinical emergency that should be treated immediately in case of hemodynamic and respiratory compromise. In stable patients, absence of a lung point does not allow a definitive diagnosis and should prompt further investigations (e.g., chest radiography or computed tomography), as the findings may represent a false-positive result (Table).

The evidence

When performed by expert users and the clinical suspicion is high, the diagnostic accuracy of LUS for pneumothorax is superior to chest radiography. In particular, LUS

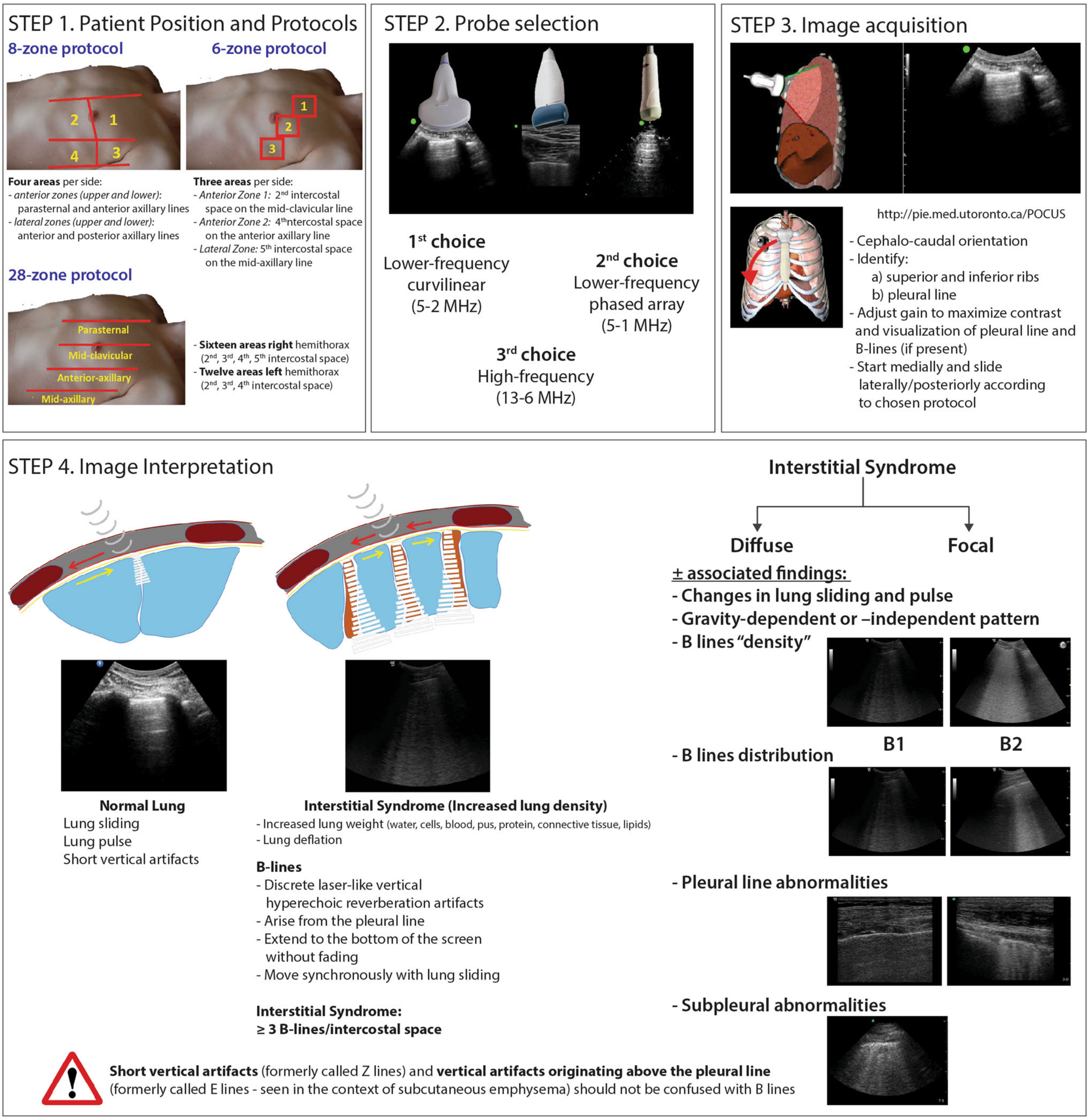


Fig. 5 Step-by-step approach to lung ultrasound for the diagnosis of interstitial syndrome. Please see the corresponding article text for detailed explanations of each step as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html. *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

