Basic Ultrasound Physics for Lung Imaging

- Explain the fundamental physics principles relevant to lung ultrasound
- Include why lungs appear different from other organs on ultrasound
- Cover acoustic impedance, reflection, and artifact generation

Understanding Ultrasound Physics

Ultrasound imaging relies on high-frequency sound waves to visualize internal structures. A transducer emits sound waves that travel through tissues, reflect off interfaces, and return to the probe to create an image. For lung ultrasound, understanding these principles is crucial because the lungs, filled with air, behave differently than solid or fluid-filled organs.

- **Sound Wave Propagation**: Sound waves travel poorly through air (as in the lungs) compared to soft tissues or fluids. This results in unique imaging characteristics.
- **Acoustic Impedance**: This is the resistance of a tissue to sound wave passage. Lungs have low acoustic impedance due to air, while soft tissues and bones have higher impedance. The mismatch between air-filled lungs and surrounding tissues causes significant reflection of sound waves, leading to artifacts.
- **Reflection and Artifacts**: When sound waves hit the pleural interface (the boundary between the chest wall and lung), most waves reflect back, creating artifacts like A-lines (horizontal lines indicating normal lung) or B-lines (vertical lines indicating pathology). These artifacts are key to lung ultrasound interpretation.

Lung Ultrasound

Ultrasound has been described for a long time as unsuitable for the exploration of the thorax since the high difference in acoustic impedance between superficial tissues and air in the lung prevents the penetration of the beam beneath the visceral pleura. Unlike organs like the liver or kidneys, which allow sound waves to penetrate and produce detailed images, air-filled lungs scatter sound waves, limiting penetration. This creates a "curtain" effect where the lung surface (pleura) is visible, but deeper structures are obscured by artifacts. These artifacts are diagnostic tools in lung ultrasound, making it distinct from other ultrasound applications.

However, in the last decades, literature demonstrated how LUS is a reliable tool for the assessment of lung diseases. In particular, it carries high sensitivity (88%) and specificity

(100%) for pneumothorax with good correlation with the gold standard technique, i.e. CT scan.

Lung Ultrasound can be performed quickly and easily in critically ill patients. It has a higher diagnostic accuracy than physical examination and chest radiography combined. Moreover, it can be performed at the bedside with any simple ultrasound machine and probe, is repeatable since not irradiating, and is easy to perform.

LUS also allows semi-quantification of pneumothorax and may guide the procedure of thoracic drainage. LUS can also be used during invasive procedures such as pulmonary needle biopsy (transthoracic and transbronchial), recruitment manoeuvres, central venous line placement, or paravertebral nerve block to promptly identify an iatrogenic pneumothorax

Probe Selection and Positioning

- Recommend appropriate ultrasound probes and frequencies
- Describe optimal probe positioning techniques
- Explain standard anatomical landmarks and scanning positions

Probe selection

US machines available in critical care settings are likely to have either a linear (vascular access probe), curvilinear (abdominal probe) or phased array (echo probe), or a combination. A great advantage of LU is that useful images can be obtained with each of these. Each probe has pros and cons.

- Curvilinear probe (3–5 MHz) is the best all-round probe for LU. Lung sliding can be easily visualized. Effusions, consolidated lung, and the diaphragm are also well imaged because of the good penetration and large sector width. The large footprint of the probe means some angulation is needed to avoid the ribs when scanning postero-laterally. (Miller 2016)
- A convex phased-array transducer (3-4.5 MHz) common to many multipurpose point-of-care ultrasound machines. The lower frequency allows visualisation of deep structures, especially in obese patients. Phased-array or micro-convex array transducers with frequencies between 2 and 5 MHz (typically 3.5 MHz) are also suitable for most pleural drainage procedures.
- Linear transducers used for vascular access may be employed. A high frequency linear probe with one focus set on the pleural line allows the best visualization of the pleural surface and of the artefacts generated at the corresponding tissue–air interface.

Patient and probe positioning

Thoracic ultrasound may be performed with the patient in a supine, semi-recumbent, or erect position (and even prone). Given the gravity dependence of fluid in the thorax, the appearance of pleural effusions depends on patient positioning, whereas other pleural line patterns are much less dependent on patient position with the exception of interstitial syndrome (i.e., normal patients can have gravity-dependent fluid that widens the interlobular septa at the lung bases), an effect that may be accentuated in the bases of an erect patient but lessened in a supine patient.

