Review

Med Ultrason 2021, Vol. 23, no. 4, 443-452
DOI: 10.11152/mu-3059

Lung ultrasound in children, WFUMB review paper (part 2)

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Abstract

Ultrasound (US) is an ideal diagnostic tool for paediatric patients owning to its high spatial and temporal resolution, real-time imaging, and lack of ionizing radiation and bedside availability. In the current World Federation of Societies for Ultrasound in Medicine and Biology (WFUMB) paper series so far (part I) the topic has been introduced and the technical requirements explained. In the present paper the use of US in the lung in paediatric patients is analysed. Lung diseases including the interstitial syndrome, bacterial pneumonia and viral infections, CoViD findings, atelectasis, lung consolidation, bronchiolitis and congenital diseases of the respiratory system including congenital pulmonary airway malformation (CPAM) and sequester but also pneumothorax are discussed.

Keywords: pneumonia; atelectasis; pneumothorax; CoViD; guidelines

1. Examination technique

In the majority of paediatric studies, a linear transducer is used as the probe of choice, especially in neonates and younger children. A convex transducer should be used when the patient has rich subcutaneous tissue, in case of larger consolidations or larger amounts of pleural fluid and in cases to evaluate B-lines. Filters and facilities (such as harmonics, compound, dynamic noise) may hinder lung ultrasound (LUS) performance, erasing precious artefacts. Thus, they should be switched off. Pathological findings are documented in two levels. Clips are helpful but not mandatory for documentation.

Healthy lungs cannot be imaged using sonography due to total reflection of the ultrasound (US) on the air-filled interface. Pathology within the lungs can be detected when there is no air-filled pulmonary tissue in between them and the transducer. Ventilation disorders (pneumonia) are most common in the paediatric population. Since they can occur in all segments of the lungs, the entire thorax has to be examined. The examination involves scanning along the anterior axillary, midclavicular and the parasternal lines in a longitudinal orientation from caudal (diaphragm) to cranial (apex of the

Received 20.12.2020 Accepted 28.01.2021
Med Ultrason
2021, Vol. 23, No 4, 443-452
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lung) or vice versa. By tilting the probe to avoid ribs, about 70% of the lung surface can be screened. The apex of the lung can be seen adequately in suprasternal and supra- or infraclavicular approach. The dorsal examination is mandatory. It can be carried out when the patient is either in a sitting or prone/decubitus position. Similar to the anterior chest examination, the lung is investigated in the posterior axillary, medial and paravertebral lines to obtain sagittal and sometimes also coronal images. The same applies for obtaining axial and oblique images. The region beneath the scapula may not be fully accessible, making it necessary to move the shoulder and to tilt the probe appropriately.

2. LUS characteristics in healthy subjects

In normal LUS, the pleural line, a hyperechoic horizontal reflection formed by the difference in acoustic impedance between soft tissue of the chest wall and aerated lung parenchyma, can be found. It appears as a smooth, regular and relatively straight hyperechoic A line, with pulmonary gliding (normal lung surface), the bat sign. Possibly some B-line artifacts (BLA) can be seen in the normal lung (less than 3). The bat sign is best seen on calcified ribs and arises when the linear transducer is placed on two consecutive ribs, causing a posterior double acoustic shadow and the projection of the pleural line and the area in the centre, which is called Merlin's Space. It is not seen when placing the transducer in the intercostal space. In M mode, a mixed image is produced: a series of wave lines resonate above the pleural line and the uniform granular dot echo (generated by lung slip) below the pleural line can form a beach-like sign known as a sandy beach sign or seashore sign [1].