sensitivity [79%; 95% confidence interval (CI), 68 to 89%] has been shown to be significantly higher than supine chest radiography [40% (95% CI, 29 to 50%)], whereas LUS specificity [98% (95% CI, 97 to 99%)] and radiography specificity [99% (95% CI, 98 to 100%)] are equally excellent.[13] Note that most of these data are from trauma and post-procedural studies and may overestimate the diagnostic performance of LUS in other settings (e.g., inability to lie supine; pre-existent lung conditions such as bullous disease and emphysema).

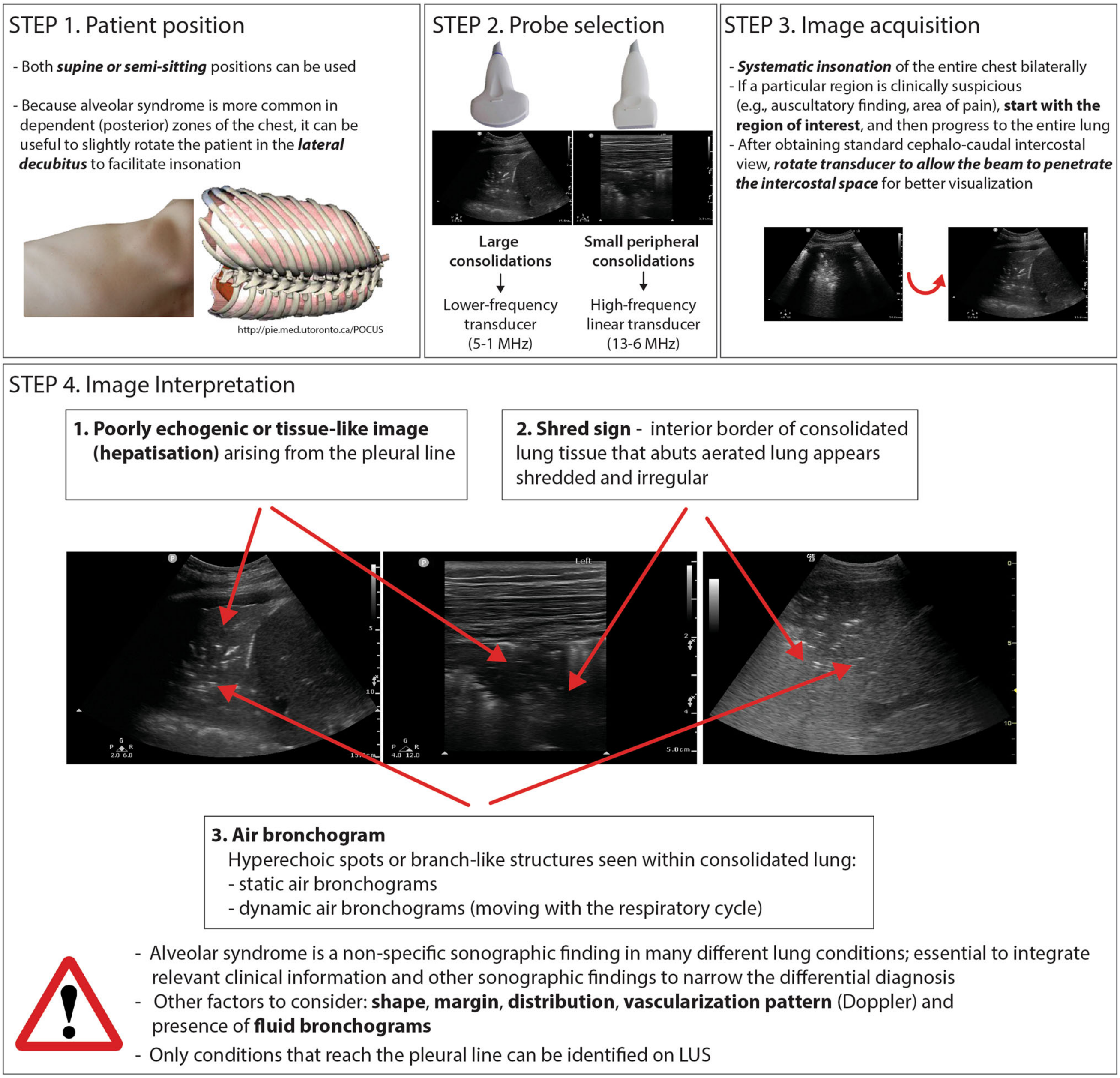


Fig. 6 Step-by-step approach to lung ultrasound for the diagnosis of alveolar syndrome. Please see the corresponding article text for detailed explanations of each step as well as the Video available as Electronic Supplementary Material and Online Tutorial: http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html. *Images adapted with permission from* http://pie.med.utoronto.ca/POCUS

Pleural effusion

How to… (Fig. 4 and Table; Video, available as ESM; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

Step 1

Patient position

Non-loculated pleural fluid distributes to the most gravitationally dependent region of the thorax. When patients are in the supine or semi-sitting position, the most dependent area is the posterior costophrenic angle. For small effusions, the semi-sitting position maximizes the effect of gravity and thereby the sensitivity of the scan. Loculated effusions, by contrast, are usually unaffected by patient positioning.

Step 2

Probe selection

In the supine or semi-sitting position, insonation of the posterior costophrenic angle is achieved from the mid-axillary line. A low-frequency (5-1 MHz) microarray, phased array, or curvilinear probe is required for sufficient depth penetration.

Step 3

Image acquisition