Proper probe placement ensures clear images and accurate findings:

- **Orientation**: Align the probe's marker (a dot or ridge) toward the patient's head (longitudinal plane) or right side (transverse plane).
- **Intercostal Approach**: Place the probe in the intercostal spaces (between ribs) to avoid rib shadows, which block the ultrasound beam.
- **Light Pressure**: Apply gentle pressure to maintain contact without compressing the lung, which could alter findings like pleural sliding.

Standard Anatomical Landmarks:

- **Midclavicular Line**: Scan the anterior chest (zones 1–2) for pneumothorax or B-lines.
- **Midaxillary Line**: Scan lateral chest (zones 3–4) for pleural effusions or consolidations.
- **Posterior Lung Fields**: Scan the back (zones 5–6) for dependent effusions or consolidations, especially in supine patients.

Normal Lung Ultrasound Appearance

  - Describe what normal lung ultrasound looks like
  - Explain key anatomical landmarks (pleural line, rib shadows)
  - Define normal artifacts and their significance

Normal lung ultrasound shows a characteristic pattern due to the air-filled lung and pleural interface:

- **Pleural Line**: A bright, horizontal line just below the chest wall, representing the parietal and visceral pleura. It's typically 0.5 cm below the rib shadows.
- **Rib Shadows**: Dark, curved areas where ribs block the ultrasound beam, appearing as black arcs with posterior shadowing.
- **A-Lines**: Horizontal, evenly spaced lines below the pleural line, caused by sound wave reverberation in air-filled lungs. They indicate normal aeration.

Key Anatomical Landmarks

- **Pleural Line**: The primary reference point, visible in all lung zones.
- **Bat Sign**: The pleural line between two rib shadows resembles a bat's wings, helping novices locate the pleural interface.
- **Diaphragm**: A curved, bright line seen in lower lung zones, moving with respiration.

Normal Artifacts and Their Significance

- **A-Lines**: Indicate normal, air-filled lungs. Their presence rules out significant interstitial pathology in that region.
  - Identified as hyper-echoic lines perpendicular to ultrasound beam; lines appear to lie within lung parenchyma field.
  - Are reverberation artifacts and may appear at multiples of pleural depth.
  - Clinical significance:
    - Cannot distinguish alveolar from pleural air.
    - Demonstration of A-lines presence essential for confirming normal aeration of lung.
    - Some lung pathologies cause disappearance of A-lines (for example, pulmonary edema).
    - Lung sliding plus A-lines confirms alveolar air in the visualized field.

- **Pleural Sliding**: The visceral and parietal pleura slide against each other during breathing, visible as a shimmering or "ants marching" motion at the pleural line.
    - Less visible when ultrasound beams are tangential instead of perpendicular to the pleura.
    - “Lung pulse" is produced when cardiac motion causes pleura to slide with respect to one another.
    - Clinical significance of presence of lung sliding:
        - Indicates changing lung volume.
        - Confirms absence of pneumothorax (pleural surfaces are adjacent).
    - Clinical significance of absence of or diminishing of lung sliding:
        - May indicate hypoventilation such as during low tidal volume ventilation, regional hypoventilation in obstructive lung disease, or contralateral bronchial intubation.
        - May suggest pneumothorax.

Identifying Pleural Sliding

- Explain what pleural sliding is and why it's important
- Describe how to recognize pleural sliding visually
- Include confirmation techniques and troubleshooting tips

Pleural sliding is the dynamic movement of the visceral pleura against the parietal pleura during respiration. It indicates that the lung is in contact with the chest wall, ruling out pneumothorax in that area.

How to Recognize Pleural Sliding

- **Visual Cue**: Look for a shimmering or "ants marching" motion at the pleural line during breathing. This is best seen with a linear probe in the anterior chest (midclavicular line).
- **M-Mode Confirmation**: Use M-mode (motion mode) to capture pleural sliding:
  - **Seashore Sign**: Normal sliding appears as a granular pattern (like waves on a beach) below the pleural line, with straight lines above (chest wall).
  - **Barcode Sign**: Absent sliding (e.g., in pneumothorax) shows only straight lines, resembling a barcode.

