Bedside lung ultrasound in critical care practice

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Management of critically ill patients requires imaging techniques, which are essential for optimizing diagnostic and therapeutic procedures. The diagnosis and drainage of localized pneumothorax and empyema, the assessment of lung recruitment following positive end-expiratory pressure and/or recruitment maneuver, the assessment of lung overinflation, and the evaluation of aeration loss and its distribution all require direct visualization of the lungs. To date, chest imaging has relied on bedside chest radiography and lung computed tomography (CT).

General and cardiac ultrasound can be easily performed at the bedside by physicians working in the intensive care unit (ICU) and may provide accurate information with diagnostic and therapeutic relevance. It has become an attractive diagnostic tool in a growing number of situations, including evaluation of cardiovascular status, acute abdominal disease such as peritoneal collections, hepatobiliary tract obstruction, acalculous acute cholecystitis, diagnosis of deep venous thrombosis and ventilator-associated sinusitis [1]. Furthermore, ultrasound is relatively inexpensive and does not utilize ionizing radiation.

Recently, chest ultrasound has become an attractive new tool for assessing lung status in ventilated critically ill patients, as suggested by the increasing number of articles written about it by physicians practicing in chest, intensive care or emergency medicine. As a matter of fact, chest ultrasound can be used easily at the bedside to assess initial lung morphology in severely hypoxemic patients [2] and can be easily repeated, allowing the effects of therapy to be monitored.

Conventional lung imaging in critically ill patients

Bedside chest radiography

In the ICU, bedside chest radiography is routinely performed on a daily basis and is considered as a reference for assessing lung status in critically ill patients with acute lung injury. Limited diagnostic performance and efficacy of bedside portable chest radiography have been reported in several previous studies [3-5]. Several reasons account for the limited reliability of bedside chest radiography. First, during the acquisition procedure, the patient and the thorax often move, decreasing the spatial resolution of the radiological image. Second, the film cassette is placed posterior to the thorax. Third, the X-ray beam originates anterior, at a shorter distance than recommended and quite often not tangentially to the diaphragmatic cupula, thereby hampering the correct interpretation of the silhouette sign. These technical difficulties lead to incorrect assessment of pleural effusion, lung consolidation and alveolar-interstitial syndrome.

Lung computed tomography

Lung CT is now considered as the gold standard not only for the diagnosis of pneumothorax, pleural effusion, lung consolidation, atelectasis and alveolar-interstitial syndrome but also for guiding therapeutic procedures in critically ill patients, such as trans-thoracic drainage of localized pneumothorax, empyema or lung abscess. Lung image formation during CT relies on a physical principle similar to that used for image formation during chest radiography: the X-rays hitting the film or the CT detector depend on tissue absorption, which is linearly correlated to physical tissue density. In the first generation of CT scanners, the tube emitting X-rays and the X-ray detector were positioned on the opposite sides of a ring that rotated around the patient. Typically, a 1 cm-thick CT section was taken during each rotation, lasting 1 second, and the table supporting the patient had to be moved to acquire the next slice, the ring remaining in a fixed position. These conventional scanners were slow and had a poor ability to reconstruct images in different planes.

In the nineties, spiral CT scanners equipped with a slip ring were introduced, giving the possibility of scanning a volume of tissue rather than an individual slice. Acquisition time was markedly reduced and high quality reconstruction in coronal, sagittal and oblique planes became possible using a work station. Current multi-slice CT scanners, the third generation of CT scanners, are equipped with multiple X-ray detectors and the tube rotates in less than one second around the thorax while the table supporting the patient moves continuously. The multiple detectors and the decrease in rotation time allow faster coverage of a given volume of lung tissue, contributing to increased spatial resolution (voxel smaller than 1 mm³). Using specifically designed computer software offering sophisticated reconstruction and postprocessing capabilities, several hundred consecutive axial sections of the whole lung can be reconstructed from the volumetric data and visualized on the screen of a personal computer. If the computer is connected to an appropriate workstation, it is then possible to ‘move into the lung’ and to measure CT attenuations in any part of the pulmonary parenchyma, providing direct access to regional lung aeration. In addition, images can be reconstructed in coronal, sagittal and oblique planes, offering the possibility of a threedimensional view of the organ. For hospitals having a computer server to store and retrieve pictures from, films are no longer necessary and physicians can derive much more accurate information on patients’ lung status.