The probe should be placed at the 8^{th}-9^{th} /9^{th}-10^{th} intercostal spaces, mid-axillary line, in a cephalocaudal orientation with slight counterclockwise rotation to allow the beam to penetrate an intercostal space. The probe should be directed posteriorly towards the vertebral column to ensure visualization of the most gravity-dependent portion of the pleural space. The image should display the lung artifact and diaphragm to the left with the liver/spleen, vertebral column, and potentially the kidney to the right. Visualization of the spine and kidney provides confirmation that the beam is interrogating the most dependent region of the thoracic cavity ensuring that small effusions will not be missed.[25] The probe should be held still while the patient inspires to assess for the curtain sign. Should pleural fluid be seen, the probe is angled anteriorly and slid cranially to evaluate its full extent.

Step 4

Image interpretation

Pleural effusions create several distinct findings at the costophrenic angle. First, pleural fluid creates an anechoic region above the diaphragm between the visceral and parietal pleura, the region formerly occupied by the lung. Within the fluid, one may see hyperechoic regions of collapsed lung and possibly respiratory movements within these regions (i.e., *sinusoid sign*).[3] Second, the *curtain sign* is absent: the lung artifacts and diaphragm do not descend with inspiration and the abdominal organs remain visible throughout. Third, a *spine sign* is present. Due to the presence of fluid, the spine is visualized above as well as below the diaphragm because the fluid conducts the ultrasound beam deeper. With regard to distinguishing between types of pleural effusions (i.e., transudates, exudates, hemothoraces, or empyemas), LUS is limited. While transudates are mostly anechoic and exudates and hemorrhages often contain internal echoes within the anechoic effusion, there is significant overlap and thoracentesis is usually required for a definitive diagnosis.[3] Quantitative assessments of effusion size have been described[26]; however, the patient's respiratory status rather than absolute effusion volume is usually the deciding factor regarding clinical management (e.g., drainage). Finally, LUS should always be considered to guide thoracentesis; either static (ultrasound-assisted) or dynamic (ultrasound-guided) techniques may be used.[27,28]