Confirmation Techniques and Troubleshooting

- **Ask the Patient to Breathe Deeply (if possible)**: Enhances sliding visibility.
- **Use Power Doppler**: Can highlight pleural motion as color signals (low-flow settings to avoid artifacts).
- **Troubleshooting**: If sliding is absent, check for pneumothorax (see section 6). Ensure the probe is perpendicular to the pleural line, as poor alignment can mimic absent sliding.

Recognizing B-Lines and Their Significance

  - Define B-lines and their ultrasound appearance
  - Explain how to identify and quantify B-lines
  - Describe the clinical significance of B-lines in different conditions

B-lines are vertical hyperechogenic artifacts. A commonly used definition is ´discrete laser-like vertical hyperechoic reverberation artifacts that arise from the pleural line (previously described as ‘‘comet tails’’), extend to the bottom of the screen without fading, and move synchronously with lung sliding´.

A more comprehensive list of B-lines characteristics are:

- Is a vertical artefact;
- Arises from the pleural line;
- Moves in concert with lung sliding;
- Does not fade and extents to bottom of the screen;
- Is well-defined, laser-like;
- Is hyperechoic (like the pleural line);
- Obliterates A-lines;

Identifying and Quantifying B-Lines

- **Appearance**: Bright, laser-like lines that move with respiration, erasing A-lines.
- **Quantification**:
  - Count B-lines per intercostal space.
  - **Normal**: 0–2 B-lines per space.
  - **Pathologic**: ≥3 B-lines per space or confluent B-lines (merging into a white-out pattern).
- **Scanning Technique**: Place probe in the anterior and lateral lung zones. Scan systematically across multiple zones.

Clinical Significance

- **Pulmonary Edema**: Multiple B-lines (≥3 per space) in bilateral lung zones suggest cardiogenic pulmonary edema.

- **ARDS**: Diffuse B-lines with irregular pleural lines indicate acute respiratory distress syndrome.
- **Pneumonia**: B-lines may be focal, associated with consolidations.
- **Fibrosis**: Persistent B-lines with thickened pleural lines suggest chronic interstitial disease.

Differentiation between various pathologies of B-lines is notoriously difficult but can be guided by lung ultrasound findings. A unilateral B-pattern is more suggestive for pneumonia whereas bilateral symmetrical B-pattern is more suggestive for cardiogenic pulmonary edema. An anterior consolidation and/or absence or reduction of lung sliding is more suggestive for pneumonia or acute respiratory distress syndrome (ARDS). Recent studies have suggested the Kigali modification of the Berlin Definition for ARDS using lung ultrasound as replacement for chest radiograph in the diagnosis of ARDS. The presence of a B-pattern and/or consolidations without associated effusion, found in at least one area on each side of the chest were considered bilateral opacities. Furthermore, lung ultrasound can also be used as a bedside tool to differentiate between focal and non-focal ARDS.

Detecting Pneumothorax

- List the ultrasound signs of pneumothorax
- Explain the scanning technique for pneumothorax detection
- Include confirmatory signs and clinical pearls

Lung ultrasound has a higher sensitivity for detecting pneumothorax than chest X-ray, especially for anterior air collections. The specificity is similar to chest X-ray and comparable to chest-CT. A major advantage is that ultrasound can be used to diagnose pneumothorax quickly in critical situations such as cardiac arrest or trauma. Lung ultrasound is therefore part of the standard approach to trauma (extended focused assessment sonography for trauma, eFAST).

Ultrasonographic appearance of pneumothorax

As air moves upward in the chest, the best position to determine whether a pneumothorax is present is anteriorly if the patient is in supine position. The preferred probe to visualize movement of the visceral pleura is the linear high frequency probe (7-11Mhz) as this gives the best resolution for pleural line analysis.

The presence of one of following sonographic findings rules out pneumothorax:

- Lung sliding (absence of lung sliding creates the “barcode sign” in M-mode;
- Lung pulse;
- B-lines (see ‘interstitial syndrome’ for explanation).

If none of these are found, a pneumothorax cannot be ruled out. In this case, one should actively search for the “lung point”. The lung point is the point where the visceral pleura separates from the parietal pleura and is dynamic as it moves with respiration. It is the only sonographic sign that has a nearly 100% specificity for pneumothorax. Therefore, only the lung point and not the absence of lung sliding confirms the diagnosis pneumothorax.

