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● *Review*

ULTRASOUND OF THE PLEURAE AND LUNGS

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Abstract—The value of ultrasound techniques in examination of the pleurae and lungs has been underestimated over recent decades. One explanation for this is the assumption that the ventilated lungs and the bones of the rib cage constitute impermeable obstacles to ultrasound. However, a variety of pathologies of the chest wall, pleurae and lungs result in altered tissue composition, providing substantially increased access and visibility for ultrasound examination. It is a great benefit that the pleurae and lungs can be non-invasively imaged repeatedly without discomfort or radiation exposure for the patient. Ultrasound is thus particularly valuable in follow-up of disease, differential diagnosis and detection of complications. Diagnostic and therapeutic interventions in patients with pathologic pleural and pulmonary findings can tolerably be performed under real-time ultrasound guidance. In this article, an updated overview is given presenting not only the benefits and indications, but also the limitations of pleural and pulmonary ultrasound. (E-mail: christoph.dietrich@ckbm.de) © **2015 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Ultrasound, Pleural effusion, Consolidations, Pneumonia, Atelectasis, Malignancies, Pulmonary thrombembolism, Interstitial syndrome.**

INTRODUCTION

Ultrasound of the lungs has been undervalued for many years. Because the ribs, sternum and aerated lungs had been considered obstacles to ultrasound waves, the prevailing opinion was that the lungs were not accessible to sonographic examination. By the laws of physics, sonographic evaluation of the chest is restricted by significant changes in impedance, and access to deeper structures is hampered by artifacts, for example, absorption, reflection, ring-down artifacts, mirroring and acoustic shadowing (Bonhof et al. 1983a, 1983b, 1984a, 1984b, 1984c; Dietrich et al. 2011b; Tsai and Yang 2003). However, many pathologic processes within the chest wall, pleurae and lungs result in profound changes in tissue composition. Inflammatory, traumatic or neoplastic processes often provide significantly improved acoustic transmission and allow for adequate sonographic evaluation. Under these conditions, non-invasive, real-time ultrasound examination serves as a powerful complementary diagnostic tool with the advantage of saving time and money in addition to easy availability and the virtual absence of complications, side effects and radiation exposure.

Ten years after initially reviewing the subject (Dietrich et al. 2003), we aim to provide an updated overview covering not only the indications and potential advantages, but also the limitations of pleural and pulmonary ultrasound. Other domains of chest ultrasound such as transthoracic ultrasound (Dietrich and Hocke 2008; Dietrich et al. 1997) and endoscopic sonography of the mediastinum and (endo)bronchial system (Dietrich 2011a, 2011a; Dietrich and Jenssen 2011), as well as contrast-enhanced ultrasound and strain imaging (Dietrich 2011b, 2012a; Piscaglia et al. 2012), have similarly increased in importance and are reviewed elsewhere.

EXAMINATION TECHNIQUES

Evaluation of the chest, lungs and associated pathologies by ultrasound requires detailed knowledge of the

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regional anatomy and potential pathologies of the chest wall, pleurae and lungs. In addition, high competence in the interpretation of results generated by complementary imaging techniques, particularly chest X-ray (CXR) and computed tomography (CT), is indispensable.

Equipment and technical requirements

The chest wall and the peripheral lungs are examined by ultrasound (linear array) transducers of higher frequency (5–17 MHz). Multifrequency transducers are of practical value. For evaluation of the lungs from the intercostal, subcostal or parasternal approach, 3.5- to 5-MHz convex or sector transducers should be used for optimimum depth penetration (Dietrich et al. 1997). In the case of narrow intercostal spaces, sector scanners might be more suitable for the evaluation of pleural and peripheral pulmonary lesions.

Lungs, pleurae and diaphragm

In general, the examination does not call for any specific preparation on the part of either the investigator or the patient. Depending on the indication, the patient remains in the supine position (for exploration of the ventral chest) or is asked to sit or stand (to assess the lateral and posterior chest). Bedridden and intensive care patients can often be examined in an oblique position. With the patient's arm lifted above the head or his or her hand positioned on the contralateral shoulder, the relative narrow intercostal spaces are expanded and the subscapular region is accessed this way.

Lungs and pleurae are best evaluated by modified application of the transducer in a the longitudinal, transverse and oblique inter- and subcostal positions (Fig. 1). The apex of the lung is additionally studied via the suprasternal and supra- and infraclavicular approaches (Dietrich et al. 2001, 2003). The brachial plexus (Wilckens et al. 2011) and the subclavian vessels can be explored with an axillary approach. The lung is identified by respiration-related movements of the visceral pleura, the so-called lung-sliding phenomenon. The diaphragm appears as a hypo-echoic (muscular) 1- to 2-mm structure with a brighter central echo line that contracts with inspiration. Contrary to common assumption, the diaphragm is not a bright line moving with respiration; the bright line merely indicates the reflection (acoustic impedance) between the air-filled lung and adjacent tissues. Sonographic examination generally makes use of the transhepatic and transplenic windows. A curtain sign can be revealed at the costophrenic angle, when air-filled lung tissue is obscuring the sonographic window on underlying tissues during deep inspiration (Dietrich 2012b; Dietrich et al. 2001).

A good view of most anatomic parts of the chest, pleure and diaphragm and/or numerous pulmonary pathologies requires careful angulation and tilting of the ultrasound probe, steady interaction with the patient and observation of her or his breathing maneuvers.

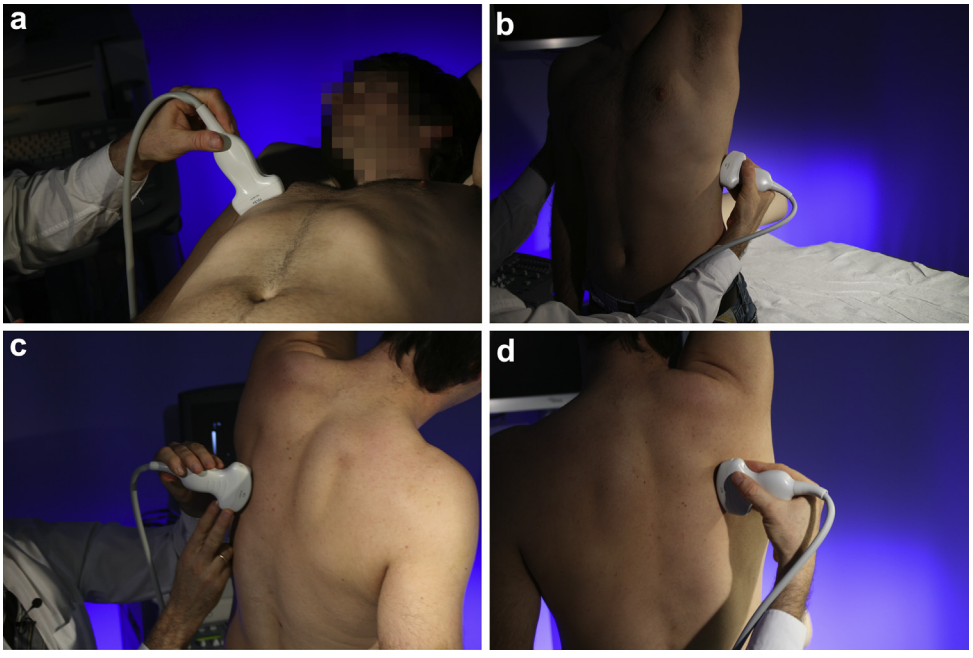

Fig. 1. Examination techniques. The supine position is used for exploration of the ventral chest (a). The sitting or standing position is suitable for assessment of the lateral and posterior chest (b, c). With the patient's arm lifted above the head, or his or her hand positioned on the contralateral shoulder, the relative narrow intercostal spaces are expanded and the subscapular region is accessed in this way (b, c). Lungs and pleurae are best evaluated by modified application of the transducer in the longitudinal (c), transverse (a) and oblique intercostal (d) and subcostal (b) positions.

