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Imaging and respiratory care

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Introduction

Imaging by chest radiographs, thoracic computed tomography (CT), magnetic resonance (MRI) or lung ultrasound can be routinely performed in ICU patients and may provide accurate information on lung status with diagnostic and therapeutic relevance. Imaging techniques are important to describe anatomic changes related to lung or thoracic diseases and are also essential for optimising therapeutic procedures and improving the management of critically ill patients. The diagnosis and drainage of localised pneumothoraces and empyaema, the assessment of lung recruitment following positive end-expiratory pressure or recruitment manoeuver, the assessment of lung over-inflation, the evaluation of aeration loss and its distribution all require direct visualization of the lungs. To date, chest imaging relies mainly on bedside radiography and CT. Recently, ultrasound has become an attractive new tool for assessing lung status in ventilated critically ill patients, as suggested by the increasing number of articles about its use in intensive care or emergency medicine. Chest ultrasound can be performed easily at the bedside to assess lung morphology in severely hypoxaemic patients [1] and can be repeated, allowing the effects of therapy to be monitored. Ultrasound is becoming more and more important in critical care practice, and will be discussed in this lecture.

Conventional lung imaging in critically ill patients

Bedside chest radiography

In the ICU, bedside chest radiographs are routinely performed on a daily basis and are considered as a reference for assessing lung status in patients with acute lung injury and a complement to physical examination. A high prevalence of findings on daily routine chest radiographs in critically ill patients has been reported [2]. Nevertheless, this daily routine remains a matter of debate, and a recent study [3] reported that stopping daily routine chest radiographs had little impact on the requirements for chest CT and ultrasound without affecting the duration of stay in ICU and the survival of the patients. This study emphasised the usefulness of lung ultrasound and chest CT in the diagnosis of chest abnormalities.

Limited diagnostic performance and efficacy of bedside portable chest radiographies has been reported in several studies [4, 5]. Several reasons account for this. First, during image acquisition, the patient and the thorax often move, decreasing the spatial resolution of the image. Second, the film cassette is placed posterior to the thorax and the X-ray beam originates anteriorly, at a shorter distance than recommended and often not tangentially to the diaphragmatic cupola thereby hampering correct interpretation of the silhouette sign. These technical difficulties lead to incorrect assessment of pleural effusion, lung consolidation and alveolar-interstitial syndrome.

In the trauma setting, the use of chest radiographs in the initial assessment facilitates emergency treatment decisions before performing full body CT scanning. Chest radiographs performed using portable apparatus at the bedside are usually not of high quality. Chest radiographs can miss 10%-20% of traumatic pneumothoraces that are subsequently diagnosed by chest CT scan. Although chest CT scan is a more accurate imaging technique for the diagnosis of haemo- and pneumothoraces, as well as pulmonary contusions, it requires transportation of the patient and takes time, leading to potential deterioration of their condition and respiratory distress in the radiological unit. Moreover, the CT scan room may not be an ideal place in which to perform emergency chest drainage. Finally, a chest CT may not be immediately available at all times. Consequently, appropriate decisions concerning chest drainage can be made safely using simple imaging techniques before performing chest CT, increasing the safety of the transport of the polytrauma patient [6].

Lung CT

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 transthoracic drainage of a localised pneumothorax, empyaema or lung abscess. In ARDS, care of the patient may be influenced by the findings of lung CT. When a patient is turned to the prone position, it restricts the expansion of the cephalic and parasternal lung regions and relieves the cardiac and abdominal compression exerted on the lower lobes. Prone positioning induces a more uniform distribution of gas and tissue along the sterno-vertebral and cephalo-caudal axis by reducing the gas/tissue ratio of the parasternal and cephalic lung regions, it also reduces regional ventilation/perfusion mismatch, prevents the free expansion of the anterior parts of the chest wall, promotes PEEP-induced alveolar recruitment, facilitates the drainage of bronchial secretions and potentiates the beneficial effect of recruitment manoeuvers.