The absence of lung sliding literally means that the visceral pleura is not sliding alongside the parietal pleura. Apart from pneumothorax, this phenomenon can occur in other situations such as selective bronchial intubation, severe pneumonia / ARDS, history of pleurodesis, bullae in COPD or blockage of main bronchial airway by blood / tumor / sputum.

An additional technique to differentiate the various scenarios is to use M-mode. The absence of lung sliding creates a trace which is mostly horizontal - barcode sign. The presence of regular interruptions within the barcode appearance, due to cardiac pulsation - lung pulse - suggests that there is no pneumothorax. This is in contrast with the more speckled appearance of the parenchyma on M-mode - the seashore sign.

In conclusion, whereas ruling out pneumothorax is straightforward, ruling in pneumothorax can be more challenging as lung point is not always found, the differential diagnosis of the absence of lung sliding is broad and the incidence of clinically relevant pneumothorax is low which impedes pattern recognition.

Assessing Pleural Effusion

- Describe the ultrasound appearance of pleural effusion
- Explain optimal scanning techniques and patient positioning
- Include methods for quantifying effusion size

Using ultrasound to assess pleural effusions has been recognized for years. Ultrasound can be used to diagnose, characterize and estimate the size of a pleural effusion and to guide thoracocentesis. The sensitivity of lung ultrasound for detecting small pleural effusions is higher than chest X-ray and lung ultrasound is more specific in differentiating pleural effusion from lung consolidation/collapse than chest X-ray.

Ultrasonographic appearance of pleural effusion

A pleural effusion is normally visualized as an anechoic space between the parietal pleura and visceral pleura. It can be found in the most dependent regions of the lung, i.e. the basal posterior zone, if not loculated.

Using M-mode, the movement of the lung towards the chest wall on inspiration and back on expiration can be visualized as a sinusoidal wave. It indicates free flowing low viscosity fluid in the effusion. It can also differentiate pleural effusion from pleural thickening. Alternatively, color flow Doppler can be used to demonstrate flow in the pleural effusion. In significant pleural effusion, the base of the lung resembles a swimming jellyfish. The free movement of the lung indicates the absence of a lung infiltrate and pleural adhesions, and the likely presence of low viscosity pleural effusion.

The presence of floating debris or small air bubbles indicates that the pleural effusion is more likely to be exudative or hemorrhagic from origin. A pleural effusion creates an excellent acoustic window to visualize the vertebral bodies above the diaphragm, which cannot be seen through aerated lungs.

Simple and complex pleural effusion

Pleural effusions and pleural irregularities are better characterized with ultrasound than with chest-CT. A pleural effusion can be simple or complex based on their appearance on ultrasound imaging. Simple pleural effusions are anechoic and free-flowing. Complex pleural effusions are echogenic and can be homogenous or heterogenic, with or without septations. Transudative effusions are usually simple and rarely become complex when they are chronic. Exudative effusions can be simple or complex. Complex pleural effusions are nearly always exudate or hemothorax. Haemothoraces are initially anechogenic, but when the blood clots the effusion becomes more echogenic due to thrombus formation and septations. Homogenously echogenic pleural effusions are usually either empyema or haemothoraces. Septations can be visualized with ultrasound and are an important factor in treatment decisions.

Quantifying volume of pleural effusion

Historically the assessment of volume of pleural effusions has been semi-quantitative; whether the effusion appears mild, moderate or severe. In most clinical cases this estimation combined with a clinical assessment is sufficient to guide patient management. The volume of pleural effusion can however be calculated by different formulas. Since fluid accumulates in the most dependent part of the thoracic cavity, patient positioning is important when using these formulas. Although sometimes cumbersome in clinical practice, lung ultrasound has shown to reliably quantify the effusion volume when compared to the actual volume of fluid collected with thoracentesis. Numerous formulae exist, but three have most support in the literature and are used commonly in clinical practice, which are described below. There is no consensus on the best formula. The used method is based on ease of calculation and (available) patient positioning.