3. Pathological findings

3.1. *Interstitial syndrome*

The interstitial syndrome consists of at least three B-line artefacts in the field of view (between two ribs). B-lines are defined using seven criteria, three of which are always present: they are laser-like, vertical reverberation artefacts that arise from the pleural line and are moving consensual with lung sliding. The other four criteria are almost always present: B-lines are long (extend to the bottom of the screen without fading), well-defined, hyperechoic and erase A-lines [2,3]. Three or four B-lines form the pattern called septal rockets. Five or more (the maximum seems to be ten) B-lines form the pattern called ground-glass rockets. Interstitial syndrome indicates that interstitial or alveolar-interstitial space is affected by a pathological process. The presence of interstitial syndrome may indicate the presence of fluid in the interstitial space (for instance, in pulmonary fibrosis) or inflammatory infiltrate within this space (fig 1). In paediatric patients, this syndrome most often occurs in the course of lower respiratory tract infections (especially viral pneumonia), acute respiratory distress syndrome, cardiogenic pulmonary oedema, hyperhydration of patients receiving haemodialysis, interstitial lung disease, cystic fibrosis and post-obstructive pulmonary oedema [4-7].

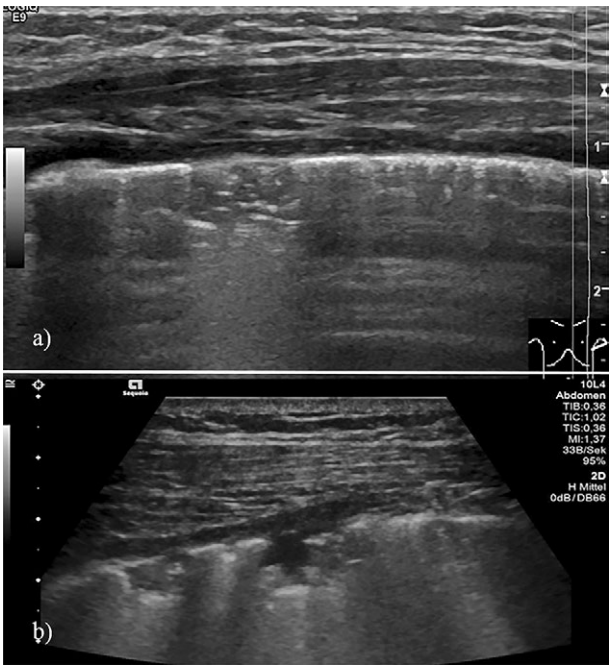

Fig 1. Viral interstitial pneumonia (a and b) is characterised by the presence of often multilocular small subpleural consolidations in combination with diffuse B-line artefacts, pleural line abnormalities and very small pleural effusions.

According to a position paper of the World Federation of Societies for Ultrasound in Medicine and Biology (WFUMB), BLA are defined by a normal pleura line and are a typical hallmark of cardiogenic pulmonary edema after exclusion of certain pathologies, whereas comet tail artefacts (CTAs) show an irregular pleura line representing a variety of parenchymal lung diseases. The dual approach using two types, low frequency transducers to determine BLA and high frequency transducer to determine the pleural surface, is recommended according to WFUMB.

3.2. *Lung consolidation*

Lung consolidation is a nonspecific term referring to a sub pleural hypoechoic region (or region with tissue-like echotexture, occasionally similar to liver or spleen) that is caused by the process (inflammatory or not inflammatory) causing fluid to replace air contained in alveoli [8]. The area can be minimal (several millimetres) or can oc-