Image creation during computed tomography relies on a physical principle similar to image formation during chest radiography: the number of X-rays hitting the film or the CT detector depends 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 site of a ring that rotated around the patient. Typically, a 1 cm-thick CT section was taken during each rotation lasting 1 s 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 were poor at reformatting in different planes. In the 1990s, 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 1 s around the thorax while the table supporting the patient moves continuously. The multiple detectors and the reduction in rotation time allow faster coverage of a given volume of lung tissue, contributing to increased spatial resolution (voxel < 1 mm^3). Using specially designed computer software offering sophisticated reconstruction and post-processing capabilities, several hundred consecutive axial sections of the whole lung can be reconstructed from the volumetric data and visualised on the screen of a personal computer. If the computer is connected to an appropriate workstation, it is possible to ‘move into the lung’ and to measure CT attenuations in any part of the pulmonary parenchyma, providing information on regional lung aeration. In addition, images can be reconstructed in coronal, sagittal and oblique planes, offering the possibility of a three-dimensional view of the organ. Three-dimensional reconstruction of the airway by a specific multi-detector CT scanner can be useful in clinical practice. Le Guen et al reported a case of post-traumatic disruption of the right bronchial tree in a blunt chest trauma patient [7]. In this case, the diagnosis was missed using a standard helical CT. Post-processing procedures including three-dimensional extraction of the tracheo-bronchial tree were fundamental in establishing the correct diagnosis and to surgical repair. Moreover, this technique was used for follow-up, allowing the diagnosis of bronchial stenosis located at the site of the rupture. Lastly, for hospitals having a picture storage system films are no longer necessary while the physician derives much more accurate information on a patient’s 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 the patients to unsafe radiation exposure. 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 easily obtained with multi-slice CT scanners, there is a potential for an increased radiation exposure [8] that has to be balanced against the total radiation dose resulting from chest radiographies performed daily at the bedside. Furthermore, to perform a lung CT scan requires transportation to the radiology department, a risky procedure necessitating the presence of trained physicians and sophisticated cardio-respiratory monitoring [9]. For these reasons, the use of lung CT remains limited in many ICUs and bedside lung ultrasound appears to be an attractive alternative and, indeed, complementary technique.

Bedside lung ultrasound in critically ill patients

Technical equipment and lung ultrasound examination

Ultrasound machines should be lightweight, compact, easy to transport and robust, allowing multiple bedside examinations. The probes and the ultrasound machine itself should comply with repeated decontamination procedures since they serve multiple patients and can be the vector of resistant pathogens in the ICU [10, 11]. The probe should be small with a convex tip, in order to be easily placed on the skin over the intercostal spaces that offer an acoustic window into the lung parenchyma. Generally, a convex array probe (3–5 MHz), such as those available on multi-purpose ultrasound machines is suitable and permits good visualisation of the lung.

The patient can be satisfactorily examined in the supine position. The lateral decubitus position, however, offers a better view of the dorsal regions of the 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 predominantly found in dependant and dorsal lung regions and can be easily distinguished from liver or spleen once the diaphragm has been located.

Normal ultrasound pattern and basic abnormalities

Normal pattern

For each 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 lung ventilation is seen 0.5 cm below the rib line, and is called 'the pleural line'. On time-motion mode, a 'sea-shore sign' is present, characterised by the motionless parietal tissue over the pleural line and a homogeneous granular pattern below it [12]. 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 'artefacts of repetition'. Thus, a normal ultrasound pattern is defined by 'lung sliding' associated with artefactual horizontal A-lines. In one-third of patients with normal lungs, however, isolated vertical B-lines can be detected in dependant lung regions and are devoid of any pathological significance. B-lines move with the pleural line and efface A-lines.

Alveolar-interstitial syndrome

In the presence of injured lung characterised by an increased amount of lung tissue extending to lung periphery [13], vertical artefacts arising from the pleura and extending to the edge of screen [14] are detected and called vertical 'B-lines' or 'comet tails'. They appear as shining vertical lines arising from the pleural line and reaching the edge of the screen. The number of these vertical B-lines is dependent on the degree of lung aeration loss and their intensity increases with inspiratory movements [1, 15]. As mentioned above, less than one or two vertical artefacts are seen in dependant lung regions in normally aerated lungs [15].

Lung consolidation

Massive lung oedema, lobar bronchopneumonia, pulmonary contusion or lobar atelectasis induce a massive loss of lung aeration that enables ultrasound waves to be transmitted towards the deeper thorax. Lung consolidation appears as a hypo-echoic tissue structure that is poorly defined and wedge-shaped. Within the consolidation, hyperechoic punctiform images can be seen, corresponding to air bronchograms (air-filled bronchi) [16]. Penetration of gas into the bronchial tree of the consolidated region of lung during inspiration produces an inspiratory reinforcement of these hyperechoic punctiform images. Several studies have demonstrated that lung ultrasound is good at diagnosing alveolar consolidation and is helpful for guiding percutaneous lung biopsy [1, 17].

