Bedside ultrasound - Lung ultrasound in the Intensive Care Unit

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Summary

- In an ICU setting, ultrasonographic evaluation has several advantages over the conventional chest x-ray in the imaging of the lung to diagnose pathologies like pneumothorax, consolidation and pleural effusion.
- A-lines are horizontal hyperechoic lines deep to the pleural line that may be seen in normal individuals and in a pneumothorax.
- B-lines or ‘comet-tail artefacts’ are almost always pathological and suggest increased extravascular lung water from fluid overload conditions such as acute pulmonary oedema or from inflammation as in acute respiratory distress syndrome (ARDS) or chronic interstitial disease.
- The presence of lung sliding indicates entry of air and therefore no pneumothorax. The absence of all of the following - lung sliding, lung pulse and B-lines suggests a pneumothorax.
- The effusion appears as a hypoechoic (i.e. dark) and homogenous structure in the dependent areas which is present both in inspiration and expiration.
- Consolidation appears as poorly defined hypoechoic solid lung tissue structure very similar to the appearance of the liver with hyperechoic air bronchograms within.

Introduction:

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 x-ray is relatively inexpensive and is available in most secondary hospital, it has a few limitations in the ICU setting.

1) It is difficult to ensure breath holding during the X-ray exposure and this leads to a reduction in the spatial resolution.

2) The x-rays are usually limited to the A-P view. Here, 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.

3) 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 critically ill patients as compared to the gold standard of a CT scan of the chest.

4) 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.
**Choice of probe**

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 high frequency linear vascular probe is used for the assessment of pneumothorax, while the low frequency echo or abdomen probe is used for consolidation and pleural effusion.

**Locations studied**

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. Seven regions, which are the same as auscultation areas - infraclavicular, mammary, axillary, infra-axillary, supra, inter and infrascapular should be systematically examined.

**Technique**

The transducer is held in each of these areas with the dot marker facing headwards. This way the ultrasound beams seem to be going across many ribs and intercostal spaces. When an ultrasound transducer is laid on a normal chest wall, the following is observed:

**Static Image:**

With the probe in the intercostal space with the marker pointing toward the head end of the patient, the cross sections of the ribs can be seen with an anechoic (black) shadow beyond it (Fig.1). In between the two ribs, there is a hyperechoic (white) 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 causing it to reflect back strongly to the probe. This is why the pleural line in well aerated lungs is bright white.

The pleural line in pneumothorax will also be bright white because there is air deep to the parietal pleura which causes the sound beam to be completely reflected. In pleural effusion and consolidation, there is no air deep to the pleura, resulting in the sound beam passing through the pleural line rather than being reflected. Hence, the pleural line is not very bright in these two conditions.

Since the pleural line completely reflects the ultrasound beam in a normal lung, no sound is actually entering the lung. Therefore, the image visualised deep to the pleural line is composed of artefacts. These air artefacts arise from the pleural line.

**Two types of artefacts can be seen:**

**A lines:** These are horizontal, regularly spaced hyperechoic lines representing reverberations of the pleural line. These are motionless and are artefacts of repetition. These occur because a part of the sound beam reflected by the pleural line, bounces off the layers of the chest wall and heads back towards the pleural line. The pleural line reflects it again to the probe. Since this beam has taken longer to return to the probe, the machine depicts it on the screen as a bright line lying deeper to the pleural line. Some beams bounce back and forth multiple times before returning to the probe, resulting in many parallel A lines deep to the real pleural line. In two-thirds of normal lungs, this is the only artefact pattern that can be seen.

**B lines:** B-lines originate in the subpleural lung parenchyma. These are vertical narrow based lines arising from the pleural line to the edge of the ultrasound screen (Fig.2). A B-line is defined as a hyperechoic, coherent bundle with a narrow base spreading from the transducer to the further border of

Figure 1: Triangles point to the ribs. The first pair of arrows point to the pleural line and the lower arrows point to the A-lines.

It is important to remember that A lines will be seen in a pneumothorax as well. The is because the air deep to the parietal pleura makes the pleural line intensely reflective, and the reflected beam reverberates within the chest wall layers.
the screen. It extends to the edge of the screen (short comet-tail artefacts may exist in other regions), and arises only from the pleural line. These are also called by the descriptive term "comet tail artefacts". When several B lines are visible, the term used is "lung rockets".

![B-lines](image)

**Figure 2: B-lines ("comet-tail" artefacts) arising from the pleural line**

In this context, 2 similar appearing artefacts should not be confused with B lines. Firstly, short, broad, ill-defined, vertical comet tail artefacts 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. 3). 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 artefacts 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.

The classification of artefacts is as follows:

- **Above Pleural Line**: air, foreign bodies
- **Below Pleural Line**:
  - Horizontal - A lines
  - Vertical Short, ill defined - Z lines, normal
  - Long well defined - B lines (originate from pleural line and go to the edge of the screen). These may be single or multiple (lung rockets).

**Mechanism of the B-line artefact:**

B-lines are frequently found in the last intercostal space in normal subjects. **Other than these, B lines are always pathological and suggest increased extravascular lung water from fluid overload conditions such as acute pulmonary edema or from inflammation as in acute respiratory distress syndrome (ARDS) or chronic interstitial disease.**

The comet-tail artefact described has the following features: it is related to a small water-rich structure (an edematous interalveolar or interlobular septum), below the resolution of the ultrasound beam (which is about 1 mm), surrounded by air (resulting in a high impedance gradient). It is present in alveolar-interstitial syndromes. A patient with increased extravascular lung water (EVLW) has multiple comet tails fanning out from the lung surface originating from water-thickened interlobular septa. Functionally, they are a sign of dysfunction of the alveolar-capillary membrane. 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.