Lung ultrasound is a complex procedure; each target area is visualized in real time by multiple cross-sectional images in several planes. In its entirety, these images look like pieces of a mosaic that have to be assembled in a complex 3-D representation of the target in its environmental context. The process of optimum data integration greatly depends on the investigator's powers of imagination. An off-line observer who is not directly participating in the examination will have difficulty in reproducing the sonographic findings and interpretation of the principal investigator because of the effect of considerable inter-observer discrepancy (Dietrich 2001, 2002; Hocke and Dietrich 2011).

ULTRASOUND OF THE CHEST WALL

Evaluation of soft tissue and/or osseous lesions is an important indication for ultrasound examination of the chest wall. Differential diagnoses include enlarged lymph nodes, lipomas, abscesses, hematomas and many other mostly benign lesions. Masses generally have variable echogenicity, and sonographic findings are too non-specific to differentiate between various etiologies. Reactive and inflammatory lymph nodes are a very common finding. Their typical sonographic appearance is an oval form; however, some are long and thin. The echogenic center (hilus fat sign) becomes larger during the healing process. Sonographic examination may allow for differentiation of reactive from malignant lymph nodes. Malignant infiltration usually shows loss of the fatty hilum, leading to a hypoechoic appearance. Malignant nodes also appear as round to oval inhomogeneous structures with irregular margins and vascularization. They typically exhibit extracapsular growth and infiltration into vessels and the surrounding tissues (Prosch et al. 2007). Despite those sonomorphologic criteria, the degree of malignancy remains uncertain. If immediate treatment is required, ultrasound-guided biopsy may help to make a rapid diagnosis.

Ultrasound is useful in the detection of rib fractures. Typical ultrasound findings include fissures (gaps), steps and hematoma. A nondislocated fracture can also be identified by a reverberation echo—the so-called chimney phenomenon. Indirect signs are pleural effusion and emphysema. In a population with suspected rib fractures, sonography revealed twice as many fractures as did CXR, including targeted X-ray (Bitschnau et al. 1997; Dietrich et al. 2001; Dubs-Kunz 1996; Martino et al. 1997; Wustner et al. 2005) (Fig. 2).

Pleural effusion, pneumothorax and contusion of the lung (18%) are found in more severe cases. A focal interstitial syndrome is often recognized. Lipomas are comparatively difficult to identify by ultrasound examination, particularly when they are small. They are usually hypo-echoic.

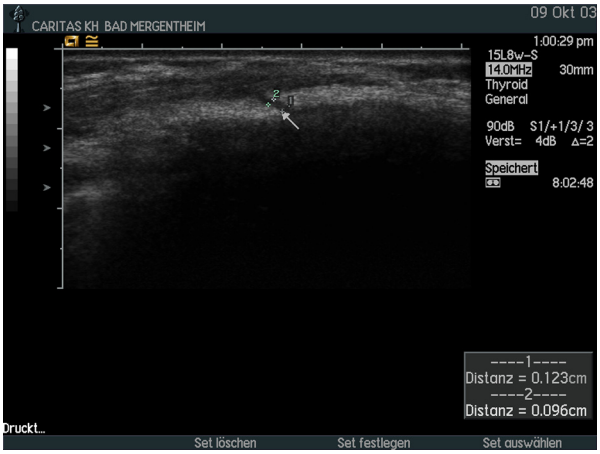

Fig. 2. Rib fracture. The discontinuation is indicated by the *arrow*.

Ultrasound examination is a powerful instrument in the evaluation of bone metastases and peripheral lung cancer infiltrating the chest wall. This is reflected by hypoechoic circular or oval lesions that cause disruption of the corticalis reflex with pathologic ultrasound transmission (Mathis 1997a). Color Doppler imaging (CDI) reveals variable vascularization depending on the entity and stage of the disease. Multiple myeloma, for instance, typically presents with neovascularization. Table 1 summarizes typical sonopathologic findings for the chest wall.

ULTRASOUND OF THE PLEURAE

Normal pleura

Ultrasound examination of the pleural space is a highly sensitive and specific diagnostic tool that is readily available for bedside diagnostics. Ultrasound is unmatched in discrimination between parietal and visceral pleurae, even in healthy controls. The normal pleura is characterized by a smooth echogenic surface and a hypo-echoic subpleural line. The normal pleura has a thickness of only 0.2 mm and reaches the limit of sonographic depiction. However, with high-resolution scanning, the visceral and parietal pleurae can be displayed as two distinct echogenic lines. Real-time imaging enables visualization of the so-called lung sliding, which is the depiction of a regular rhythmic movement synchronized with respiration. It occurs between the parietal and visceral pleurae that are either in direct apposition or separated by a thin layer of intrapleural fluid (Diacon et al. 2005; Koenig et al. 2011; Mayo and Doelken 2006).

Parietal pleura

The parietal pleura is better visualized than the visceral pleura and appears as fine echogenic line. High-definition ultrasound can reveal even a double

Table 1. Sonopathologic findings for the chest wall

Inflammatory reactions, *e.g.,* tissue swelling, edema, lymphadenopathy
Soft tissue infections, *e.g.,* abscesses, erysipelas
Hematoma
Rib fractures
Benign tumors, *e.g.,* lipomas
Malignant tumors
Metastases, neoplastic lymphadenopathy
Osteolytic and osteoblastic destruction of the bones

line, which corresponds to the anatomic combination of the parietal pleura and the endothoracic fascia. A further hypo-echoic layer beyond the parietal pleura corresponds to an individually variable extrapleural fat tissue layer (Reuss 2010).

Visceral pleura

The visceral pleura of healthy lungs is more difficult to visualize. It has been described as a delicate echogenic line, embedded in the near-total reflection of ultrasound waves over the air-filled lung (Mathis 1997a). However, in the event of lung consolidation and de-aeration, the visceral pleura can manifest with the same echogenicity as the parietal pleura. Reflection and reverberation artifacts are the dominant imaging features of the visceral pleura and its surrounding structures (Dietrich et al. 2003).