The evidence

A meta-analysis including over 1,500 subjects found LUS to be highly sensitive and specific for the diagnosis of pleural effusion with superior diagnostic accuracy to chest radiography: LUS sensitivity 94% (95% CI, 88 to 97%) and specificity 98% (95% CI, 92 to 100%) compared with chest radiography sensitivity 51% (95% CI, 33 to 68%) and specificity 91% (95% CI, 68 to 98%).[29] The evidence is also supportive of using LUS to guide thoracentesis, suggesting a lower complication rate, especially regarding the occurrence of pneumothorax.[30,31]

B lines and interstitial syndrome

When the lung tissue increases in density, whether because of increased lung weight (e.g., increased extravascular lung water, deposition of collagen and fibrotic tissue, accumulation of blood, lipids, pus, or proteins) or lung de-aeration (i.e., atelectasis), it no longer acts as a strong homogenous acoustic reflector but rather behaves as a heterogeneous surface, characterized by areas where acoustic impedance is similar to soft tissue intercalated with areas where residual air still causes a strong acoustic interface.[19] On LUS this increased tissue-air ratio is associated with the appearance of sonographic artifacts called B lines, defined as "laser-like, vertical, hyperechoic artifacts that arise from the pleural line, extend to the bottom of the screen without fading, and move synchronously with lung sliding".[1,3,7] B lines are extremely dynamic, with their appearance and resolution detectable in real time as lung density changes.[14,32,33] They appear very early in the course of interstitial involvement in lung diseases, even before radiographic changes or evidence of gas exchange deterioration.[1,34,35]

How to… (Fig. 5 and Table; Video, available as ESM; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

Step 1

Patient position and protocol

B lines can be affected by gravity and their distribution with respect to gravity is important in distinguishing their etiology; thus, it is essential to consider and document patient position when performing and interpreting LUS in patients with these findings.[4,5,7] Several scanning protocols have been described, all of which systematically insonate the entire chest bilaterally.[3,4,7,17,36] Eight-zone or abbreviated six-zone protocols limited to the anterior and lateral chest have been shown to be useful in the emergency department population and in critically ill patients with acute severe respiratory failure.[6-8] A 28-zone protocol in the anterior and lateral chest has been used in an ambulatory population of patients with chronic heart failure for monitoring interstitial syndrome.[37] In the examination of patients with pulmonary fibrosis, a scanning protocol that includes the posterior chest is mandatory.[38] Finally, when the assessment of interstitial syndrome is combined with the assessment of alveolar syndrome for monitoring of lung aeration in critically ill patients, a protocol including posterior zones of the chest is recommended[17] (see below).

Step 2
Probe selection
Although high-frequency (13-6 MHz) transducers can be used, low-frequency probes (5-1 MHz) are preferred as the increased depth penetration allows better visualization of the vertical extent of B lines and avoids misclassification of short vertical artifacts.

Step 3
Image acquisition
As described for pneumothorax, the probe should be held over an intercostal space in a cephalocaudal orientation to allow visualization of at least two ribs and the pleural line in between. Gain should be adjusted to maximize contrast and visualization of the pleural line and B lines, if present. The entire chest should be systematically insonated bilaterally using the correct scanning protocol adapted to clinical setting, clinical question, and patient condition and status.

Step 4
Image interpretation
Three or more B lines in an intercostal space represent a positive region of increased lung density (interstitial syndrome).[3] The absolute number of B lines correlates with the severity of the disease and loss of lung aeration.[14,39-43] Moderate loss of aeration is associated with the presence of $\geq$ three well-defined spaced B lines/intercostal space (B1 pattern), while severe loss of lung aeration displays multiple coalescent B lines/intercostal space (B2 pattern).[17,44,45] Although very sensitive for increased lung density, B lines lack specificity and have a broad differential diagnosis.[19] The clinical context and specific sonographic findings (e.g., B line distribution, B line density, gravity-dependent *vs* -independent pattern, associated changes in lung sliding and pulse, associated pleural line and subpleural abnormalities, presence of fluid or air bronchograms) can be sought to narrow the differential diagnosis and increase specificity.[4,6,16,22]