These comet-tail artefacts 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. 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 artefact composed of all the micro-reflections. Each reflection of the beam is displayed on the screen behind the previous reflection. A distance of about 1 mm separates each reflection (Fig. 3).
Dynamic Changes:

The pleural line "slides" (to and fro movement) with respiration. This happens because the visceral pleura slides over the parietal pleura as the lung expands with inspiration. The movement is distinctive as the surrounding chest wall structures are still or move in an opposite direction to the lung. This is pleural / lung sliding. Its amplitude is greater at the base than at the apex where it may be imperceptible.

The presence of lung sliding allows us to make two inferences

1) The presence of lung sliding means that the visceral pleura is in contact with the parietal pleura and hence a pneumothorax is ruled out.

2) The lung is sliding because it is expanding, and therefore presence of lung sliding suggests that air entry into that part of the lung is good.

It is possible to place an M-mode cursor in the intercostal space through the pleural line and produce an M-mode image. In this M mode image the superficial parietal layers are motionless and have a horizontal pattern of continuous 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.4).

The absence of lung sliding and the lung pulse sign

If the lung sliding is absent, it could indicate two possibilities, a pneumothorax with separation of the pleural layers or a lack of air entry into that part of the lung (for e.g. a right main bronchial intubation will result in absent lung sliding on the left side).

The only way to distinguish between these two situations is to look for a sign called the "lung pulse"

When there is no air entry to a part of the lung, no lung sliding will be visible there. However brief, small amplitude pulsatile movements of the pleural line will be visible. This is the lung pulse sign. These are transmitted pulsations from the heart. These will not be seen in pneumothorax because the visceral pleura is not in contact with the parietal pleura.

Lung ultrasound in different lung pathologies

Pneumothorax

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

a. Absence of lung sliding with no lung pulse: If lung sliding is present, pneumothorax can be ruled out. Usually examination of the most non-dependant area of the chest is sufficient to rule out a pneumothorax. However, loculated posterior, mediastinal and apical pneumothoraces can be missed.

If lung sliding is absent, lung pulse should be looked for. If it is present, it rules out a pneumothorax and suggests absent air entry. If it is absent, it is a possible pneumothorax.

The M mode of a pneumothorax will show absence of the normal granular pattern deep to the pleural line - the whole picture will show a number of horizontal lines (Fig. 5). This is called the "barcode" or "stratospheric" sign.
Figure 5: M-mode of pneumothorax. Both lines above and below the pleural line are continuous.

b. Absence of B-lines:

B-lines originate in the subpleural lung parenchyma. Hence, the presence of B-lines rules out a pneumothorax.

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 (Fig. 6). 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 (Fig. 7).

The probe must be held motionless in one location to elicit this sign. A suspected tension pneumothorax is one situation where a lung point does not have to be looked for as it is time consuming. Moreover, a lung point is usually not present because the collapsed lung is surrounded by air.

A suggested systemic sequential evaluation for pneumothorax is given below (Fig. 8):
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![Algorithm for the ultrasound diagnosis of pneumothorax](image)

**Figure 8: Algorithm for the ultrasound diagnosis of pneumothorax**

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.

![Left sided pleural effusion with the spleen on the right and consolidated lung on the left separated by the diaphragm (arrow)](image)

**Figure 9: Left sided pleural effusion with the spleen on the right and consolidated lung on the left separated by the diaphragm (arrow)**

The effusion appears as a hypoechoic (i.e. dark) and homogenous structure in the dependent areas which is present both in inspiration and expiration. (Fig. 9)
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)** The Image must be bounded at the superficial surface by a straight line - the parietal pleura visible between the ribs and > 0.5cm deep.
- **d)** The image is limited in depth by a regular line - the visceral pleura.
- **e)** Dynamic sign - the parietal pleural line is fixed while the visceral pleural line moves 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-expiration and is less 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 guided thoracocentesis:**

Ultrasound is also useful to mark for and guide thoracocentesis. An assessment of adequacy of fluid for drainage can be made. It is suggested that an interpleural distance of at least 15mm in end-inspiration, with effusion visible at the adjacent superior and inferior intercostal spaces is necessary in order to perform a safe pleural tap. For loculated pleural effusions, it is safe to drain it under direct visualization on the ultrasound.

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

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**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. Consolidation appears as poorly defined hypoechoic lung tissue structure very similar to the appearance of the liver (the lung appears "hepatized"). In contrast, the tissue structure of normal lung cannot be seen.

![Figure 10: Consolidated lung with air bronchograms (white scattered specks). Note the small septate pleural effusion around the consolidation.](image)

Within the consolidation, hyperechoic punctiform images can be seen corresponding to air in the bronchi - a so called ultrasound air bronchogram (Fig. 10). 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.

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").

In the early stages consolidations start as localized areas of B-lines. As the disease progresses, the B-lines become denser and eventually form consolidations. Resolution occurs in the reverse order, i.e. Consolidation - dense B-lines - sparse B-lines - A-lines. 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)

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 - it took less than 3 minutes for each study and was completed within 20 minutes of admission. The authors worked out a decision tree and the ‘BLUE protocol’ to reach a diagnosis with 90.5% accuracy using ultrasound.

Conclusion:

Ultrasound of the lung in sick patients is technically easy and can be learnt within a short time. It is very rewarding, when done in the ward or ICU as we have found that ultrasound reveals a lot of information which cannot be gleaned from clinical information or X-rays.