Lung Ultrasound

Traditionally, air has been considered the enemy of ultrasound and the lung has been considered an organ not amenable to ultrasonographic examination. Visualizing the lung is essential to treating patients who are critically ill. The commonest investigation used to image the lung in the ICU is the bedside chest X-ray. While the bedside roentgenogram is relatively inexpensive and is available even in most secondary hospital ICUs, it has a few limitations. It is difficult to ensure breath holding during the X-ray exposure and this leads to a reduction in the spatial resolution. The cassette is placed posteriorly and the X-ray beam originates anterior, at a shorter distance than recommended and quite often not tangentially to the diaphragmatic cupola, thereby hampering the correct interpretation of the silhouette sign. These problems lead to the incorrect assessment of pleural effusion, consolidation and the alveolar interstitial syndrome.

The chest X-ray is also not always useful for the diagnosis of a pneumothorax in a ventilated patient in the ICU. In such a patient the air in the pleural space tends to accumulate anterior to the lung in the supine position, causing it not to be seen on an AP view X-ray. In addition, mechanically ventilated lungs do not collapse even in the presence of a pneumothorax. For these reasons, X-rays have a sensitivity of only 53% in detecting pneumothoraces in such critically ill patients as compared to the gold standard of a CT scan of the chest.

Add to these, the logistic difficulty of obtaining an urgent chest X-ray quickly, and it becomes clear that a faster, more reliable tool is needed to image the lung in the ICU. While the CT scan of the chest is considered the gold standard for the imaging diagnosis of all the conditions listed so far, it is neither inexpensive nor available within the intensive care unit, necessitating potentially dangerous transport to the radiology department. In addition, it exposes the patient to high doses of ionizing radiation.

Ultrasound compares favourably with CT scan in the diagnostic ability for some disease conditions, most prominently pneumothorax, where it has a sensitivity of 92% compared to CT. In addition it is relatively cheap and is readily available at the bedside making it easier and faster to get an ultrasound imaging than a chest X-ray. For these reasons, ultrasound is fast becoming an essential part of the chest imaging armamentarium in the ICU.

Technique of lung ultrasound

A range of frequencies (4 to 12MHz) can be used to visualize the lungs. High frequencies are useful to look at the periphery of the lung with a high resolution as in looking for 'lung sliding' and other signs of pneumothorax, as well as studying lung comets. Lower frequencies help with the imaging of deep lung tissues as in looking at consolidation and pleural effusion. Hence a vascular probe is used for the assessment of pneumothorax, while the ultrasound probe is used for consolidation and pleural effusion.

In the supine position, the anterior and lateral lung areas can be easily scanned, but the patient may have to be turned to a lateral decubitus position for scanning posteriorly. Six regions, delineated by the anterior and posterior axillary lines should be systematically examined: upper and lower parts of the anterior, lateral and posterior chest wall.

When an ultrasound transducer is laid on a normal chest wall, the following is observed:

Static Image:

The probe is kept in the intercostal space with the marker pointing toward the head end of the patient. The ribs yield artefactual anechoic shadow images (black). In between the two ribs, there is a hyperechogenic line > 0.5cm deeper to the probe. This line is the interface between the soft tissues of the chest wall and the aerated lung the - "pleural" line. The air in normally aerated lungs stops progression of the ultrasound beam and hence the ultrasound "image" of the lung is composed of artifacts. These air artifacts arise from the pleural line. Two types of artifacts can be seen:

A lines: Horizontal, regularly spaced hyperechogenic lines representing reverberations of the pleural line. These are motionless and are artifacts of repetition. In two-thirds of normal lungs, this is the only artifact pattern that can be seen.
B lines: Vertical narrow based lines arising from the pleural line to the edge of the ultrasound screen. The "comet-tail image" (Ultrasound Lung Comets, ULC) is a sonographic image detectable at the bedside with ultrasound probe positioned over the chest. It is defined as a hyperechogenic, coherent bundle with a narrow base spreading from the transducer to the further border of the screen. It extends to the edge of the screen (short comet-tail artifacts may exist in other regions), and arises only from the pleural line. These are also called by the descriptive term "comet tail artifacts". When several B lines are visible, the term used is "lung rockets".