Pleural effusion

Quantification of pleural effusion. The sensitivity of conventional CXR is limited when it comes to the discrimination of pleural effusions. Even under favorable conditions (stance, deep inspiration), the threshold for fluid detection is above 150 mL. The data are much worse in the supine position (500 mL) or in the presence of superimposed parenchymal pulmonary pathologies (infiltrations, atelectases) (Dietrich et al. 2001). In contrast to CXR, ultrasound is far more sensitive and permits the detection of even minute pleural effusions (<5 mL) (Kocijancic et al. 2004). When the patient is sitting or standing, pleural effusions accumulate in the lateral costodiaphragmatic angles, and on real-time ultrasound examination, they can be perceived as breath-related shifting. Ultrasound is particularly helpful in revealing peridiaphragmatic and subpulmonal fluid collections, which are easily overlooked on conventional CXR and CT alike. However, pleural effusions trapped in the interlobar spaces may escape ultrasound as well.

Because of variable geometric configurations and respiration-related changes, precise sonographic quantification of the effusion volume is difficult. Many procedures have been suggested for determination of the volumes of pleural effusions, but all methods are estimates rather than exact measurements. An easily implemented volume estimation method for the seated patient is measurement of the vertical effusion height in the laterodorsal position. Multiplication of the height of the effusion in centimeters by the empirical factor 90 yields the quantity of the effusion in millimeters. A coefficient of correlation with a value of 0.74 is only moderately favorable (Reuss 2010). In supine patients, for example, in intensive care units, the pleural fluid volume can be estimated with the simplified formula V (mL) = 20 × Sep (mm), where Sep is the maximal distance between the parietal pleura and visceral pleura (Balik et al. 2006).

In most clinical circumstances, a rough estimation and differentiation of the effusion volume (minor, medium, large) by measurement of the longitudinal and transversal diameters will be sufficient and operator independent reproducible. This distinction should always consider the patient's symptoms (*e.g.*, dyspnea) and the presence and extent of secondary sonographic findings (such as compression atelectasis).

Etiology of pleural effusion. In terms of the vast spectrum of differential diagnoses, ultrasound does often not suffice to discriminate between the different etiologies and compositions of effusions. Some sonomorphologic features can nevertheless be distinguished, and the sonographic appearance of a pleural effusion may vary depending on its nature, cause and chronicity: Transudation, frequently related to heart failure, is usually completely anechoic and homogeneous, because the liquid does not contain ultrasound reflectors. The pleura is smoothly delimited. Compression atelectasis, small and acute angled, with varying inflation on inspiration, is often associated with the degree of effusion volume to which it correlates. Complex, septated or echogenic pleural effusions or particles within the fluids (*i.e.*, floating cells, agglomerations of proteins) point to an exudative process (Yang et al. 1992b). However, about two-thirds of exudates and cellular effusions are also anechoic. Therefore, definitive differentiation on the basis of this criterion is not possible. The lung pulse or fluid color sign is the most sensitive and specific sonographic evidence differentiating effusions from pleural thickening and may be elicited with color Doppler. It refers to movement of effusion echoes in synchrony with respiratory or cardiac cycles, while artifacts and static echoes follow the course of the transducer probe. The fluid color sign was reported to have a sensitivity of 89% and a specificity of 100% for the detection of minimal fluid collections (Wu et al. 1995).

Septations and strands within the fluid may occur depending on the stage and can have clinical implications (chest tube placement, fibrinolytic therapy, decortication surgery) (Bonhof et al.1983a, 1983b; Chen et al. 2000; Tu

Table 2. Sonographic signs of pleural fluid (Reuss 2010)

Anechoic zone separating the parietal and visceral pleura with change of shape as a function of respiration
Mobile echoic particles and septations within the pleural space
Mobile, partially atelectatic pulmonary tissue within the fluid
"Fluid color" sign (lung pulse) in duplex sonography (due to cardiac contractions) [(Wu et al.1995)]

et al. 2004). Ultrasonography is the most sensitive method for verification of septa. Diffuse involvement of the pleura alludes to ongoing inflammation. Empyema is marked by densified echoes and irregular signals at various positions. A chylous effusion, often linked with thoracic malignancies, is also variably echogenic owing to the reflections occurring at lipid aggregates (Yang et al. 1992b). Septic pleural effusions are due to bacterial infection, for example, in the case of complex parapneumonic effusions, empyema and (subpleural) abscess formation. Ultrasound findings are stage dependent (exudative, fibrinopurulent and organized stages [pleura peel]) (Table 2). Evaluation of past medical history is helpful, including questions about infections (pneumonia), trauma, interventions (thoracocentesis, surgery) and other factors.

Malignant effusions are more often echogenic than echo free and are typically accompanied by pleural and/or diaphragmatic thickening. Pleural/diaphragmatic nodularity is the most relevant feature for malignant pleural effusion (Bugalho et al. 2014).

A definitive diagnosis is made by thoracocentesis. Even minor effusions can effectively and tolerably be sampled by sonographically guided needle aspiration. The specific diagnosis of pleural effusion requires the immediate examination of fluids for blood chemistry and bacteriologic and cytologic analysis.

Hemothorax

Bleeding into the pleural space (hemothorax) is common in both blunt and penetrating trauma, but may also be related to inflammation (*e.g.*, tuberculosis) or malignancies. Hematothorax or hematopericardium, with or without pneumothorax, can reliably be identified by ultrasound examination. Fresh blood collection is echo poor, whereas old blood is increasingly echogenic, with large structures representing clots (Reuss 2010). Ultrasound can be used during the first minute of trauma assessment to decide on the necessity for urgent chest tube placement. It is now an essential step in the extended focused assessment with sonography in trauma (EFAST) algorithm. The sensitivity of ultrasound in detecting hemothoraces after trauma was found to be equivalent to that of CXR, but ultrasound proved to be a much faster procedure, taking about 1 min versus 15 min for chest radiography (Kirkpatrick et al.2004; Ma and Mateer 1997; Scalea et al. 1999; Sisley et al. 1998). On the contrary, ultrasonic access to deeper thoracic structures may be dramatically reduced in the presence of cutaneous emphysema. Hemothorax can usually be managed by placement of an ultrasonically guided simple chest tube.

Pleural diseases

The pleural tissues are involved in a multitude of benign and malignant processes. Some sonomorphologic characteristics allow for discrimination of underlying pathologies by ultrasound examination.

Pleural inflammation. In acute and, more pronounced, in chronic inflammation, ultrasound can visualize irregularities of the pleural margins. Frequently, small bands of subpleural consolidations can be discriminated. Other ultrasound features include hypo-echoic—often harmonic—but sometimes "rough" thickening of the pleura, small roundish (<10 mm) or wedge-shaped subpleural consolidations, pleural effusion with or without fibrinous echogenic bands and septa. Those changes are indicative of infectious diseases (*e.g.*, pleuritis tuberculosa), autoimmune-triggered polyserositis (*e.g.*, systemic lupus erythematosus) and interstitial lung diseases (Kroegel et al. 1999; Mathis 2004a; Wohlgenannt et al. 2001) (Fig. 3).