Ultrasound assessment of alveolar recruitment and lung re-aeration

Lung ultrasound has been recently shown to allow quantitative assessment of lung re-aeration with antimicrobial therapy in 24 critically ill patients with ventilator-associated pneumonia [18]. The whole lung was examined at the bedside, as described above, and each region of interest was attributed a score according to four stages of lung aeration before and after antimicrobial therapy: normal, interstitial syndrome, alveolar-interstitial syndrome and alveolar consolidation. A good correlation was found between pulmonary re-aeration measured by lung CT and the change in the 'ultrasound score'. Further studies are required to confirm that lung ultrasound may enable the measurement of alveolar recruitment from PEEP or other recruitment manoeuvres.

Pleural effusion

Pleural effusion should be sought on a longitudinal view in dependant lung regions delineated by the chest wall and the diaphragm. It appears as a hypo-echoic and homogeneous structure with no gas inside which is present during expiration and inspiration [19]. Assessment of a 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 colour Doppler to examine the intrasplenic and intrahepatic blood vessels; or by visualisation of a sinusoidal inspiratory movement of the visceral pleura from deep to the periphery [20].

The lung ultrasound approach has been proposed for quantifying pleural effusion volume [21]. 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 [22]. The measurement of the interpleural distance can be performed either at end-expiration or end-inspiration [21] but seems less reliable when measured on the left side [21]. All studies agree that ultrasound measurement of the interpleural space at the lung base is not accurate enough to quantify small (≤ 500 ml) or very large (≥1000 ml) pleural effusions [21]. Recently, another ultrasound approach has been proposed for quantifying pleural effusion: multiplication of the height of the pleural effusion by its transverse area, measured half-way between the upper and lower limits. An excellent correlation was found between the volume of pleural effusion assessed on CT of the whole lung and ultrasound determination [23].

Although the nature of a pleural effusion (transudate or exudate) cannot be accurately assessed by ultrasound examination, some ultrasound patterns are suggestive. Transudates are always anechoic while exudates often appear echoic and loculated [24].

Lung ultrasound is increasingly used for guiding bedside thoracocentesis [20, 25]. It allows detection of pleural adherences that may hamper efficient thoracic drainage and that make thoracocentesis risky.

Pneumothorax

Pneumothorax is defined by the interposition of gas between the visceral and parietal pleural. As a consequence, lung sliding is abolished, ultrasound waves cannot be transmitted to the lung parenchyma and 'comet tails' (vertical B-lines) are not visible. Only longitudinal reflections of motionless pleural line (horizontal A-lines) can be seen [26]. The ultrasound diagnosis of pneumothorax is difficult: prolonged experience is required to acquire appropriate skills that rely on the ability of recognising lung sliding and its abolition [20]. The diagnosis is even more difficult with a partial pneumothorax. To confirm the diagnosis the ultrasound examination should be extended to lateral regions of chest wall to localise 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).

Conclusions

Imaging is an essential part of respiratory care. Several imaging techniques are available, and 'one size does not fit all'. Chest radiographs are useful in the initial assessment of a trauma patient to make appropriate decisions concerning chest drainage before performing chest CT and to provide safer transport conditions. In ICU, the benefit of daily routine chest radiographs should be evaluated in each unit according to local medical practice. Thoracic CT provides accurate information on lung status with diagnostic and therapeutic relevance. Diagnosis and drainage of localised pneumothoraces, pleural effusions and empyaema, the assessment of lung recruitment following positive end-expiratory pressure or recruitment manoeuvers, assessment of lung over-inflation, evaluation of aeration loss and its distribution are best performed by chest CT. The accuracy of lung ultrasound for diagnosing pneumothorax, lung consolidation, alveolar-interstitial syndrome and pleural effusion is well established. Consequently, chest ultrasound has become an attractive imaging technique for assessing lung status and morphology in critically ill patients and can be easily repeated, allowing the effects of therapy to be monitored.

Key Learning Points

- The lung may be monitored using imaging techniques.
- Different imaging techniques are available, each with their own indication.
- Useful information can be provided which may modify the patient's care (such as, directing lung recruitment, identifying a pleural effusion).

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