In this context, 2 similar appearing artifacts should not be confused with B lines. Firstly, short, broad, ill defined, vertical comet tail artifacts arising from the pleural line but not reaching the distal edge of the screen are not B lines. These are called Z lines and are found in normal persons as well as in those with pneumothorax (Fig.1). They are less echogenic than the pleural line, usually taper off at after 2-4 cms, do not erase A lines and do not move with lung sliding. Second, comet tail artifacts can be seen superficial to the pleural line in those with parietal emphysema or parietal echogenic multiple foreign bodies (shot gun pellets). These are called E lines.

Mechanism of the artifact:
The comet-tail artifact appears when there is a marked difference in acoustic impedance between an object and its surroundings. The reflection of the beam creates a phenomenon of resonance. The time lag between successive reverberations is interpreted as a distance, resulting in a center that behaves like a persistent source, generating a series of very closely spaced pseudo-interfaces. The beam is "trapped" in a closed system, resulting in endless to-and-fro echoing. The figure below shows the mechanism. The path of the sound beam is shown as a function of time. When the beam meets the sub-pleural end of the thickened septum, it reflects indefinitely at a speed of 1,450 m/s, resulting in an artifact composed of all the micro-reflections. Each reflection of the beam is displayed on the screen behind the previous reflection. A distance of
These interfaces yield, on the screen, a narrow-based laser-like ray extending to the edge of the screen. At the surface of the lung, the prominent element is air. Its acoustic impedance is very different from that of bone, parenchyma, and water. Bony tissues are not expected to be found at the surface of the lung. Normal lung contains predominantly air and little water, the comet-tail artifact described has the following features: it is related to a small water-rich structure, below the resolution of the ultrasound beam (which is about 1 mm), surrounded by air (resulting in a high impedance gradient). It is absent under normal conditions and present in alveolar-interstitial syndromes. This element has to be present at and all over the surface of the lung, and each element is separated from each other by an average distance of 7 mm. It is frequently found in the last intercostal space in normal subjects. Acute pulmonary edema as well as chronic interstitial disease cause "the artifact."

The classification is as follows:

**Above Pleural Line:** air, foreign bodies

**Below Pleural Line:**
- Horizontal - A line
- Vertical - comet tail
- Short, ill defined - normal
- Long well defined - B lines (originate from pleural line and go to the edge of the screen)
- Single
- Multiple - lung rockets

**Dynamic Changes:**
The pleural line "slides" (to and fro movement) with respiration. The movement is distinctive as the surrounding chest wall structures are still or move in an opposite direction to the lung (See first video). This is pleural / lung sliding. The sliding movement seen sonologically is the lung which moves on respiration. Its amplitude is greater at the base than at the apex where it may be imperceptible. The image best seen in an M mode as the superficial parietal layers are motionless and have a horizontal pattern of lines while the area deep to the pleural line appears "granular" as the motion of the pleural line is reflected all over this area. This is also known as the "seashore sign" (Fig.3).
Fig. 3 The granular pattern below the pleural line in the left half of the picture is lung parenchyma, while the horizontal lines above it indicate the chest wall. The right half of the picture depicts artefacts due to movement of the probe - note the discontinuity of lines above the pleural line.

In a sense, sonographic evaluation of the lungs involves analyses of true images as well as the artifacts.

**Pneumothorax**

In the supine patient, a free pneumothorax usually collects in the anterior and non dependent area. The signs are best with a high frequency probe. A probe > 5 MHz is advisable. High frequency linear (such as a vascular) probes will give a clearer picture.

a. **Absence of lung sliding**: This is a sign of pneumothorax. If lung sliding is present, pneumothorax can be ruled out. However, loculated posterior, mediastinal and apical pneumothoracies can be missed. For a complete examination, the probe must be placed along the anterior, lateral and posterior intercostals spaces and observation must include a whole respiratory cycle at each point. In an M mode, this will show absence of the normal granular pattern deep to the pleural line - the whole picture will show a number of horizontal lines (Fig. 4).