Pleural fibrosis is distinguished from pleural effusions by its mixed echogenic or hypo-echoic (in earlier stages) appearance that varies in neither shape nor location. The post-inflammatory pleural peel is frequently vascularized and thus efficiently well-defined against effusions using CDI or contrast-enhanced ultrasound (CEUS). Connective tissue components present with echogenic or calcified areas at times. For unmistakable differentiation, however, sonographically guided biopsy is required (Gehmacher et al. 1997; Gorg et al. 2005).

Diffuse pleural thickening. Diffuse pleural thickening is frequently associated with—or residual to—exudative pleural effusion, hemothorax and/or empyema (Gehmacher et al. 1997). Other causes (*e.g.*, drug-related pleural disease, malignant infiltration) have to be taken into consideration as well. Involvement of the visceral pleura can be responsible for restricted ventilation. The ultrasonic picture of fibrosis is typically hypo-echoic in earlier stages, followed by mixed echogenicity, with or without calcifications, during the course of the disease.

Circumscribed (focal) pleural thickening. Circumscribed pleural thickening is indicative of inflammation (pleuritis) and malignant infiltration. Pleural plaque formations (fibrosis, asbestosis) have to be considered as well. The latter frequently present in the form of hypo-echoic elliptical and smooth pleural thickening. Predilection sites of asbestosis include the posterolateral parts of

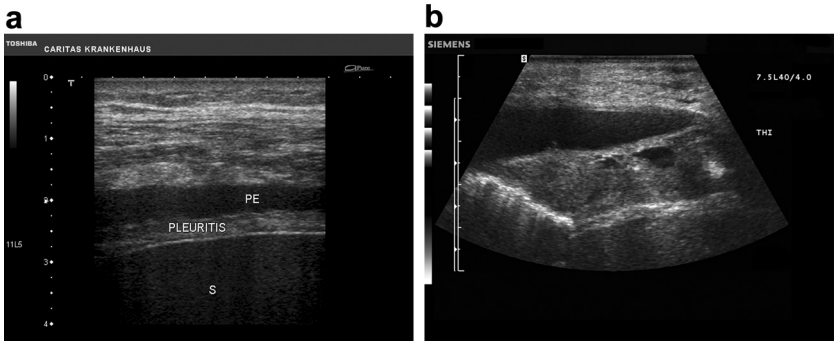

Fig. 3. Pleuritis in a patient with viral infection with only slight thickening of the pleura (PLEURITIS) and small amount of pleural effusion (PE) (a). Pleuritis with asymmetric thickening in a patient with systemic lupus erythematosus (b). S = spleen.

the parietal pleura. About 10% of cases present with calcifications (Mathis 1997a).

Pleural neoplasia. Benign tumors of the pleura (non-malignant mesothelioma, lipoma, fibroma, chondroma, neurinoma and mixed forms) are relatively rare and account for only 5% of the neoplastic lesions in this region (Saito et al. 1988). On ultrasound examination, benign lesions are often round or oval-shaped, well encapsulated or demarcated and hypo-echoic or moderately echogenic.

More common by far are malignant pleural tumors, such as malignant mesothelioma, metastases and transpleural growth of lung tumors. Irregularly outlined thickening of the pleura with a heterogeneous echo pattern, associated pleural effusions and infiltration of the adjacent structures are signs of malignancy (Adams and Gleeson 2001; Adams et al. 2001; Beckh and Bolcskei 1997; Dietrich et al. 2003; Yang et al. 1992a). Pleural mesothelioma is a particularly aggressive pleural tumor that infiltrates the chest wall and diaphragm (striped hypo-echoic ramifications) and is commonly associated with a history of occupational asbestos exposure (Reuss 2010). Pleural metastases frequently occur in breast and lung cancers. High-definition ultrasound equipment and thorough examination are mandatory for their detection because of their occasionally small size (<5 mm) and low echo contrast in comparison to the surrounding tissue (Bandi et al. 2008; Beckh et al. 2002).

Biopsy. The differentiation between benign tumors and malignancies is a diagnostic endeavor in neoplastic pleural disease. Ultrasound-guided (core) needle biopsy can today avoid more invasive procedures such as thoracoscopies and thoracotomies. However, ultrasound-guided biopsies can be rather challenging, as tissue lesions are frequently elastic and tend to dislocate under the pressure of the needle. These interventions should therefore be carried out by a particularly skilled investigator. Different techniques have been described (Dietrich 2008; Dietrich and Nuernberg 2011; Gottschalk et al. 2009, 2010; Seitz et al. 1999; Stigt and Groen 2014).

Pneumothorax

Chest X-ray on expiration still remains the method of choice for the diagnosis of pneumothorax in hospitalized patients. Use of ultrasound in the evaluation of pneumothorax is a relatively new concept and requires more experience than the detection of pleural fluid. To evaluate the anterior chest wall, ultrasound examination is best performed with the patient in the supine position, but other positions might be useful as well. During interpretation of the results, it is particularly important to compare the sonographic findings with those for the contralateral side. To increase the sensitivity of ultrasound-based diagnosis, a combination of negative and positive signs of pneumothorax should be applied: The sonographic signs of pneumothorax include the absence of lung sliding, the absence of lung pulse, the absence of B-lines and the presence of the lung point. Lung sliding, characterized by breath-related movements of the pleural line, is a strong negative predictor for pneumothorax (Koenig et al. 2011; Lichtenstein et al. 2005; Volpicelli 2011). The presence of lung pulse suggests other causative factors for the absence of lung sliding (*e.g.*, pleural effusion). B-Lines (not to be confused with B-mode imaging or brightness mode), previously described as comet tails, are defined as discrete laser-like vertical hyper-echoic reverberation artifacts that arise from the pleural line. They extend to the bottom of the screen without fading and move synchronously with lung sliding (Koegelenberg et al. 2012; Lichtenstein and Meziere 2008; Volpicelli et al. 2012). As B-lines originate from the visceral pleura, their presence proves that the visceral pleura is opposing the parietal pleura, thereby virtually excluding the presence of pneumothorax. When lung sliding and B-lines are absent, the ultrasound transducer should be moved in

the laterocranial direction until lung sliding and B-lines re-appear, which would confirm the diagnosis of pneumothorax. The re-appearance of these two signs was described as the lung point (Lichtenstein et al. 2000). However, in cases of complete lung retraction, the lung point cannot be visualized. The simplest sign of pneumothorax is the delineation of air within the pleural effusion (hydropneumothorax) (Fig. 4).