The evidence

Since the first publication correlating B lines and diseases affecting lung interstitium,[1] B lines have been consistently found to be useful and accurate in the diagnosis and monitoring of several lung conditions including inflammatory diseases such as acute respiratory distress syndrome (ARDS),[16] lung contusion,[46] lung infections,[47,48] and connective-tissue disorders/lung fibrosis.[49] Further, several observational studies and a recent meta-analysis suggest higher accuracy of LUS for the diagnosis of heart failure than routine clinical workup, including chest radiography and natriuretic peptides.[6,8,9,50,51] Repeated LUS examinations allow monitoring of changes in lung aeration and/or extravascular lung water as a result of interventions such as dialysis,[14,52] heart failure treatment,[32,53] changes in positive pressure ventilation,[17,44,45] and whole lung lavage.[33] B lines may also have a prognostic role in heart failure and end-stage renal disease.[54-56]

Alveolar syndrome

When the lung density increases extensively and the tissue-air ratio is extremely high (with complete or near-complete disappearance of alveolar air), LUS in the affected area will reveal an anatomical tissue-like pattern that has been termed alveolar syndrome. There are multiple possible etiologies of alveolar syndrome including infective consolidations, atelectasis, pulmonary infarcts, tumours, and contusions.

How to… (Fig. 6; and Table; Video, available as ESM; Online Tutorial at http://pie.med.utoronto.ca/POCUS/POCUS_content/lungUS.html).

Step 1
Patient position
Except for specific conditions (e.g., dynamic changes in consolidation patterns in the context of prone positioning for ARDS),[57,58] patient position is less crucial for the assessment of alveolar syndrome compared with pneumothorax, pleural effusion, and interstitial syndrome. Therefore, either supine or semi-sitting positions can be used. Since lung consolidations are often located in the dependent (posterior) zones of the chest, it can be useful to slightly rotate the patient to the contralateral side to facilitate insonation of dorsal areas.

Step 2
Probe selection
Alveolar syndrome can be seen with both low- and high-frequency probes although one type may be preferable depending on the size of the consolidation. For large

consolidations, low-frequency (5-1 MHz) transducers are recommended, since they facilitate better evaluation of the extension of the condition,[3] whereas for small peripheral consolidations and in children, high-frequency (13-6 MHz) transducers allow better delineation and characterization.

Step 3

Image acquisition

As previously described for interstitial syndrome, assessment for alveolar syndrome should involve systematic insonation of the entire chest bilaterally. Nevertheless, if a particular region is clinically suspicious (e.g., auscultatory finding, area of pain), the sonographic assessment may start with that region and then progress to the entire lung.[3]