Balik formula

- Patient supine with 15° trunk elevation
- Probe perpendicular to dorsolateral chest wall
- Maximum distance (C, in millimeters) between visceral and parietal pleura at end-expiration
- Pleural effusion volume (mL) = measured distance x 20

Eibenberger formula

- Patient supine
- Probe perpendicular to chest wall
- Maximum distance (C, in millimeters) between the visceral and parietal pleura at end-inspiration
- Pleural effusion volume (mL) = (47.6 x distance) – 837
- Note: this formula gives false negative values if the distance between the pleural layers is less than 17 millimeters, in that case the Balik formula is preferred

Goecke formula

- Two variants exist, the one shown here appears to have the highest level of accuracy
- Erect position
- Probe dorsolateral chest wall
- Craniocaudal extent of effusion (H, in centimeters) + maximum distance between lung base and mid-diaphragm (D, in centimeters)
- Pleural effusion volume (mL) = (H + D) x 70

Lung Consolidation Patterns

- Define consolidation and its ultrasound characteristics
- Explain different types of consolidation patterns
- Describe associated findings like air bronchograms

Lung ultrasound is a sufficient alternative diagnostic tool to chest-CT for diagnosing consolidation. It is considered to be more accurate than chest X-ray for distinguishing different types of consolidations.

Ultrasonographic appearance of consolidated lung

Consolidated lung is a real image, in contrast to A-lines and B-lines which are artefacts. Due to the increase of fluid and loss of aeration, ultrasound waves are easily transferred into the consolidated lung, generating a real image. There are roughly two specific types of consolidations: nontranslobar and translobar. It has to be kept in mind that consolidations that do not reach the pleural line cannot be visualized using ultrasound. Nontranslobar consolidations are usually found in anterior or lateral zones of the lung and show a so-called shred sign. The shred sign can be recognized by an irregular border between aerated and consolidated lung.

Translobar consolidations usually develop at the basal posterior zone of the lung (so called PLAPS point). These types of consolidations appear as a tissue-like pattern, reminiscent of liver tissue. Because a translobar consolidation can resemble a liver or spleen, it is important to visualize the diaphragm to ensure that the tissue-like pattern is intrathoracic. Sometimes hyperechoic punctiform or linear images can be visualized within the consolidation. These are called air bronchograms depicting the air-filled bronchi within the consolidated lung.

Causes of consolidations

In patients with static air bronchograms, color Doppler imaging can be used to rule out pneumonia as cause of the consolidation. In obstructive consolidations, alveolar filling with air becomes more difficult than in non-obstructive etiologies, thus causing more local hypoxia and more vasoconstriction, leading to less flow. In consolidations where there is an absence of flow, atelectasis becomes more likely to be the cause of the consolidation. For this assessment the color Doppler window is set over the consolidated area. The color window is minimalized to avoid interference from adjacent structures. The area is searched for the presence of any pulsatile tree-like, torturous or homogeneously distributed fragmented vascular structures. If there is no flow observed during multiple respiratory cycles in any part of the consolidated tissue, pneumonia can be ruled out as cause for the consolidation.

Common Artifacts and Troubleshooting

- Identify common artifacts that can confuse beginners
- Provide troubleshooting guidance for technical problems
- Include tips for optimizing image quality

Common Artifacts

- Mirror Image Artifact: Reflections of chest wall structures above the pleural line, mimicking pathology.
- Reverberation Artifacts: Repeated echoes (e.g., A-lines) caused by air or metal objects.
- Z-Lines: Short, vertical lines that fade quickly, unlike B-lines. These are normal and not pathologic.

Troubleshooting Technical Problems

- Poor Image Quality:
  - Adjust gain to brighten or darken the image.
  - Increase depth for obese patients or decrease for superficial structures.
  - Ensure adequate gel to improve probe contact.
- No Pleural Line Visible: Reposition the probe in the intercostal space, avoiding ribs.
- Absent Sliding Misinterpretation: Confirm with M-mode and check multiple zones to rule out pneumothorax.

Tips for Optimizing Image Quality

- Probe Angle: Keep the probe perpendicular to the pleural line.
- Clean Probe: Remove dried gel or debris to avoid artifacts.
- Patient Positioning: Adjust to optimize access to lung zones (e.g., sitting for effusions).

Limitations of Lung US:

- Like other ultrasound techniques, lung ultrasound is operator-dependent and requires training for image acquisition and interpretation.