By use of the above definitions and techniques, bedside ultrasonography has been found to be equally or more sensitive than CXR in detecting pneumothorax (Agricola et al. 2011; Cunningham et al. 2002; Ding et al. 2011; Dulchavsky et al. 2001; Lichtenstein et al. 2000, 2005; Reissig and Kroegel 2005; Rowan et al. 2002; Volpicelli 2011). It is highly accurate (particularly in ruling out pneumothorax) and quickly done at the bedside. Therefore, ultrasound examination can be used to reliably exclude a pneumothorax after medical interventions (*e.g.*, transbronchial biopsy, sensitivity = 100%, specificity = 83%) (Kreuter et al. 2011). Soldati et al. (2008) reported that lung sonography was superior to chest radiography in pneumothoraces after blunt chest trauma. In their prospective study, they were able to report that ultrasound examination performed by an experienced operator had a sensitivity of 92% (spiral CT was used as the gold standard) whereas only 52% of pneumothoraces were visible on routine chest radiographs. Chest ultrasound is particularly useful in the intensive care unit and pre-clinical settings, where radiographic equipment is not readily available. It can be paramount in situations where missing a pneumothorax could result in significant deterioration, for example, in patients requiring positive pressure ventilation or emergency (air) transport. In recent years, ultrasound examination has thus become an integral part of the EFAST algorithm (Kirkpatrick et al. 2004) and of the international evidenced recommendations for point-of-care lung ultrasound (Volpicelli et al. 2012). The sensitivity of lung ultrasound in the diagnosis of pneumothorax is limited in certain settings, including obesity, diaphragmatic paralysis, prior pleurodesis or pleural adhesions and emphysema (Chan 2002; Ding et al. 2011).

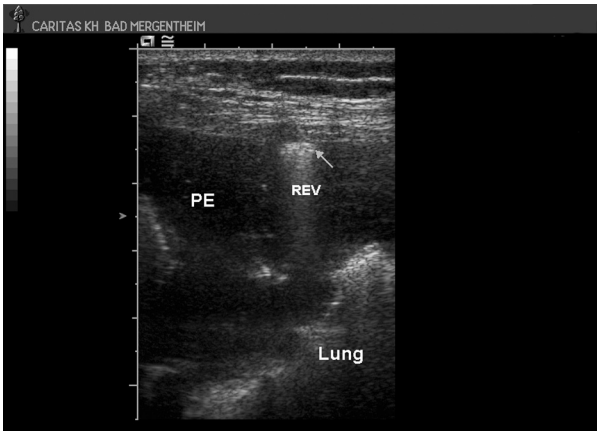

Fig. 4. The simplest sign of pneumothorax is the delineation of air (*arrow*) within a pleural effusion (PE). Reverberation artifacts (REV) are indicated. Pneumonia was the reason for pneumothorax. The lung is indicated as well.

SONOGRAPHY OF THE LUNGS (TABLE 3)

Lung consolidations

Contrary to the pleural and subpleural tissues, the healthy and ventilated lungs cannot be assessed by ultrasound examination, even if high-definition equipment is at hand (Tsai and Yang 2003). In contrast, numerous pathologies of the lung can effectively be investigated by ultrasound when they lead to reduced airway ventilation, are located in the lung periphery and are in physical contact with the pleurae (Table 4).

Lung consolidation is currently accepted as a nonspecific term referring to a subpleural echo-poor region or one with tissue-like echotexture, depending on the extent of air loss and fluid predominance. Ultrasound examination can reliably discriminate consolidations from pleural effusions, particularly in critically ill patients. Additional signs (*e.g.*, presence of B-lines, vascular pattern within the consolidations, air or fluid bronchograms) may aid in distinguishing the various causes, including pneumonia; pulmonary thrombembolism; lung cancer and metastases; compression and obstructive atelectasis; and lung contusion (Koegelenberg et al. 2012; Volpicelli et al. 2012).

Pneumonia

Pneumonic infiltrations are often accompanied by pleural effusions, which account for marked improvement of the sonographic window. In the initial phase of disease, the pneumonic consolidation exhibits a liver like echotexture. Air in the bronchi (air bronchogram) is seen in up to 90% of patients with pneumonia (Gehmacher et al. 1995; Mathis 1997b; Reissig et al. 2012b). Pneumonic infiltrations are characterized by irregular, serrated and somewhat blurred margins (Mathis et al. 1992) (Fig. 5). In pneumonia the air bronchogram is dynamic depending on breathing movement, distinguishing it from obturation atelectasis (Lichtenstein et al. 2009). The fluid bronchogram is marked by anechoic/hypo-echoic branched tubular

Table 3. Sonopathologic findings for the lungs

Pneumonia (peripheral location)
Tumors (carcinoma, metastases)
Atelectasis
Pulmonary thrombembolism, pulmonary infarction

Table 4. Ultrasound findings in pneumonia

"Hepatization" (in the early stages, lung tissues resembling hepatic parenchyma)
Air trapping
Air bronchogram
Fluid bronchogram (post-stenotic)
Blurred and serrated margins of the infiltrated lung tissues
Reverberation echoes in the margin
Abscess formation

structures in relation to the bronchial tree (Lichtenstein et al. 2004). Bronchial obstruction (caused by mucus plaques, neoplasm) must be taken into account in the case of a persistent fluid bronchogram (Liaw et al. 1994; Targhetta et al. 1992; Yang et al. 1990) and should be confirmed/treated by appropriate intervention (*e.g.*, bronchoscopy) (Mathis 1997b).

In later stages, the echo pattern becomes more dense and inhomogeneous. The re-appearance of air echoes in bronchi and alveoli may be viewed as a sign of restitution and as a precursor to reventilation. Reverberation artifacts are the typical ultrasound finding at this stage (Table 4). Lung ultrasound has recently been found to be a highly effective tool in the diagnosis and follow-up of pneumonia in adults as well as in children. Lung ultrasound detects more (12%–25%) pneumonias than X-ray confirmed by chest CT (Copetti and Cattarossi 2008; Parlamento et al. 2009). Lung ultrasound is a non-invasive, bedside-available tool used for high-accuracy (sensitivity = 93.4%, specificity = 97.7%) diagnosis of community-acquired pneumonia. This is especially important if radiography is not available. About 8% of pneumonic lesions are not detectable by lung ultrasound; therefore, an inconspicuous lung ultrasound does not rule out pneumonia (Reissig et al. 2012a). Repeated lung ultrasound control examinations may reflect the dynamics of pneumonia under therapy and serve as a therapy guide (Reissig and Copetti 2014).

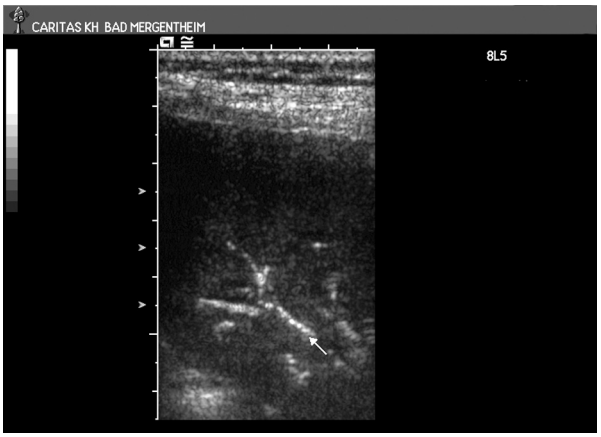

Fig. 5. Pneumonia. Typical pneumo-alveologram and pneumo-bronchogram (*arrow*) are visible.