Step 4

Image interpretation

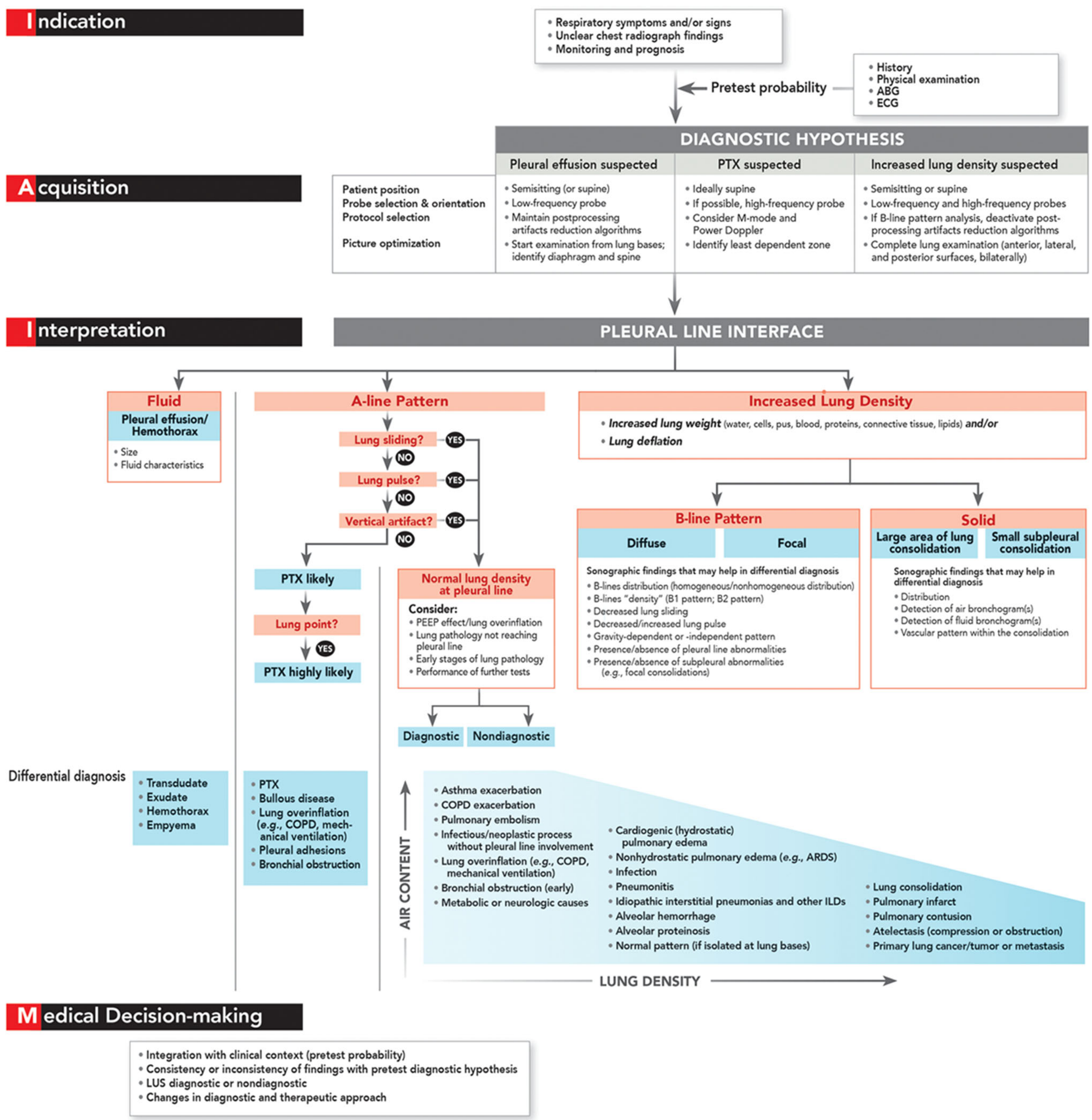
On LUS, an area affected by alveolar syndrome appears as a poorly echogenic or tissue-like image (hepatisation) arising from the pleural line.[3,4] Note that only conditions reaching the pleural line can be identified on LUS. When alveolar syndrome is present but does not abut the pleural line, LUS can be misleading and give the false impression that alveolar syndrome is absent.[4,11] Like interstitial syndrome, alveolar syndrome is a non-specific sonographic finding in many different lung conditions; thus, it is essential to integrate relevant clinical information and other sonographic findings to narrow the differential diagnosis. Shape, margin, distribution, vascularization pattern on Doppler imaging, and presence of air and fluid bronchograms have been shown to assist in identifying the etiology.[11,59-63]

The evidence

Lung ultrasound has been shown to be accurate for the diagnosis of alveolar syndrome when compared with clinical examination and chest radiography. In a study of patients presenting to the emergency department with respiratory symptoms and undergoing computed tomography (CT), LUS detected alveolar syndrome in 81 of the 87 patients with lung consolidation on CT (sensitivity 82.8%; specificity 95.5%). Compared with chest radiography, LUS had greater sensitivity (81.4% *vs* 64.3%) but similar specificity (94.2% *vs* 90%) for lung consolidation.[64] For particular etiologies of alveolar syndrome, the evidence varies. For example, for the diagnosis of pneumonia, systematic reviews and meta-analyses[65,66] found LUS sensitivity and specificity to range between 85-93% and 72-93%, respectively, with excellent pooled diagnostic odds ratios (151.2-173.6) and receiver-operating characteristic curves (0.901-0.978). Nevertheless, one should be cautious in using LUS to rule out pneumonia as one of the largest studies of patients with suspected pneumonia ($n = 362$) found the number of false-negative results to be significant (7.9%).[11] For the diagnosis of pulmonary embolism, another potential etiology of alveolar syndrome, LUS may show peripheral infarcts, but alone does not have adequate accuracy when compared with CT [sensitivity 85% (95% CI, 78 to 90%), specificity 83% (73 to 90%)].[67] Nevertheless, LUS still represents a valid alternative diagnostic tool when CT cannot be performed or is contraindicated.[60] Moreover, an integrated multiorgan approach using focused cardiac, lung, and venous ultrasonography has been shown to achieve significantly higher diagnostic accuracy for pulmonary embolism (sensitivity 90%, specificity 86.2%).[68]