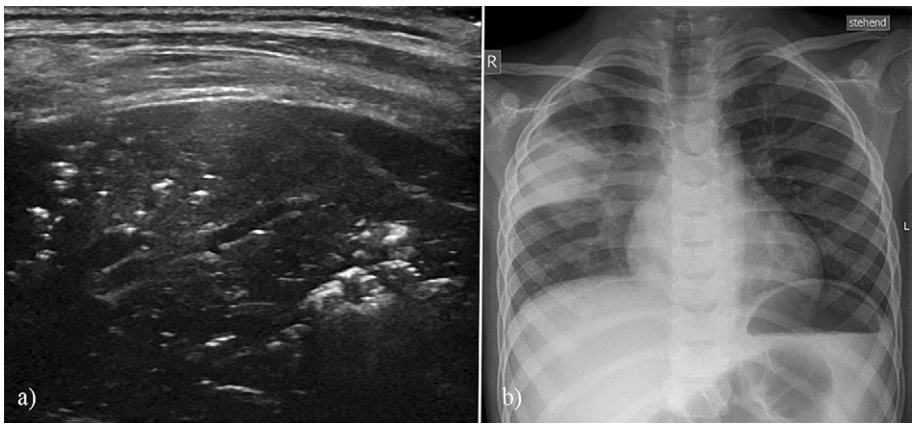

Fig 2. Bacterial pneumonia, ultrasound (a) and radiographic (b) examination. Bacterial pneumonia is characterized by larger lung consolidation with air bronchograms and variably pleural effusion.

cupy the whole lung lobe. Consolidation can be formed by viral (fig 1), bacterial (fig 2 and 3) and non-infectious reasons. Large consolidations have a characteristic liver-like appearance, referred to as hepatisation. The use of high frequency transducers allows clear distinction in most of such cases due to the more heterogenous pattern compared to the liver but published evidence is lacking. Usually, consolidation is poorly circumscribed with a blurred margin and has several associated features. These include:

1) Loss of pleural line echogenicity over the area of consolidation and the absence of A-lines within the area.
2) B-lines arising from the deep edge of the consolidation rather than from the pleura (some authors refer these artefacts to as C-lines, because Lichtenstein defined B-lines as arising from the pleural line).
3) Increased B-lines surrounding the area of consolidation.
4) Air bronchograms within the area of consolidation, which are observed as multiple hyperechoic punctuate or lenticular specks or as branching tree-like structures. Air bronchogram can be:
   - Dynamic – the specks and branches have intrinsic movement consensual to breathing.
   - Static – the specks and branches do not move together with breathing movements.
5) Fluid bronchogram - within the area of consolidation, it is observed as anechoic or hypoechoic branched tubular structures along the airways, often with hyperechoic walls. It can be differentiated from vessels using colour Doppler (CD) [9].
6) Vascular pattern in CD mode – observed as branching tree-like structures with blood flow; in pulmonary inflammatory lesions it is anatomical, in atelectasis the tree pattern is usually denser (resulting from pathophysiology of atelectasis), but still anatomical, whereas in neoplastic, embolic or mycotic changes it can be atypical, irregular or absent. It must be mentioned, that colour Doppler evaluation is often affected by artefacts related to cardiac and respiratory movements, making a study of vascular signals ineffective in some locations particularly pericardial. The use of modern microvascular visualisation techniques might address the issue of artifacts and provide better results.

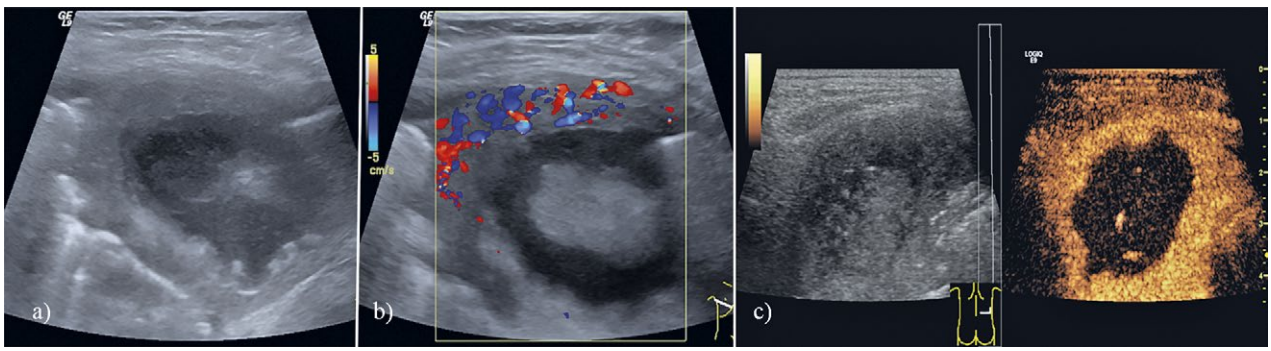

Fig 3. Bacterial pneumonia with abscess formation (a, b). The abscess formation can be proven by non-enhancing areas using contrast enhanced ultrasound (c).