Pulmonary abscesses

Within the framework of pulmonary infections, ultrasound evaluation may be of particular value in the early detection of complications such as abscess formation. Abscesses >20 mm are quite common in patients with pneumonia, particularly after staphylococcal infection. The sonomorphologic image of abscesses features irregularly outlined and hypo-echoic focal lesions. Further in the course of the disease, these areas are progressively isolated, and the surrounding pulmonary tissue features a more pronounced echogenic border (anachoretic effect) (Fig. 6).

When adequate respiratory shifting of the visceral and parietal pleurae is documented during sonographic examination, an abscess is rather unlikely. CDI reveals marked vascularity, and CEUS reveals early and strong contrast enhancement (Dietrich 2012b; Dietrich et al. 2003; Gorg and Bert 2004; Reissig and Kroegel 2007; Yang 1996). CEUS is helpful for differential diagnosis of abscesses by microvascular analysis: Abscesses are not vascularized, whereas neo-angiogenesis is generally present in neoplastic lesions. In cases of resistance to (antibiotic) treatment, CEUS-guided needle biopsy is used to drain the abscess and to provide samples for microbial cultures (Dietrich and Nuernberg 2011; Dietrich et al. 2012; Piscaglia et al. 2012).

Pulmonary tuberculosis

Pulmonary tuberculosis is verified by a variety of mediastinal, pleural and pulmonary traits including pleural effusion and disruption of the visceral pleura with subpleural consolidations and cavities or abscess formation. Tuberculosis lesions are often irregularly outlined with a homogeneous hypo-echoic texture. Miliary tuberculosis is sonographically characterized by multiple hypo-echoeic small subpleural nodules (<5 mm) (Schlesinger and Perera 2012).

Atelectasis

Compression atelectases in voluminous effusions are marked by the consolidation of pulmonary tissues and (partial or complete) absence of ventilation. On ultrasound examination, they present as acute-angled, smoothly delimited, often biconcave structures because of decreasing volume in the lungs (Gorg 2007; Gorg et al. 2006a; Mathis 2004b). The acoustic pattern is moderately echogenic with air trapping, depending not only on the composition of the associated effusion, but also on the angle of ultrasound wave admission. The picture usually resembles the parenchyma of the liver with aerobilia. During inspiration, the atelectatic share of the lung may be floating and re-inflating, to the effect that atelectasia temporarily disappears. A secondary pneumonic infiltration can significantly alter the

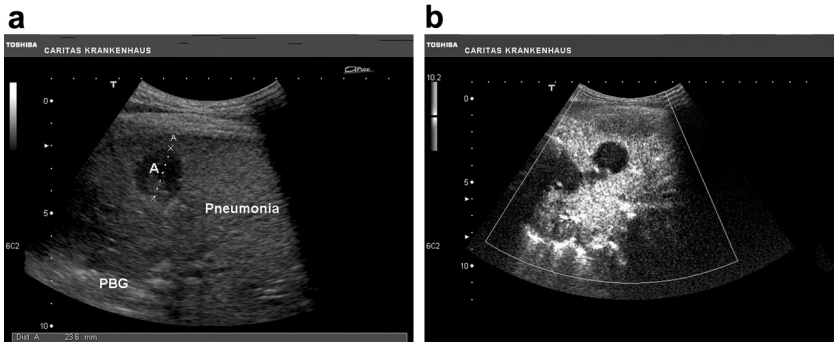

Fig. 6. B-mode ultrasound (a) and contrast-enhanced ultrasound (b) images of pneumonia with abscess. The abscess formation is identified as a non-enhancing area (b). The pneumobronchogram is also indicated (PBG).

appearance of the atelectasis: As the volume increases, the borders turn (bi)convex, and breathing-related variations in shape are replaced by more rigid manifestations with weak echogenicity (Fig. 7). CDI depicts a harmonic arboroid and ramified vascular architecture (Gorg and Bert 2004).

Obstructive atelectasis frequently occurs distally of airway stenosis (*e.g.*, bronchial carcinomas, mucous plaques). In contrast to compression atelectasis, pleural effusion is usually absent and less dependent on respiration with respect to shape and size (Dietrich et al. 2001, 2003). In the course of post-stenotic pneumonia, the picture resembles hepatization. Airways, however, are typically characterized by fluid bronchogram rather than bronchoaerogram. Depending on the duration of atelectasis, echogenic airway contents and vascular structures may distinctly be approached by ultrasound technique; in some cases, underlying causes of atelectases (*e.g.*, centrally located neoplasms) can be visualized (Gorg 2007).

Lung contusion

Ultrasound is helpful in the detection of contusions of the pulmonary parenchyma, especially in patients who had chest trauma and serial rib fractures. Alveolar edema and hemorrhage can be visualized (18%) in the form of hypo-echoic, peripherally located small focal lesions of different shape (Rocco et al. 2008; Wustner et al. 2005). Such findings are easier to discriminate when pleural effusion exists. A recent trial, comparing bedside chest ultrasound with clinical examination indicated that sonography had higher diagnostic accuracy in the evaluation of chest trauma patients, especially for pneumothorax and lung contusions (Hyacinthe et al. 2012).

Lung tumors

Pulmonary carcinomas and metastases present in varied circular, oval or polycyclic shapes with hypo-echoic texture and serrate margins. Infiltrations of the adjacent tissues with prominent inflammatory reaction can frequently be unveiled by ultrasound examination. Central necrotic or hemorrhagic lesions present as distinctly anechoic areas and are indicative of malignancy (Bugalho et al. 2014). Tumor infiltration of the pleura and the subjacent structures is reliably revealed by sonomorphologic pleural disruption and extension through the chest wall, aside from lack of breathing-related mobility of the tumor mass (Sugama et al. 1988). In a study comprising 120 patients with lung cancer, ultrasound was able to identify all 19 patients with

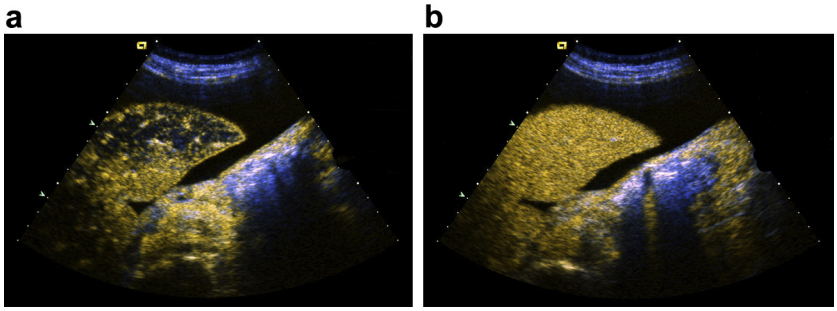

Fig. 7. Contrast-enhanced ultrasound examination images of atelectasis with early pneumonic infiltration. The homogeneous contrast enhancement rules out abscess formation. The enhancement patterns in the early (a) and late (b) arterial phases are indicated.