Putting it all together

In our recently published algorithm[4] (Fig. 7), we suggested an approach that highlights four key steps in the performance and interpretation of LUS examinations.[69] The algorithm begins with the **indication** for the scan. Since LUS is a useful tool for both diagnostic[6,7,70-72] and monitoring purposes,[17,56,57] we suggest that it be considered in the diagnostic approach to every patient presenting with unexplained respiratory symptoms or signs or with unclear chest radiography findings.[4,6,72] After formulation of the initial diagnostic hypothesis, optimal image **acquisition** requires choosing the most appropriate patient position, probe, and scanning protocol to maximize diagnostic accuracy for the suspected pathology. It also requires careful attention to the ultrasound settings (especially gain, depth, and focus adjustments), probe location and angulation, and final image quality to avoid the risk of misinterpretation of findings due to inadequate acquisition. We suggest initiating the third step, **interpretation** of LUS findings, with assessment of the pleural line. At this interface, three different patterns can be observed: 1) A line pattern (marker of normally aerated lung or intrapleural air); 2) anechoic pattern (indicating the presence of pleural effusion); 3) B line or consolidation pattern (marker of increased lung density). An A line pattern can be associated with the presence or absence of pleural line movements (lung sliding and/or pulse) and vertical artifacts. Absence of all of these findings is highly suggestive of pneumothorax, while identification of even one of them immediately rules out pneumothorax. An A line pattern associated with pleural line movements indicates normal lung density immediately below the visceral pleura; this is seen in normal lung but also in



pathologies not necessarily visible on LUS (e.g., lung overinflation, pathologies not reaching the pleural line, early stages of lung disease, pulmonary vascular diseases). As previously discussed, identification of an anechoic pattern indicates fluid beneath the pleural line while a B line pattern or lung consolidation is suggestive of increased lung density.[3,16,73-76] The process of acquisition and interpretation should always be repeated in multiple zones of the chest, in a systematic approach that insonates the lungs bilaterally, anteriorly, laterally, and posteriorly, or only in part of these zones, when clinically indicated.[3,4,17] Ultrasound findings can vary at different locations (e.g., pleural effusion at the level of supra-diaphragmatic regions and B lines in the anterior, non-dependent zones) and integration of findings from all zones is essential in the generation of an ultrasonographic differential diagnosis. Further, consideration of other point-of-care applications (e.g., focused cardiac ultrasound, vascular ultrasound, diaphragmatic and abdominal ultrasound) can be made when needed (e.g.,