3.3. Atelectasis

Atelectasis is a type of consolidation that is caused by lung collapse (obstructive or compressive), in which the first three above-mentioned features of consolidation are also observed. An air bronchogram can be static or absent, a fluid bronchogram can also be present and the vascular pattern in CD option is described in point 6. In large atelectatic areas, the lack of local respiratory movements or lung sliding and the presence of the pulse sign are often observed (fig 4 and 5). Differentiating atelectasis from consolidation of other origins may be not possible in every case [10]. However, LUS has proved to be an accurate diagnostic tool to image anaesthesia-induced atelectasis in children with MRI as a reference method [11].

3.4. Bronchiolitis

In bronchiolitis US findings are present in both lungs. They are seen as areas of small diameter (5-10 mm) sub pleural consolidations and areas of focal multiple B-lines (i.e., interstitial syndrome, which is the most frequent sign in bronchiolitis) that tend to coalesce to form areas of white lung mixed with normal areas (properly aerated lung) [12]. Moreover, there are also pleural line abnormalities defined as an irregular appearance of the pleural line [13]. The extent of the changes seen on LUS correlates with the severity of the clinical picture and thus can be used to define the prognosis of the individual patient [13-17]. There is a single publication showing that LUS has a higher accuracy in diagnosing bronchiolitis than the X-ray [18]. Interestingly, it was also reported that US diaphragmatic values (e.g., diaphragmatic excursion) correlated with the clinical outcome of bronchiolitis. Recently a study has been published showing that in 29% of infants (25 out of 87) with this disease entity, concomitant pneumonia was diagnosed (both with LUS and X-ray) [19]. The Italian group, with vast experience in performing LUS in bronchiolitis, has vigorously discussed this publication [20]. This is a hot topic since it represents a prevalent clinical dilemma for the paediatricians managing these infants. The borders between the clinical diagnosis of pneumonia and bronchiolitis are not definitely designated. It seems that US findings for both entities lack these borders as well. The reason for such a situation is age-dependent specific physiology and pathophysiology of the respiratory system. The criterion to define pneumonia on LUS in this study was finding of hypoechogenic areas with poorly defined borders and compact B-lines. Also, small areas of consolidation (i.e. <10 mm) were defined as bacterial if they had air-bronchogram within. However, no microbiological test was conducted to prove this hypothesis. The number of studies on LUS usage in bronchiolitis is very limited and there are no meta-analyses. Further research on this topic is warranted.

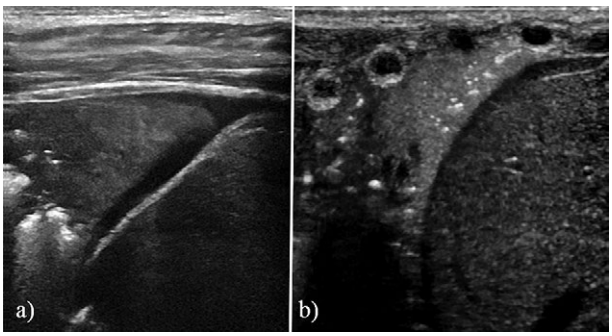

Fig 4. Atelectasis, compressions (a) and resorption (b). Atelectasis is a type of consolidation caused by lung collapse (obstructive or compressive).

Fig 5. Newborn with multiorgan failure. Completely missing ventilation of the left lung and demarcation of the superior and inferior lobe with the aspect of hepatisation.