b. **Absence of B-lines**: Although this is not specific for pneumothorax, the presence of B-lines rules out a pneumothorax. B-lines with absent lung sliding may be seen in lower lobe consolidations. Absent B-lines with lung sliding present may be seen in emphysema or hyperinflated lung states.

c. **The lung point**: Since the air in the pleural space moves anterior and the lung collapses to a dependent position posteriorly, there is a point, usually in the lateral regions where the lung and air may be visualized in the same view. On moving from anterior to lateral, a pneumothorax pattern gives way to a fleeting appearance of lung pattern in a particular location of the chest wall.
When the above pattern is seen, a pneumothorax is likely. If there is a sudden change during respiration - a “pneumothorax” pattern which changes to a normal pattern during respiration - it signifies that the pleural air has been displaced elsewhere during lung expansion. On an M mode, this will be seen as parallel lines in one part of the screen with a sudden change to a granular pattern - the lung point (see Fig. 2 and 3). The probe must be held motionless in one location to elicit this sign.

Video 2. Lung point with motionless horizontal lines replaced by lung artefacts from the left on inspiration (Bouhemad et al Critical Care 2007, 11:205 (doi:10.1186/cc5668))

Video 3. Lung point with motionless horizontal lines of pneumothorax on left and lung with dense B lines moving in from the right

A suggested systemic sequential evaluation for pneumothorax is as follows:
With this approach, ultrasound can diagnose pneumothorax with a sensitivity of 92%, compared to CT scan. This is vastly superior to the sensitivity of a bedside chest X-ray. In addition, the time taken for a complete ultrasound evaluation of the chest for air takes about 10 minutes, less than that taken to order a chest X-ray. However, examination for a pneumothorax is also technically more challenging and the acquisition of skills for the same is the most difficult part of lung ultrasound training. The low incidence of pneumothorax as compared to consolidation or pleural effusion also contributes to a longer learning curve.

**Pleural Effusion**

Pleural effusions can be rapidly diagnosed and small effusions can be localized for aspiration at the bedside. Effusions are looked for in the dependent lung areas delineated by the chest wall and the diaphragm. The standard ultrasound probe is used. The probe should be placed in the intercostal space with the long axis of the foot of the probe parallel to the adjacent rib.

The effusion appears as a hypoechoic (i.e. dark) and homogenous structure in the dependent areas which is present both in inspiration and expiration.

The diaphragm must be identified and the liver on the right and the spleen on the left should be visualized as these may rarely be confused with pleural fluid. The following must be kept in mind:

- a. The image must be anatomic (not artefactual)
- b. It must be located above the diaphragm (to avoid confusion with intraperitoneal fluid)
- c. Image must be bounded at the superficial surface by a straight line - the parietal pleura visible between the ribs and > 0.5cm deep
- d. Image limited in depth by a regular line - the visceral pleura
- e. Dynamic sign - the parietal pleural line is fixed while the visceral pleural line moved with the respiratory cycles. The interpleural distance decreases with inspiration (sinusoidal waveform on M mode). This inspiratory centrifugal shifting of the visceral pleura with decrease in apparent thickness of the effusion is known as the "sinusoid sign" and is specific for pleural effusion.
- f. Identification of the lung behind the pleura is necessary before introducing a needle - it may be consolidated or aerated. In massive effusions, the lung will seem to swim in the effusion with frank undulations.

It is difficult to measure the volume of pleural fluid accurately with ultrasound. If the depth of fluid is more than 5cms, then it is likely that there is more than 500ml of fluid. This interpleural distance can be measured in end inspiration or end-expiration and is left reliable on the left side.

Fibrin strands swimming in the fluid with undulations, debris or loculations suggest pus or blood. Other than this, the nature of pleural effusions cannot be accurately defined on an ultrasound.

Ultrasound is also useful to mark for and guide thoracocentesis. Pleural adhesions which hamper adequate drainage can be avoided (see video below). An assessment of adequacy of fluid for drainage can be made. It is suggested that an interpleural distance of at least 15mm, with effusion visible at the adjacent superior and inferior intercostal spaces is necessary in order to perform a safe pleural tap. It may be done laterally (in a supine patient) or posteriorly (in the lateral decubitus position). When an optimal location for tapping has been identified on the ultrasound, the position of the transducer on the skin is marked by an indelible marker. The probe is taken away and the drainage is performed at the marked point.