With the old generation of conventional CT scanners, obtaining contiguous 1.5 mm-thick CT sections from the apex to the diaphragm would have exposed patients to unsafe radiation levels. With the new generation of multi-slice CT scanners, the ionizing radiation is slightly greater than from a single slice spiral scanner. However, because more slices and images can be...
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Technical equipment

Ultrasound machines should be lightweight, compact, easy to transport and robust, allowing multiple bedside examinations. They should be equipped with a high-performance screen and a paper recorder allowing transmission of medical information and subsequent comparisons. Generally, basic models presented by manufacturers combine all these features, and have the additional advantage of being reasonably priced. Such ultrasound machines are available in many emergency wards, ICUs, units of medical transportation and even in space [8-11].

Another technical characteristic should be required for the use of lung ultrasound in the ICU: the probes and the ultrasound machine should comply with repeated decontamination procedures since they serve multiple patients, and can be the vector for resistant pathogens that could be disseminated in the ICU [12-24]. The efficiency of the decontamination procedure is facilitated by a compact ultrasound machine equipped with a waterproof keyboard. This latter characteristic is present on a few ultrasound machines only, restricting choice.

Ultrasound machines are classified as non-critical items that contact only intact skin and require low level disinfection with chlorine-based products, phenolic, quaternary ammonium compounds or 70% to 90% alcohol disinfectant [25]. In critically ill patients, the skin and the digestive tract are considered as reservoirs from which nosocomial infections can issue. By transmitting nosocomial cutaneous flora from patient to patient, the probe may contribute to the dissemination of multi-resistant strains in the ICU and increase the incidence of nosocomial infections. If lung ultrasound is to be used routinely, our recommendation is to set up a rigid cleaning procedure in the ICU. The probes and the ultrasound machine should comply with repeated decontamination procedures since they serve multiple patients, and can be the vector for resistant pathogens that could be disseminated in the ICU [12-24]. The efficiency of the decontamination procedure is facilitated by a compact ultrasound machine equipped with a waterproof keyboard. This latter characteristic is present on a few ultrasound machines only, restricting choice.

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Cleaning and disinfecting procedure of ultrasound machine and probe in the Surgical ICU of La Pitié-Salpêtrière hospital.

**Table I**

**Cleaning and disinfecting procedure of ultrasound machine and probe in the Surgical ICU of La Pitié-Salpêtrière hospital.**

<table>
<thead>
<tr>
<th>Reduction of environmental contamination</th>
<th>Disinfection procedure at the end of the examination</th>
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<tbody>
<tr>
<td>- Avoid as much as possible contact between ultrasound machine and patient’s environment</td>
<td>- Cleaning of examiner’s hands</td>
</tr>
<tr>
<td>- Use single-patient package of coupling gel</td>
<td>- Cleaning of the ultrasound machine, including the probe holder</td>
</tr>
<tr>
<td>- Limit the probe contact to patient’s skin</td>
<td>- Cleaning of the keyboard</td>
</tr>
<tr>
<td>- During examination, restrict contacts with the ultrasound machine to the probe and the keyboard</td>
<td>- Removing of gel with paper towel</td>
</tr>
<tr>
<td>- At the end of the examination, leave the probe on the bed</td>
<td>- Cleaning of the probe</td>
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</tbody>
</table>

**a.** Avoid using a gel bottle because the tip may be contaminated by contact with the probe or the patient’s skin. Such contact may result in the contamination of the gel contained in the bottle.

**b.** The contaminated probe should not be placed in the probe holder before decontamination.

**c.** We use a detergent-disinfectant based on a quaternary ammonium compound with a processing time of at least 60 seconds. It cleans by removing organic material and suspending grease or oil and disinfects. After 11 years of experience, we have not found evidence of this causing material damage, including significant alterations of acoustic properties of the probe.