malignant chest wall infiltration (sensitivity = 100%, specificity = 98%, accuracy = 98%), whereas CT scan missed the diagnosis in 6 cases (sensitivity = 68%, specificity = 66%, accuracy = 98%) (Suzuki et al. 1993). In a further study, chest wall invasion by tumor was noted in 26 patients during surgery and final pathologic examination of the tissue. Of these patients, Ultrasound correctly identified 23 of these 26 patients as having tumor invasion, whereas CT diagnosed only 11 patients as having tumor invasion (Bandi et al. 2008). Because CT assessment of mediastinal and/or chest wall infiltration may not be sufficient, additional methods such as thoracic ultrasound and magnetic resonance imaging are recommended (Goeckenjan et al. 2011). Ultrasound of the supraclavicular and lower cervical lymph nodes has a special role in the staging of bronchial carcinoma because lymph node metastases are identified in 16%–26% of all patients. For non-small cell lung cancer, supraclavicular lymph node metastases correspond to an N3 lymph node station, representing an inoperable stage. Lymph nodes farther in the cranial direction are defined as distant metastases (M1 station). Ultrasound is superior to both palpation and CT in identifying enlarged supraclavicular lymph nodes (Fultz et al. 2002; Prosch et al. 2007, 2008; van Overhagen et al. 2004).

Against the background of a concomitant inflammatory reaction and post-stenotic pneumonia, sonography might overrate the dimensions of a malignant lesion. Ultrasound criteria alone do not suffice to discriminate between primary tumor, metastasis, post-stenotic pneumonia and abscess. CDI and CEUS are important tools in differentiation between malignant and benign pulmonary masses (Hsu et al. 1998; Liaw et al. 1993). CDI will reveal pathology in approximately 65% of peripheral malignant masses because of increased vascularity. At least one study found that CDI revealed a reduction in residual peripheral metastases after chemotherapy (Yang et al. 1990). CEUS reveals typically delayed and attenuated contrast enhancement compared with the encircling collapsed parenchyma of the lung. Irregular architecture of the vessels is typical (Gorg et al. 2006a, 2006b, 2006c).

Peripheral pulmonary lesions, out of reach of endobronchial intervention, can often be displayed and successfully sampled under ultrasound guidance. Core biopsies for histologic investigation are superior to cytologic specimens (Heilo 1996; Koegelenberg and Diacon 2011; Koegelenberg et al. 2012).

The rate of complications is closely related to the extent of ventilated lung tissue that has to be passed. The overall complication rate is low (pneumothorax: 2%–4%, hemoptysis: 1%–2%) (Diacon et al. 2004; Mathis et al. 1999). Table 5 summarizes the indications and diagnostic values of ultrasound procedures with respect to lesions of the chest wall, pleurae and lungs.

"White hemithorax"

Color duplex sonography is capable of providing important information in terms of differential diagnosis regarding the so-called "white lung," or opacification of the unilateral hemithorax on chest radiography. This phenomenon may occur in total atelectasis as a result of extensive pleural effusion and/or central bronchial obstruction. Complete occlusion of the main bronchus after pneumonic or malignant infiltrations can sometimes be visualized, as hemithoracic opacifications may serve as an "ultrasonic window" for penetration of the ultrasound waves (Kreuter and Mathis 2014; Yu et al. 1993).

Pulmonary thrombembolism

In lung ultrasound, subpleural lung consolidations resulting from pulmonary embolism are echo poor, small (0.5–3 cm), pleural based, mostly triangular, sharpely outlined and not vasulcarized in the center (Fig. 8). These lesions are frequently seen in multiple areas of both lungs, mostly dorsobasal (Mathis et al. 2005). The ultrasound criteria of peripheral pulmonary embolism are listed in Table 6.

Table 5. Indications for and diagnostic values of ultrasound procedures with respect to lesions involving the chest wall, pleurae and lungs

	Diagnostic value*
Chest wall	
Defined thoracic pain	0
Percussion (difference in side)	+
Attenuated breathing sound	+
Differentiation of palpable soft tissue tumors (*e.g.*, lymph nodes)	+
Osteolytic and osteoplastic bone destruction	+
Traumas with fractures and their complications	+
Pleurae (including follow-up examination)	
Pleural effusion	+++
Quantification of effusion volume	+
Echogenicity of fluid	+
Defined solid formations, tumors	+
Suspected pneumothorax	+
Lungs, visceral pleura	
Evaluation of lung opacities on X-ray images	+
Differential diagnosis "white hemithorax" (effusion, abscess, hematoma, pneumonia, atelectasis, tumor)	+
Pneumonia, detection of complications: Abscess formation, follow-up	+
Tumor evaluation, staging, follow-up during therapy	0
Suspected pulmonary thrombembolism, pulmonary infarction, particularly if computed tomography is unavailable	+
Interventional sonography, ultrasonically guided biopsy	
Biopsy of unclear masses within the chest wall, pleurae and lungs	+
Biopsy and drainage of fluid accumulation (exudation, transudation hematothorax, empyema, chylous effusion, abscess formation)	+++
Biopsy of pericardium and drainage in case of pericardial tamponade	+

* 0 = limited value, + = helpful, +++ = essential.

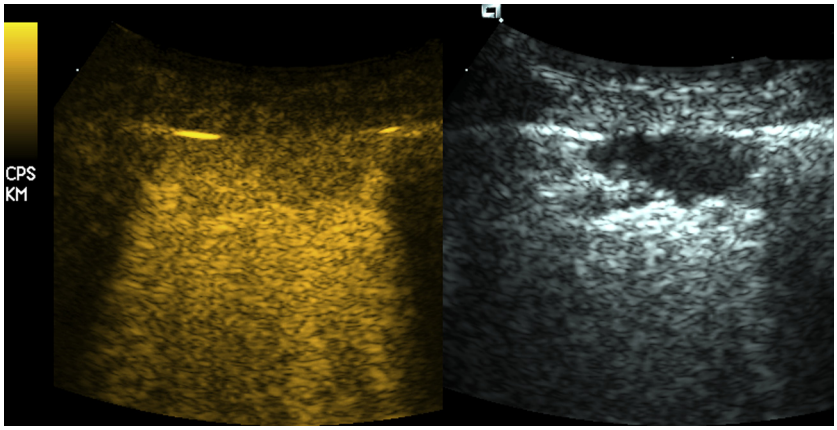

Fig. 8. Pulmonary thrombembolism. Because of the loss of surfactant production, the alveolar spaces fill up with fluids within minutes after the thrombembolic accident. B-Mode sonographic imaging reveals a variably hypo-echoic lesion (right). The time frame and certainty of diagnosis can be sometimes improved by contrast-enhanced ultrasound (left).