For loculated pleural effusions, it is safe to drain it under direct visualization on the ultrasound. The ultrasound probe with some jelly is passed into a sterile sheath or glove and is used to visualize the needle tip during thoracocentesis and guide its entry into the locule. The details of the procedure are similar to the guided central venous cannulation described in the next tutorial.

Identification of pleural effusion is the easiest of the lung ultrasound skills to learn.

Consolidation

A standard ultrasound probe is used to image consolidations. Water is a good transmitter of ultrasound and a consolidated lung is water rich. Alveolar consolidation usually reaches the lung surface. Collapsed lung segments can resemble consolidation sonologically. It appears as
poorly defined hypoechoic lung tissue structure. In contrast, the tissue structure of normal lung cannot be seen. What is seen is the artifacts that arise at the pleural line.

Within the consolidation, hyperechoic puntiform images can be seen corresponding to air in the bronchi - a so-called ultrasound air bronchogram (figs. 7 and 8). These air bubbles can be seen to move in the bronchi during respiration. The size of a consolidation does not change with respiration, in contrast to a pleural effusion.

It is very easy to mistake the liver or spleen for consolidation and vice versa. Hence, the thorax should be demarcated sonologically from the abdomen by locating the diaphragm - usually at the mid clavicular line (Fig.9).
The following are needed to sonologically diagnose alveolar consolidation:

1. abnormal pattern should be in thorax (should be differentiated from the liver or spleen)
2. should arise from the “pleural line”
3. it should be a real image (not artefactual, like an aerated lung)
4. there should be a tissue like pattern (similar to liver echotexture)
5. anatomic boundaries must be present:
   a. superficial boundary of consolidation should be at the pleural line or, if an effusion is present (and the consolidation is deeper to the effusion), at the deep boundary of a pleural effusion.
   b. deep boundary of the consolidation may be irregular (aerated lung boundary) or regular (if whole lobe is consolidated).
6. absence of sinusoid sign (see above under pleural effusion). In consolidation, caudal inspiratory movement (from left to right of the ultrasound screen) may be present or impaired but there will be no inspiratory centrifugal shift (from the bottom to the top of the screen, an axis called “core-to-surface axis”).

Peripheral lung abscesses with pleural contact or embedded within a consolidation can also be seen with the ultrasound.

Ultrasound diagnosis of consolidation helps in clarifying the cause of respiratory failure, guiding lung aspiration or bronchoscopy, and assessing degree of aeration as a measure of effectiveness of therapy (PEEP effect or antibiotic effect on the consolidation)

Alveolar interstitial syndrome

A standard ultrasound probe in high resolution mode is used for this. It has been shown that multiple B-lines 7mm apart are caused by thickened interlobular septa representing interstitial edema (see first video), whereas B-lines 3mm or less apart are caused by ground glass areas characterizing alveolar edema (see second video). The number and intensity of B-lines increases with the degree of loss of aeration.


It should be remembered that a few B-lines may be seen normally in lower dependent lung regions and this does not represent the alveolar interstitial syndrome.

Correlation with Extravascular Lung Water (EVLW):
The "lung rockets" image consists of multiple "tails" fanning out from the lung surface. It originates from water-thickened interlobular septa. Functionally, they are a sign of dysfunction of the alveolar-capillary membrane. They are probably the ultrasonic equivalent of Radiologic Kerley B lines. A patient with increased extravascular lung water (EVLW) has multiple comet tails fanning out from the lung surface originating from water-thickened interlobular septa. The comet-tail images appear when there is a marked difference in acoustic impedance between an object and its surroundings. The reflection of the beam creates a phenomenon of resonance. The time lag between successive reverberations is interpreted as a distance, resulting in a center that behaves like a persistent source, generating a series of very closely spaced pseudo-interfaces. A normal lung contains much air and little water on the lung surface, so with sonographic imaging, no dense structures are visible in normal subjects. The normal ultrasound lung pattern is characterized by roughly horizontal, parallel lines. whereas pulmonary interstitial edema yields roughly vertical, parallel lines. The comet-tail image is related to a small water-rich structure, below the resolution of the ultrasound beam surrounded by air, and this element has to be present at the surface of the lung. Subpleural interlobular septa thickened by edema perfectly combine all of these properties. The subpleural end of a thickened septum is too thin to be visualized by the ultrasound beam, but it is thick enough to "disturb" the beam and create a difference in acoustic impedance with the surrounding air.