**d.** Remaining ultrasound gel on the lung ultrasound probe has shown bacterial growth when left overnight [20].

Lung ultrasound examination

The patient can be satisfactorily examined in the supine position. The lateral decubitus position offers, however, a better view on dorsal regions of lower lobes. A complete evaluation of both lungs requires a systematic protocol of examination. First, the operator should locate the diaphragm and the lungs. Lung consolidation or pleural effusion are found predominantly in dependant and dorsal lung regions and can be easily distinguished from liver or spleen once the diaphragm has been located. Using anterior and posterior-axillary lines as anatomical landmarks, each chest wall can be divided into six lung regions that should be systematically analyzed: upper and lower parts of the anterior, lateral and posterior chest wall. In a given region of interest, all adjacent intercostal spaces offer acoustic windows that allow the assessment of the lung surface by moving the probe transversally. Dorsal lung segments of upper lobes, located behind the scapula, are the only regions that cannot be explored by lung ultrasound. To provide an exhaustive assessment of lung aeration and pleural effusion, the ultrasound examination should cover both lungs, just as for auscultation. To be comprehensive, a chest ultrasound examination should take around 15 minutes, although with enough knowledge and skills, users can perform lung examination more quickly.

Normal ultrasound pattern and basic abnormalities

Normally, ultrasounds are not transmitted through anatomical structures filled with gas and the lung parenchyma is not visible beyond the pleura. The injured lung is characterized
by a marked increase in tissue extending to lung periphery that produces ultrasound artifacts resulting from the abnormal gas/tissue interface. A number of recently published studies have demonstrated the ability of bedside lung ultrasound to accurately assess lung aeration in patients with acute lung injury.

When the loss of aeration is massive and results in lung consolidation, or when a pleural effusion is present, ultrasounds are transmitted to deep intra-thoracic structures. As a consequence, intramediastinal organs like the aortic arch can be visualized in the presence of consolidation of upper lobes [26]. Several studies have clearly established the value of lung ultrasound for detecting and quantifying pleural effusion and lung consolidation. For physicians beginning their lung ultrasound training on critically ill patients on mechanical ventilation, the detection of pleural effusion and lung consolidation in dependant lung regions is the easiest part and the basic skill is generally acquired over a very short period of time [27].

**Normal pattern**

For each considered intercostal space, the probe should be positioned perpendicular to the ribs. Using a longitudinal view, the ribs, characterized by a posterior shadowing, should be identified. A hyperechoic and sliding line, moving forward and back with ventilation, is seen 0.5 cm below the rib line, and is called the ‘pleural line’. In time-motion mode, a ‘seashore sign’ is present, characterized by motionless parietal tissue over the pleural line and a homogeneous granular pattern below it [28]. The pleural line results from the movement of the visceral pleura against the parietal pleura during the respiratory cycle. Beyond this pleural line, motionless and regularly spaced horizontal lines are seen: they are meaningless and correspond to ‘artifacts of repetition’. Thus, a normal ultrasound pattern is defined by ‘lung sliding’ associated with artifactual horizontal A-lines (Fig. 1). In onethird of patients with normal lungs, however, isolated factual horizontal A-lines (Fig. 1, Fig. 2a) are generated by the interface gas/tissue. By analogy with percutaneous drainage of abdominal

**Alveolar-interstitial syndrome**

In the presence of injured lung characterized by an increased amount of lung tissue extending to lung periphery [29], vertical artifacts arising from the pleura and extending to the edge of the screen [30] are detected and called vertical ‘B-lines’ or ‘comet tails’. They appear as shining vertical lines arising from the pleural line and reach the edge of the screen. The number of these vertical B-lines depends on the degree of lung aeration loss, and their intensity increases with inspiratory movements [2, 31]. As mentioned above, less than one or two vertical artifacts can be detected in dependant lung regions in normally aerated lungs [31].