Post mortem observations in animals (Dudrick et al. 1966) and humans (Mathis and Dirschmid 1993) alike, as well as *in vivo* examinations, including one multicenter study (Mathis et al. 2005) and two meta-analyses (Nazerian et al. 2014; Reissig et al. 2001; Squizzato et al. 2013), corroborated the high sensitivity (80%–87%) and diagnostic accuracy (94%) of ultrasound examinations of the lung alone in the diagnosis of peripheral pulmonary embolism.

Until today, a large percentage of pulmonary embolisms go either undetected or the proper diagnosis is not made in time. International guidelines for the evaluation of pulmonary embolism recommend high-definition computed tomography for first-line diagnosis (Torbicki et al. 2008, 2009), but its use is limited by availability and radiation exposure, particularly in young patients and when follow-up examinations are needed. Mortality has slightly decreased during the last decades probably because of the use of CT. On the other hand, it has also been found that the use of multislice spiral CT cannot substantially reduce mortality from pulmonary embolism and that increased diagnoses may lead to overtreatment accompanied by undesirable side effects (Burge et al. 2008; Newman and Schriger 2011; Wiener et al. 2013).

Table 6. Sonomorphology of peripheral pulmonary thrombembolism

Pleura-based, 2/3 dorsobasally located
Typically 5 to 30 mm in size
Hypo-echoic
Triangular > round shape
Well demarcated
Loss of perfusion
Average of 2.5 lesions per patient
Concomitant small pleural effusion
Central bronchial reflexion (>3 cm)

In patients with unstable hemodynamics, diagnosis is often made by echocardiography in emergency rooms. Whereas the sensitivity of echocardiography in proving right heart strain in shocked patients is very high (90%), it is only 25%–50% for pulmonary embolism (Dresden et al. 2014). In case of a suspected pulmonary embolism, compression sonography of the leg veins is recommended. It can be performed within 2 min but, on average, yields a positive result in only half of the cases of pulmonary embolism. The source (leg vein sonography), transmission and hemodynamics (echocardiography) and arrival (lung ultrasound) of thrombembolic disease can be detected with a single ultrasound system, in one procedure, thus "killing three birds with one stone" with a sensitivity of 90%–92% (Mathis 2014).

Interstitial syndrome

The involvement of interstitial tissues in pulmonary fibrosis, interstitial lung infections, heart failure and acute respiratory distress syndrome has a similar sonographic pattern described as interstitial syndrome (Volpicelli et al. 2006). Interstitial syndrome is a condition in which alveolar air is impaired because of an increase in fluids in the interstitium. The sonographic technique is based on the visualization of some vertical reverberation artifacts, the B-lines, which prevent the mirror effect and are expressions of high-impedance discontinuities caused by close opposition between alveolar air and increased interstitial fluids—"the sound of lung water." In the evaluation of patients with acute respiratory failure, the B-line pattern allows for differentiation between a cardiogenic origin and a respiratory origin of the disorder, because exacerbations of chronic obstructive pulmonary disease, pulmonary embolism, pneumonia and pneumothorax yield a non-interstitial sonographic pattern (Lichtenstein and Meziere 1998; Volpicelli 2013;

Volpicelli et al. 2012). Initially, B-lines are present in the lung base, but extend with increasing capillary venous pressure to the superior lung. In cardiac edema, interstitial syndrome is usually bilateral and symmetric, with only a few pleural abnormalities, whereas acute respiratory distress syndrome presents with subpleural consolidations, "spared areas" of normal parenchyma, pleural line abnormalities and a non-homogeneous distribution of B-lines (Volpicelli et al. 2012). A diffuse and non-homogeneous distribution of B-lines, in conjunction with fragmentation and thickening of the pleural line, is also characteristic of pulmonary fibrosis (Copetti et al. 2008; Kreuter and Mathis 2014; Volpicelli et al. 2006).

INTERVENTIONS

Several pathologies of the lungs and chest can today be sampled by ultrasonically guided biopsy. There are obvious advantages compared with CT-guided or surgical procedures: availability and portability of ultrasonoscopes (even in pre-hospital settings), high-definition imaging of small structures, tolerable real-time and multiplanar guidance of interventions, procedure performance in varied body positions (*e.g.*, upright position in patients with respiratory distress), low costs and no exposure to radiation. Disadvantages are the invisibility of aerated tissues and failure to reach more centrally located lesions within the chest (Klein et al. 1995). Ultrasound guidance of diagnostic and therapeutic thoracocentesis including pleural sclerotherapy (*i.e.*, instillation of doxycycline, tetracycline and sterile talcum) is substantially more effective and more tolerable compared with physically guided techniques. Placement of needle and catheter (Parulekar et al. 2001) and optimum repositioning of the drainage can be monitored in real time (Shankar et al. 2000). Peripheral tumors are suited for transthoracic ultrasound-assisted biopsy, provided that no aerated lung needs to be traversed (*e.g.*, chest wall contact). The presence of pleural effusion reduces the risk of complications (pneumothorax). For more detailed descriptions of sonographic interventions, we refer to the recently published literature (Dietrich and Nuernberg 2011; Stigt and Groen 2014; Stigt et al. 2012).

CONCLUSIONS AND PERSPECTIVES

In a variety of intra- and extra-thoracic pathologies, ultrasonic pleural and pulmonary investigation provides an efficient contribution to diagnosis/differential diagnosis and subsequent treatment. Ultrasound is a valuable tool not only in the detection of complications, but also for follow-up examinations. It has been established in the diagnosis of chest wall lesions, pleural effusions, pneumothoraces and pulmonary consolidations, including neoplasms. It helps in guiding biopsies of solid masses and draining fluid collections. Recently, typical sonomorphologic patterns and examination techniques have been described for the diagnosis and follow-up of pulmonary thrombembolism and interstitial syndromes, such as pulmonary edema and fibrosis.

In the light of recent advances in ultrasound technology, it has to be emphasized that the interpretation of ultrasound results always requires scrutiny of the patient's history and the clinical results as well previous findings of complementary imaging techniques. Despite substantial progress in the past decade, non-invasive examination of the chest by ultrasound is not routinely performed in most centers. Transthoracic sonography is a highly operator-dependent procedure, and simultaneous image acquisition and interpretation requires longstanding expertise. There is increasing demand for the standardization of sonographic nomenclature and structured training (Havelock et al. 2010; Kaplan and Mayo 2009; Mayo et al. 2009). The European Federation of Societies for Ultrasound in Medicine and Biology has compiled a curriculum for chest sonography and training recommendations that includes standards for theoretical knowledge and practical skills (http://www.efsumb-portal.org/ep/article.php?id=42). It is intended for clinicians who perform diagnostic and therapeutic thoracic ultrasound. We recently reported that an objective structured clinical examination training concept for focused thorax and lung ultrasound is highly effective in imparting theoretical knowledge and practical skills to medical staff, particularly in emergency and critical care medicine (Breitkreutz et al. 2013; Cuca et al. 2013). We therefore propose that instruction of basic transthoracic ultrasound skills and some form of certification should be mandatory for all respiratory physicians in training.

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