3.5. Pneumonia

3.5.1. Bacterial pneumonia

In most of the published studies concerning LUS in cases of pneumonic consolidation, in the presence of air bronchograms and pleural effusions, the diagnosis of bacterial pneumonia was considered [8]. According to three meta-analyses, pooled sensitivity of LUS in diagnosing childhood pneumonia amounted to 96-97% and pooled specificity to 87%-95%, whereas pooled sensitivity and specificity of X-ray were 87-90% and 94-98% respectively [21-23]. One of these studies reported high rates of diagnostic accuracy in both expert and even novice sonographers with accuracy of over 90% [21]. Several studies showed substantial interobserver agreement (kappa 0.79-0.91) for the interpretation of LUS [24,25], whereas interobserver agreement for X-ray is reported to be fair to moderate (kappa 0.33- 0.51) [26,27]. Although multiple studies have shown LUS to be effective in diagnosing pneumonia in children, this procedure has still not been implemented as the recommended standard imaging method when pneumonia is suspected. A randomised

controlled trial on a group of 191 children suspected of having pneumonia in the Emergency Department showed that it might be feasible and safe to substitute LUS for X-ray with no missed cases of pneumonia or increase in the rate of adverse events [26]. LUS has been found not only to be a highly effective tool for the diagnosis of pneumonia but also to monitor the course of the disease [28]. There are however limitations of LUS. There are locations which are not reachable with this imaging method including consolidation not reaching the pleural surface where all deep regions are covered with properly aerated lung tissue particularly around the perihilar regions) and regions covered with bony structures (retroscapular, retroclavicular or glenohumeral joint regions). Small consolidations (<10 mm) are more often US incidentally observed than expected and, therefore, there is still an open question about their diagnosis and clinical importance. There are also singular studies showing that LUS has similar accuracy to CT in diagnosing pneumonia complications such as pleural fluid, necrosis and abscess of lung parenchyma [29-31]. CEUS helps to evaluate consolidated lung parenchyma and identify necrotizing pneumonia and to describe pleural thickening and inflammation [32-35].

3.5.2. Viral pneumonia

There is a general acceptance for the notion that an interstitial pattern represents viral or atypical bacterial origin for the pneumonia, but direct microbiologically confirmed evidence is lacking [8,25]. Literature concerning viral pneumonia in children focuses mainly on the H1N1 influenza A infection and most recently on Corona virus related diseases. Distinguishing viral from bacterial pneumonia is of key importance for patients visiting emergency departments with symptoms of respiratory tract infections. The study by Tsung et al proposes a protocol to differentiate between the two aetiologies [36]. Viral pneumonia is characterised by the presence of small sub pleural consolidations less than 5 mm in diameter, single and focal with multiple and diffuse B-line artefacts (white lung sign), small pleural effusions and pleural line abnormalities (thickened > 2 mm) [36,37]. Patients were classified as positive or negative for bacterial pneumonia based on the presence or absence of lung consolidation with air bronchograms [36]. Abnormalities in viral pneumonia most frequently occur within lower lung fields, over the posterior and lateral chest surface [37].

Abnormalities in severe viral pneumonia correspond to the ultrasound image of acute respiratory distress syndrome (ARDS). In this patient group, the following findings are typical: multiple B-line artefacts forming a pattern of alveolar-interstitial syndrome or white lung sign, an absence of areas with a normal pattern ('spared areas'), sub pleural consolidation, pleural effusion and diminished lung sliding as well as lung pulse [38-40].

The typical sonographic signs of COVID-19 infections include pathological changes of the pleura: thickened, irregular (coarse) and fragmented pleural line and a small amount of superficially located pleural fluid as a sign of severity and other signs of interstitial pneumonia and specific artefacts (B-line artefacts and multiple initially small consolidations). Initially and during recovery respiratory dependent lung sliding (A pattern), combined with B-line artefacts (mixing A and B patterns) can be seen. The signs are more specific when there is a very high pretest probability of COVID-19 infection. The initial lung involvement is often posterobasal. US allows detection of complications including pneumothorax and pulmonary embolism and follow up at the point of care (case of the month, www.wfumb.org).