It has been demonstrated that multiple B-lines 7 mm apart are caused by thickened interlobular septa characterizing interstitial edema (Fig. 2a). In contrast, B-lines 3 mm or less apart are caused by ground-glass areas characterizing alveolar edema (Fig. 2b).

**Lung consolidation**

Massive lung edema, lobar bronchopneumonia, pulmonary contusion and lobar atelectasis all induce a massive loss of lung aeration that enables ultrasounds to be transmitted towards the depth of the thorax. Lung consolidation appears as a hypoechoic tissue structure that is poorly defined and wedge-shaped [32]. Within the consolidation, hyperechoic punctiform images can be seen, corresponding to air bronchograms (air-filled bronchi) [33]. Penetration of gas into the bronchial tree of the consolidation during inspiration produces an inspiratory reinforcement of these hyperechoic punctiform images. The ultrasound size of the consolidation is not influenced by respiratory movements (Fig. 3a, 3b). Several studies have demonstrated that lung ultrasound has a high performance in diagnosing alveolar consolidation and is helpful for guiding percutaneous lung biopsy [2, 34-37].

Peripheral lung abscesses with pleural contact or included inside a lung consolidation are also detectable by lung ultrasound [32, 35, 38, 39]. They appear as rounded hypoechoic lesions with outer margins (Fig. 4). If a cavity is present, additional non-dependant hyperechoic signals are generated by the interface gas/tissue. By analogy with percutaneous drainage of abdominal

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**Fig. 1.** Ultrasound pattern of normal lung. The pleural line (white arrow) is a roughly horizontal hyperechoic line 0.5 cm below the upper and lower ribs identified by acoustic shadow (R). A single vertical artifact arising from the pleural line and spreading up to the edge of the screen (comet-tails, indicated by asterisk) can be seen in dependant regions in normally aerated lungs.

**Fig. 2.** Ultrasound aspects of alveolar-interstitial syndrome. (a) B-lines 7 mm apart or spaced comet-tail artifacts. The pleural line (white arrow) and the ribs (R) with their acoustic shadow. Spaced comet-tail artifacts (indicated by asterisks) or B-lines arising from the pleural line and spreading up to the edge of the screen are present. These artifacts correspond to thickened interlobular septa on chest CT scan. (b) B-lines 3 mm or less apart. The pleural line (white arrow) and the rib (R) with their acoustic shadow. Contiguous comet-tails arising from the pleural line and spreading up to the edge of screen are present. These artefacts correspond to ground-glass areas on chest CT scan.

**Fig. 3.** Ultrasound signs in lung consolidation. Massive lung edema, lobar bronchopneumonia, pulmonary contusion and lobar atelectasis all induce a massive loss of lung aeration that enables ultrasounds to be transmitted towards the depth of the thorax. Lung consolidation appears as a hypoechoic tissue structure that is poorly defined and wedge-shaped [32]. Within the consolidation, hyperechoic punctiform images can be seen, corresponding to air bronchograms (air-filled bronchi) [33]. Penetration of gas into the bronchial tree of the consolidation during inspiration produces an inspiratory reinforcement of these hyperechoic punctiform images. The ultrasound size of the consolidation is not influenced by respiratory movements (Fig. 3a, 3b). Several studies have demonstrated that lung ultrasound has a high performance in diagnosing alveolar consolidation and is helpful for guiding percutaneous lung biopsy [2, 34-37].

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collections, ultrasound-guided percutaneous drainage of lung abscesses has proved to be a safe and effective alternative to CT-guided drainage [32, 35, 38, 39].

A tight correlation was found between pulmonary re-aeration measured by lung CT and the change in the ‘ultrasound score’. Further studies are required to confirm whether lung ultrasound, using similar principles, provides the possibility of measuring alveolar recruitment resulting from positive end expiratory pressure (PEEP) or recruitment maneuver.