Comet-tail images arising from the pleural line can be localized or disseminated to the whole lung surface. They are considered multiple when at least three artifacts are visible in a frozen image in one longitudinal scan with a distance < 7 mm between two artifacts. A positive study is defined as bilateral multiple comet-tail images, either disseminated (defined as all over the anterolateral lung surface) or lateral (defined as limited to the lateral lung surface). A negative study is defined as: an absence of comet-tail images (replaced by the horizontal line); isolated comet-tail images visible; or when multiple comet-tail images are confined laterally to the last intercostal space above the diaphragm.

The sonographic examination is performed with patients in the supine position. The ultrasound scanning of the anterior and lateral chest is obtained on both the right and left hemithorax, the second to fourth (on the right side down to the fifth) intercostal spaces, and the parasternal to midaxillary line. In each intercostal space, the number of comet-tail images is registered at the parasternal, midclavicular, anterior, and mid axillary lines.

The sum of the comet-tail images is added as an echo comet score of the extravascular fluid of the lung. Zero is defined as a complete absence of comet-tail images on the investigated area. Using the above criteria, in a study published in 2005, the mean content of EVLW in a negative test result was below the normal limit of EVLW (< 500 ml). The sensitivity and specificity of the negative test result for detection of a content of EVLW < 500 ml were 90% and 89% respectively, whereas the sensitivity and specificity of the positive test result for detection of a content of EVLW > 500 ml (which is associated with pulmonary edema), were 90% and 86%, respectively. Finally, a positive test result had a sensitivity and specificity to detect an excess of EVLW below the threshold of alveolar edema of 87% and 89%, respectively.

Putting it all together - the BLUE protocol
A study published in 2008 evaluated the usefulness of lung ultrasonography in patients admitted with respiratory failure to the ICU. It concluded that lung ultrasound could help the clinician make a rapid diagnosis in patients with acute respiratory failure.
The lung ultrasonography compared results on initial presentation with the final diagnosis by the ICU team. Uncertain diagnoses and rare causes (frequency<2%) were excluded.

Three items were assessed:
1.artifacts (horizontal A lines or vertical B lines indicating interstitial syndrome),
2.lung sliding, and
3.alveolar consolidation and/or pleural effusion.
The results showed the following:
1. Predominant A lines plus lung sliding indicated asthma (n=34) or COPD (n=49) with 89% sensitivity and 97% specificity.
2. Multiple anterior diffuse B lines with lung sliding indicated pulmonary edema (n=64) with 97% sensitivity and 95% specificity.
3. A normal anterior profile plus deep venous thrombosis indicated pulmonary embolism (n=21) with 81% sensitivity and 99% specificity.
4. Anterior absent lung sliding plus A lines plus lung point indicated pneumothorax (n=9) with 81% sensitivity and 100% specificity.
5. Anterior alveolar consolidations, anterior diffuse B lines with abolished lung sliding, anterior asymmetric interstitial patterns, posterior consolidations or effusions without anterior diffuse B lines indicated pneumonia (n=83) with 89% sensitivity and 94% specificity.

The use of these profiles would have provided correct diagnoses in 90.5% of cases.

The Algorithm suggested (Bedside Lung Ultrasound in Emergency - BLUE protocol) is as follows:

![Algorithm Diagram]

**Fig.10 Decision tree indicating a way of reaching 90.5% accuracy with lung ultrasound:** Lichenstein et al Chest July 2008 134:117-125

The procedure used a 5 MHz microconvex probe. It took less than 3 minutes for each study and was done within 20 minutes of admission. The authors comment that echocardiography completes the study in critically ill patients. However, echocardiography provides only indirect evidence of what is happening while lung ultrasonography provides a direct approach to respiratory failure.