3.6. Tuberculosis (TB)

The following US abnormalities have been identified in children with tuberculosis (TB): pleural effusion (30%), enlarged mediastinal lymph nodes (on average 1.5 cm) and sub-pleural consolidation. Consolidation rarely occurs in the first month in patients with a confirmed diagnosis of TB, but gradually appear over the following months and slowly resolve as treatment progresses. Literature dealing with this issue is scarce and further research is necessary [41]. A noteworthy systematic review published in 2018 presented valuable data, focused on five fields of interest for the diagnosis of TB using chest US: detection of pleural effusion, assessment of residual pleural thickening, the value of trans-thoracic needle biopsy, assessment of mediastinal lymphadenopathy and detection of pulmonary involvement in miliary TB [42].

3.7. Lung carcinomas and metastases

Primary lung tumours in children are rare and lung carcinomas in children are extremely rare [43]. Most malignant lesions in children are metastases [44]. In the majority of cases, clinical signs such as cough and radiologic findings including pathologic mass, inflammatory densities, pleural effusion and pneumothorax are nonspecific [45-47]. Diagnosis of lung carcinomas and metastases is based on the US criteria applied to adults [48,49]. When distinguishing malignant and benign pulmonary masses, the following options are used: colour (CD), power (PD) and spectral Doppler (Pulsed Wave Doppler) but solely based on US examination it is not possible to distinguish benign and malignant lesions [50]. Subpleural metastases are hypoechoic, characterised by round, oval or polymorphic shapes and disorganised flow in CD and PD imaging [51]. CEUS is also used to distinguish between benign and malignant lesions [52,53].

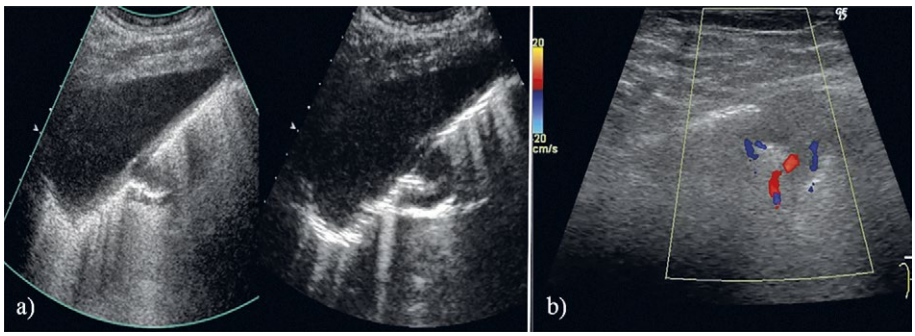

Fig 6. Pulmonary embolism with pleural effusion and subpleural consolidations examined by B mode (left) and contrast enhanced ultrasound (right, non-enhancing) (a). The use of colour Doppler imaging shows disrupted vessel at the base of the consolidation (b).

Lung and diaphragm ultrasound is recommended for patients at risk of secondary lesions (e.g. neurofibromatosis type I). This patient group is at a higher risk of developing malignancy and lung ultrasound is recommended especially in the case of recurrent lower respiratory tract infections, when chest radiography shows a basal lung opacity [54].

3.8. Pulmonary embolism

Pulmonary embolism in children is most frequently secondary to antiphospholipid syndrome, congenital heart defect, carcinomas, and blood cancers.

Pulmonary embolism in adolescents can be seen in girls with typical risk factors (obesity, smoking, contraception) for deep venous thrombosis of the lower extremity and the pelvis, as well as in children with former vessel pathologies (e.g. catheterism in neonatal period, former preterm born babies, and occlusion and/or thrombosis of venous vessels).

Signs of pulmonary embolism on US are well described based on adult patients [55]. In paediatric patients US findings of pulmonary embolism include bilateral, peripheral, sub pleural, hypoechoic, triangular and oval lesions, accompanied by pleural effusion [56] (fig 6). US is not the first diagnostic tool used in paediatric patients. But it could be a helpful tool for follow up of peripheral (superficial) lung lesions. Due to scarce scientific reports, further multi-centre studies are necessary.