**Pleural effusion**

Pleural effusion should be sought on a longitudinal view, in dependent lung regions delineated by the chest wall and the diaphragm. It appears as a hypoechoic and homogeneous structure with no gas inside and is present during expiration and inspiration [41]. In other words, it appears as a dependent dark zone free of echo (Fig. 3a, 3b). Since pleural effusion acts as an acoustic window, lung can be seen as a bright pleural line if it remains aerated. If the pleural effusion is abundant enough to be compressive, the lung is seen consolidated and floating in the pleural effusion (Fig. 5). Assessment of pleural effusion requires attention to spleen or liver and diaphragm, especially when pleural puncture is considered. Pleural effusion can be easily distinguished from spleen or liver by using color Doppler that shows intrasplenic and intrahepatic blood vessels; or by visualization of a sinusoidal inspiratory movement of the visceral pleura from depth to periphery [42]. The skills required to detect pleural effusion are easy to acquire, as suggested by several publications [43-45].

The lung ultrasound approach has been proposed for quantifying pleural effusion volume [45-48]. In the supine position, an interpleural distance at the lung base, defined as the distance between the lung and the posterior chest wall, ≥ 50 mm is highly predictive of a pleural effusion ≥ 500 ml [45, 48]. Measurement of the interpleural distance can be performed at either end-expiration or end-inspiration [46], with no difference between them, and seems less reliable when measured on the left side [46]. All studies agree that ultrasound measurement of the interpleural space at the lung base is not accurate enough to quantify small (≤ 500 ml) and very large (≥ 1,000 ml) pleural effusions [45-47]. Recently, another ultrasound approach has been proposed for quantifying pleural effusion: by multiplying the height of the pleural effusion by
its transversal area, measured half-way between upper and lower limits. An excellent correlation was found between the volume of pleural effusion assessed by CT of the whole lung and the ultrasound determination [49].

Although the nature of pleural effusion (transudate or exsudate) cannot be accurately assessed on ultrasound examination only, some ultrasound patterns are evocative. Transudates are always anechoic but exsudates appear often to be echoic and loculated [50].

Last but not least, lung ultrasound is increasingly used for guiding thoracocentesis at the bedside [42, 51]. It provides the possibility of detecting pleural adherences that may hamper efficient thoracic drainage and transform thoracocentesis into a risky procedure (Fig. 6). It enables the safe thoracic drainage of small and/or loculated pleural effusions. It may reduce the risk of intrafissural or intraparenchymal placement of thoracic tubes [52].

Fig. 6. - Consolidated lung and adjacent pleural effusion with pleural adherences. The pleural effusion (Pe) is abundant and the lung is seen consolidated and floating (C) in the pleural effusion with pleural adherences (A).

**Pneumothorax**

Pneumothorax is defined by the interposition of gas between visceral and parietal pleural layers. As a consequence, lung sliding is abolished, ultrasounds cannot be transmitted through the injured lung parenchyma and comet tails (vertical B-lines) are no longer visible. Only longitudinal reverberations of motionless pleural line (horizontal A-lines) can be seen [53]. In some circumstances, such as the presence of a thoracic tube, pleural adherences, bullous emphysema and advanced chronic obstructive pulmonary disease, lung sliding can be abolished in the absence of pneumothorax. The diagnosis remains uncertain in patients with normal lung aeration whereas in patients with lung injury, the presence of vertical B-lines rules out the diagnosis.

The ultrasound diagnosis of pneumothorax is the most difficult part of training: long experience is required to acquire appropriate skills that rely on the ability to recognize lung sliding and its abolition [42]. When possible, the use of higher emission frequencies (5 to 10 MHz) facilitates the recognition of lung sliding abolition. The diagnosis is even more difficult in the presence of partial pneumothorax. The patient should lie strictly supine to allow location of pleural gas effusion in non-dependant lung regions. To confirm the diagnosis of partial pneumothorax, examination should be extended to lateral regions of the chest wall to localize the point where the normal lung pattern (lung sliding and/or the presence of vertical B-lines) replaces the pneumothorax pattern (absent lung sliding and horizontal A-lines). This point is called the ‘lung point’ [54]. Utilization of the time motion mode can facilitate detection of the lung point (Fig. 7).