- Simple findings can be easily acquired with a short training: anesthesia residents were able to rule out pneumothorax after 5 minutes of on-line training, and pleural effusions were easily detected by ICU residents after a few hours of theoretical and hands on work, but for more advanced skills, such as lung ultrasound score computation, a longer training is required.
- Lung ultrasound is an additional workload for the healthcare professional.
- Lung ultrasound depends on transmission of ultrasound beams through the chest wall to the lung surface. This propagation from skin to lung can be prevented by subcutaneous emphysema or large thoracic dressings.
- Once the ultrasound beams are transmitted and the lung is aerated, the examination only allows analysis of the lung surface. This means that only fields immediately beneath the probe are explored, thus underlying the need for as comprehensive and systematic an examination as possible.
- Moreover, caution is recommended in the interpretation of lung ultrasound findings in diseases that may have no or minimal extension to peripheral fields (i.e., deep peri-bronchial mass/abscess, histiocytosis, tuberculosis, aspergillosis, bronchiectasis).
- No specific lung ultrasound sign has been found for detecting lung over-inflation.

Clinical Integration and Decision-Making

- Explain how to integrate lung ultrasound findings with clinical assessment
- Provide guidance on when to use lung ultrasound
- Include safety considerations and limitations

Integrating Lung Ultrasound with Clinical Assessment

Lung ultrasound is a bedside tool to complement, not replace, clinical evaluation. Combine findings with:

- **History**: Symptoms like dyspnea, fever, or chest pain guide interpretation.
- **Physical Exam**: Auscultation, vital signs, and oxygen saturation provide context.
- **Other Tests**: Correlate with chest X-ray, CT, or lab results when available.

When to Use Lung Ultrasound

- **Indications**:
  - Acute dyspnea (e.g., rule out pneumothorax, pulmonary edema).
  - Suspected pneumonia or pleural effusion.
  - Trauma (e.g., FAST exam including lungs).
- **Settings**: Emergency departments, ICUs, or outpatient clinics where rapid diagnosis is needed.

Lung ultrasound scores and protocols

Besides as a diagnostic tool, lung ultrasound can be used as a monitoring tool for extravascular lung water. There are multiple scoring systems to quantify the severity and amount of extravascular lung water. The most used scoring system is the lung ultrasound score or lung aeration score; a scale describing the progressive loss of aeration of lung tissue. For each scanning zone a score is assigned dependent on the worst pattern observed:

- Score 0, A-pattern, A-lines or less than three B-lines.
- Score 1, B1-pattern, moderate loss of aeration (three or more well-spaced B-lines);
- Score 2, B2-pattern, severe loss of aeration (multiple coalescent B-lines);
- Score 3, C-pattern (consolidation), complete loss of aeration (consolidation).

The lung ultrasound score is typically performed with a 12-zone protocol: six per hemithorax (upper and lower part of the anterior, lateral and posterior chest wall). The amount of lung zones to be scanned is dependent on the used protocol. Besides the 12-zone protocol, commonly used protocols are 6-, 8- and 14-zone protocols. The 6-zone protocol, used in the BLUE protocol, is a very useful protocol for rapid diagnosis in patients with acute respiratory distress in the critical care setting. The 8-zone protocol (upper and lower part of the anterior and lateral chest wall) is commonly used in the emergency department. The 14-zone protocol is similar to the 12-zone, however the posterior chest wall is divided into three zones. There is currently no consensus on the most appropriate lung ultrasound to be used in the critical care setting. For quick assessment, the 6- and 8- zone protocols are more suitable since these protocols take only 3 minutes to perform. The 12- and 14- zone protocols usually take up to 10 minutes and might be more suitable for monitoring the lung in critical ill patients.

How can lung ultrasound help me?

While it may seem counterintuitive to use ultrasound in the lungs (as air scatters and reflects US waves), predictable findings and patterns can be used for diagnosis of different lung pathologies, and US can help to make invasive chest procedures safer.

Table 1: Summary of the uses of lung ultrasound in critically ill:

Diagnosis	● Pleural Effusion ● Pneumothorax ● Pulmonary Oedema ● Consolidations
Procedural Guidance	● Thoracocentesis ● Intercostal drain insertion