3.9. Congenital diseases of the respiratory system including congenital pulmonary airway malformation (CPAM), sequester

Currently in developed countries the majority of congenital abnormalities of the respiratory tract are diagnosed prenatally, using US as the first line diagnostic tool and MRI as the second [57]. LUS is not the first line imaging modality to diagnose postnatally these diseases. These are rare entities and there is a lack of publications on the subject. Based on clinical experience and the views published by Donoghue et al [58] LUS could be useful in the following congenital chest malformations: agenesis and aplasia of the lung (with associated anatomical abnormalities of surrounding organs of the chest), cystic congenital pulmonary airway malformation (CPAM), sequestration, chylothorax and congenital diaphragmatic hernia [59].

There are few publications concerning LUS in congenital lung lesions. There is one publication describing LUS findings in five neonates with CPAM, correlated with CT findings in these patients [60]. They varied from a single large cystic lesion, multiple hypoechoic lesions to consolidation. The lesions were often heterogenous, anechoic, well-defined, but not vascularised. LUS can also show a multilocular cystic mass [61]. In sequestration, LUS can demonstrate a non-aerated mass (consolidation), which is found in the left lower lobe adjacent to the diaphragm in 66% of cases, and the artery with the systemic supply on colour and power Doppler options. In a case series of seven neonates (four with pulmonary sequestration, three with CPAM (fig 7)) LUS was effective for diagnosis with a high degree of consistency with CT findings (fig 8) [62].

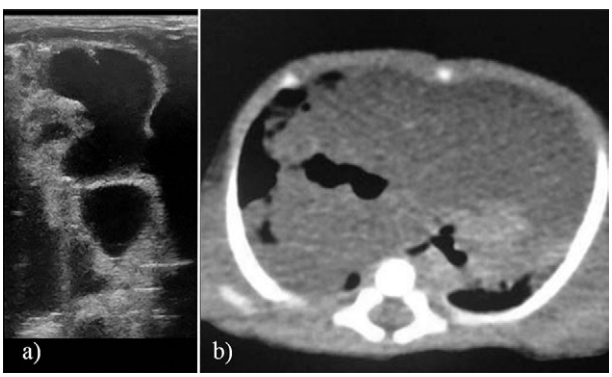

Fig 7. Cystic congenital pulmonary airway malformation in a 3-hours old newborn, intubated for dyspnoea with rapid respiratory failure. Hypoechoic "fluid filled", multiloculated cystic lesion of the right lung, "bordered" by hypo inflated lung parenchyma. Absence of A lines but the lung sliding was present during ventilation driven excursions. The CT image is also shown (b).

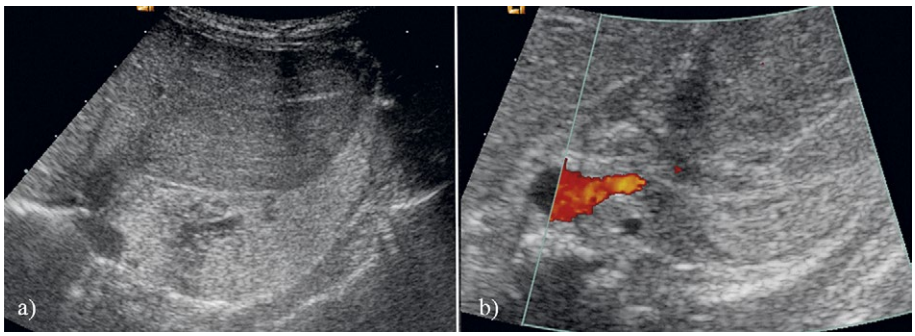

Fig 8. Sequestration; lung ultrasound can demonstrate a non-aerated mass (consolidation) in the left lower lobe adjacent to the diaphragm (a) and the artery with the systemic supply on power Doppler (b).

In the case of an infradiaphragmatic mass, extralobar sequestration is possible and has to be considered as a differential diagnosis. The identification of a systemic artery is helpfully. The LUS finding in chylothorax is a pleural effusion. In congenital diaphragmatic hernia, LUS reveals the presence of abdominal organs in the chest.