The ultrasound pattern characterizing pneumothorax was described in the early 1990s [55-57]. Several studies have demonstrated that bedside lung ultrasound is more efficient than bedside chest radiography for diagnosing pneumothorax in emergency conditions if rapidly performed by the clinician in charge [28, 58-60]. Recently, interest in lung ultrasound for diagnosing pneumothorax in emergency and trauma patients has been reported [61]. Using a portable ultrasound device and a 3.5 to 7 MHz probe, three emergency physicians, having received formal 28 hour training for emergency bedside ultrasound, systematically performed lung ultrasound in 135 trauma patients admitted either to the resuscitation or the Emergency ICU of the Second Affiliated Hospital of Hangzhou (China). At admission, all patients had frontal chest radiography and 131 a thoracic computed scan of the whole lung, which served as gold standard for the diagnosis of pneumothorax. The sensitivity and specificity of lung ultrasound for diagnosing pneumothorax were 86% and 97%, respectively, whereas conventional chest radiography had sensitivity and specificity of 28% and 100%, respectively. Lung ultrasound over-diagnosed pneumothorax in two patients with pleural adherences. Bedside chest radiography missed all partial pneumothoraces whereas lung ultrasound detected the majority of them by identifying the lung point. In addition, lung ultrasound allowed the detection of pneumothorax within 2 to 4 minutes compared to 20 to 30 minutes for the chest radiography.

![Time-motion mode lung ultrasound. (a) Normal lung and (b) pneumothorax patterns using time-motion mode lung ultrasound. In time motion mode, one must first locate the pleural line (white arrow) and, above it, the motionless parietal structures. Below the pleural line, lung sliding appears as a homogenous granular pattern (a). In the case of pneumothorax and absent lung sliding, horizontal lines only are visualised (b). In a patient examined in the supine position with partial pneumothorax, normal lung sliding and absence of lung sliding may coexist in lateral regions of the chest wall. In this boundary region, called the ‘lung point’ (P), lung sliding appears (granular pattern) and disappears (strictly horizontal lines) with inspiration when using the time-motion mode.](image)
Limitations of lung ultrasound

When adopting lung ultrasound as a routine monitoring tool in the ICU, physicians should be aware of its limitations. Lung ultrasound examination and correct interpretation of the resulting images require formal training aimed at acquiring the necessary knowledge and skills. If several lung ultrasound examinations are performed on a daily basis, the learning curve for acquiring skills for diagnosing pleural effusion, lung consolidation and alveolar-interstitial syndrome is short, less than six weeks. The intra- and inter-observer variability is small, less than 5% [2]. The learning time for acquiring skills required for diagnosing pneumothorax is probably longer due to its low incidence in the critical care environment. In fact, the acquisition of the skills for diagnosing pneumothorax is the most difficult part of lung ultrasound training.

Lung ultrasound has intrinsic limitations that are not operator dependent but patient dependent. Obese patients are frequently difficult to examine using lung ultrasound because of the thickness of their rib cage. The presence of subcutaneous emphysema or large thoracic dressings alters or precludes the propagation of ultrasound beams to the lung periphery. Last but not least, it has to be pointed out that lung ultrasound cannot detect lung over-inflation resulting from an increase in intrathoracic pressures.

Conclusion

Accuracy of lung ultrasound for diagnosing pneumothorax, lung consolidation, alveolar-interstitial syndrome and pleural effusion in critically ill patients is clearly documented. The routine use of lung ultrasound appears as an attractive alternative to bedside chest radiography: it is non-invasive, easily repeatable at the bedside and provides an accurate evaluation of the respiratory status of patients with acute lung injury. In ICUs where it is used as a routine monitoring tool, the indications of bedside chest radiography can be restricted to the assessment of the intrathoracic position of catheters and endotracheal tubes and to patients where lung ultrasound performance is not feasible. As a consequence, radiation exposure to physicians, nurses and patients is drastically reduced as well as costs. Lung ultrasound performed by physicians in charge of ICUs appears to be one of the most promising techniques for respiratory monitoring and should rapidly expand in the near future.

REFERENCES