◀**Fig. 7** Clinical algorithm for the performance and interpretation of lung ultrasound. Please see the corresponding article text for a detailed step-wise explanation of each step of the algorithm. In this algorithm four key steps in the performance and interpretation of LUS examinations are described. 1) INDICATION for the scan. We suggest considering LUS in the diagnostic approach to every patient presenting with unexplained respiratory symptoms or signs or with unclear chest radiography findings. 2) ACQUISITION. After formulation of the initial diagnostic hypothesis, optimal image acquisition requires choosing the most appropriate patient position, probe, scanning protocol, and settings (especially gain, depth, and focus adjustments), probe location, and angulation. 3) INTERPRETATION. We suggest initiating interpretation with assessment of the pleural line. Three different patterns can be observed: A) A line pattern (i.e., normally aerated lung or intrapleural air); B) anechoic pattern (i.e., pleural effusion); C) B line or consolidation pattern (i.e., increased lung density). Ultrasound findings can vary at different locations and integration of findings from all zones is essential in the generation of an ultrasonographic differential diagnosis. 4) MEDICAL DECISION-MAKING. Lung ultrasound is only one piece of the diagnostic puzzle, and the sonographic findings must be integrated with the clinical context and results of other available tests. ABG = arterial blood gas; ARDS = acute respiratory distress syndrome; COPD = chronic obstructive pulmonary disease; ECG = electrocardiogram; ILDs = interstitial lung diseases; PEEP = positive end-expiratory pressure; LUS = lung ultrasound; PTX = pneumothorax. Image reproduced with permission from Wolters Kluwer: *Kruisselbrink R, Chan V, Cibinel GA, Abrahamson S, Goffi A.* I-AIM (indication, acquisition, interpretation, medical decision-making) framework for point-of-care lung ultrasound. Anesthesiology 2017; 127: 568-82.[4] Promotional and commercial use of the material in print, digital, or mobile device format is prohibited without the permission from the publisher Wolters Kluver. Please contact healthpermissions@ wolterskluver.com for further information

examination of the left ventricle in the context of finding homogenous, gravity-dependent, bilateral B line artifacts in the pulmonary parenchyma, likely secondary to cardiac dysfunction; or examination of the veins of lower extremities in the context of dyspnea and normal lung examination/small peripheral consolidations, in a patient with risk factors for pulmonary edema/deep vein thrombosis). Finally, for **medical decision-making**, remember that LUS is only one piece of the diagnostic puzzle, and the sonographic findings must be integrated with the clinical context and results of other available tests.[4]

Three patients

Having reviewed the principles of LUS image acquisition and interpretation, we can now apply LUS to three patients with dyspnea and/or respiratory failure.

Patient 1

You have just performed a left supraclavicular brachial plexus block for a patient scheduled to undergo left wrist arthroscopy. Immediately following block insertion, the patient reports shortness of breath and chest pain. There are distant breath sounds on the left side. On LUS, lung sliding, lung pulse, and vertical artifacts are all absent over the anterior left hemithorax and a lung point is detected more laterally. Together with the clinical history and examination, these sonographic findings are decisive for the diagnosis of a large left pneumothorax and a pigtail catheter should be inserted for drainage.

Patient 2

You have been called to the trauma bay to assist with the management of a 25-yr-old multisystem trauma victim. He was intubated at the scene by paramedics. On physical examination, there is decreased air entry on the right side. A right-sided subclavian line has been inserted. On LUS, lung sliding is not identified but both lung pulse and several vertical artifacts can be seen on the anterior right hemithorax. Left endobronchial intubation is suspected and the endotracheal tube is withdrawn a few centimetres. New LUS post-endotracheal tube withdrawal shows reappearance of lung sliding on the right, confirming the diagnostic hypothesis.

Patient 3

You are working in the intensive care unit. A 39-yr-old patient with out-of-hospital cardiac arrest has developed severe ARDS. A chest radiograph shows diffuse bilateral airspace disease. Lung ultrasound confirms the presence of severe diffuse bilateral interstitial syndrome but also shows bilateral dense consolidations with dynamic air bronchograms. A lung recruitment maneuver is attempted and the positive end-expiratory pressure is increased to 20 cmH_2O. Oxygenation and lung compliance significantly improve and repeated LUS shows near complete resolution of the dependent consolidations.

Conclusion

Since the original publication demonstrating a role for LUS in the evaluation of the pulmonary parenchyma, many studies have shown its utility in multiple respiratory conditions. Because of the unique physical properties of the lungs, only a careful and systematic analysis of both artifacts and anatomical images allows accurate interpretation of sonographic findings. Future studies exploring the use of software for automatic interpretation, quantitative methods for the assessment of interstitial syndrome, and continuous monitoring devices may further simplify and expand the use of this technique at the bedside in acute medicine and the perioperative setting.

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