3.10. Interstitial lung diseases with pulmonary fibrosis

The authors know no publications in English language available in medical databases concerning LUS in paediatric interstitial lung diseases (ILD). Research on this topic is needed. Currently, we can only extrapolate the knowledge from the studies conducted on adult patients [63]. The most important US signs for ILD are B-lines. However, they are not specific and the origin of this artefact is still debated. The interstitial syndrome may be diffuse bilateral or focal, may have a homogenous or non-homogenous distribution. Furthermore, the alterations of the pleural line, fragmentation, irregularity and thickening, are also found in ILD.

3.11. Cystic fibrosis

Cystic fibrosis (CF) is the most common life-threatening autosomal disorder among Caucasians. CF is characterized by polymorphic clinical appearances from pancreatic insufficiency to bone disease [64]. But, despite the significant clinical variety, it is the lung disease that mainly influences the outcome [65]. The lung impairment is characterised by the formation of bronchiectasis, air trapping, mucous plugging with subsequent atelectasis and consolidation. Lesions will be detected in varying degrees of severity depending on the patient's age and disease progression [66]. CT is the gold standard for diagnosis of structural lung impairment and MRI an emerging tool in CF patients, showed a good correlation between the two methods [67].

There is no consistently described US appearance for air trapping or small bronchiectasis. A study suggested the presence of B lines were typical for small bronchiectasis [68], but it has been demonstrated that B line profile lacks specificity as they are seen in several diseases including interstitial inflammation and fibrosis [69]. It has been stated that a good correlation exists between LUS, expressed by an adapted bronchiolitis score [13] and chest X-ray evaluated by a modified Crispin Norman score, highlighting that, given the variability of the diseases described by B lines, it would be inadequate to make the diagnosis of CF lung only by ultrasound [6]. A small study compared a LUS score (evaluating only the presence of consolidation and B-lines pattern) with the modified Bhalla CT score and showed a correlation between the two methods and some partial correlation with the lung function expressed by FEV1 and FVC [70]. Another study evaluated LUS changes compared to lung function expressed by the lung clearance index in CF children patients, revealing a consistent correlation between structure and function but only in patients with severe lung deterioration [71]. No correlation was found in patients with mild disease, because of the lack of US artefacts specific for early CF lung disease. Although US was not demonstrated to be reliable in the detection of early structural changes such as tubular bronchiectasis or emphysema, a study described pseudo-consolidation for saccular bronchiectasis, using a low frequency 3-5 MHz convex transducer [68].

The image of the bronchiectasis depends on the transducer used. The convex transducer 3-5 MHz shows coalescent B lines, without bronchogram corresponding on CT as mucus filled large bronchiectasis; the same lesion seen with the linear 7-12 MHz, in a 15-year-old patient with cystic fibrosis reveals only B lines, because of low penetrance.

Also, LUS is promising in children with CF but CT remains superior for the sensitive description of the lung disease. It has been suggested that US might be use for rapid and safe evaluation in exacerbations. Lesions were "age-dependent", with more severe lesions in older patients, but the small, tubular bronchiectasis were not

detected by LUS, showing a low LUS/CT correlation (r=0.14, p <0.9) [72].

Another study evaluated the diagnostic value of LUS in patients with rare cystic lung diseases such as lymphangioleiomyomatosis, pulmonary Langerhans cell histiocytosis and Birt-Hogg-Dubé syndrome and found limited value as LUS was normal in these patients, with severe cystic lung disease seen on CT [73], establishing that cystic lesions and bronchiectasis are not reliably diagnosed using LUS.

Conclusion

In the late 80ies and early 1990s, LUS was introduced mainly to determine pleural effusion. Lung ultrasound has been slowly extended to more general paediatric applications including all forms of pneumonia, pulmonary embolism and typical chest and lung diseases of childhood. Herewith, current applications in paediatric lung patients have been summarized to further distribute the knowledge of US in the world of paediatric patients [74].

Conflict of interest: none

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