Recommendations for Operation, Measurement, Reporting and Application of Pediatric Lung Ultrasound: Chinese Experts Consensus

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Introduction

Based on changes in the ratio of air to water or lung tissue, pathological mechanisms, and acoustic phenomena, lung ultrasound is no longer limited to the diagnosis of pleural effusions. Lung ultrasound has been used for the diagnosis of lung parenchymal diseases in critical care settings and surgeries to reduce unnecessary radiation exposures.

It is necessary to further understand and standardize operational methods to improve the diagnostic ability of pediatric lung diseases. This article focuses on the operation, measurement, and reporting of lung ultrasound, with the purpose of promoting the clinical application of pediatric lung ultrasound.

Access to Clinical Evidence

Publications from January 2000 to January 2020 were searched on PubMed, MEDLINE, CBMDisc (Chinese Biomedical Literature Database), and CNKI (China Knowledge Network Full-text Database). A combination of the following medical keywords (MeSH) was used

for searching: “ultrasonography”, “chest sonography”, “lung ultrasound”, “diagnostic imaging”, “respiratory tract diseases”, “Pneumonia”, “Pulmonary embolism”, “pneumothorax”, “cardiogenic pulmonary edema”, “non-cardiogenic pulmonary edema”, “lung tumor”, “atelectasis”, “interstitial lung disease”, “pulmonary fibrosis”, “pleural effusion”, etc.

We validated the references and selected the articles based on the relevance and level of evidence. The selected references included meta-analysis, case-control studies, randomized-control studies, cohort studies, guidelines, and expert consensus. Finally, 203 publications were included in the process of creating the recommendations.

Evidence Level and Recommendation

Lung ultrasound has been used in neonates and children for more than 10 years [1]. Few articles have published in regard to expert consensus on lung ultrasound in neonates and neocoronavirus-19 lung infections [2, 3]. Based on the practical experience

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of every medical center and the discussion in several national academic conferences, the Children's Ultrasound Group of the Ultrasound Professional Committee of the China Medical Education Association was established

in 2018 to discuss and formulate this expert consensus. This consensus document will continue to be improved according to feedback in the future. The recommendation level of this consensus is shown in Table 1 [4,5].

Table 1 Recommended level

Recommendation strength	Quality of evidence for recommendation
A: Strong recommendation for the statement	I : Data come from many randomized trials with clinical outcomes and/or meta-analyses
B: Moderate recommendation for the statement	II : Data come from individual randomized trials and/or large non-randomized trials
C: Optional recommendation for the statement	III: Expert opinion and/or data from small studies, retrospective studies, or case reports

Indications

Lung ultrasound has high accuracy in the diagnosis of lung consolidation, lung pleural effusion, and pneumothorax. Therefore, it is useful for diagnosing severe trauma, respiratory failure, and shock for pediatric patients [4,6]. The changes in the ratio of air to fluid in the lung glandular lobule result in different images of pulmonary interstitial lesions, pulmonary edema, and lung consolidation [7]. Lung ultrasound can be used for the screening of pneumonia, differential diagnosis of cyanosis, hypotension, and severe infectious diseases as well [8]. In open surgery, lung ultrasound can also be utilized in patients with unstable cardiopulmonary conditions or suspected pneumothorax [9,10]. For neoplastic diseases, lung ultrasound can identify nodules and metastatic lesions in the pleural cavity and sub-pleural areas [11]. In interventional surgery, guiding the biopsy of sub-pleural lung parenchyma or lung nodules in real time is another application of lung ultrasound [12]. Since there are no contraindications for pediatric lung ultrasound, it could be safely carried out in pediatric patient population [13,14].

Equipment and Methods

Instrument

Color Doppler ultrasound for lung exam is best performed with linear transducers for chest wall, convex or micro-convex transducers for subcostal scanning, and phased-array transducers for parasternal and suprasternal scanning. With enough penetration, the frequency should be set as high as possible. Convex transducer (3–5 MHz) is used for fat or deep lesions, and higher frequency linear transducer (7.5–12 MHz) is used for pleural or sub-pleural lesions. It is better to use linear transducer (> 7 MHz) in neonate. Convex or phased-array transducer (3–7.5 MHz) is used for mediastina scanning.

Regulation

Clinicians should aware that ultrasound wave can create mechanical forces causing pressure changes and release of various reactive molecules, and gas-containing organs (e.g., lung) are susceptible to the effects of acoustic cavitation. Following the principle of as low as reasonably achievable (ALARA), the potential benefits and risks should be considered in each examination. Lowering the output power to $MI < 0.6$, increasing the gain, adjusting the TCG curve, and using harmonics, compound imaging, and logiqview to display all lesions could help reduce the risk of mechanical tissue injury from lung ultrasound. Moreover, the imaging depth should be at least 3 to 4 times the distance between the A-lines, and the color Doppler should be adjusted to a scale of 5–20 cm/s.

Imaging mode

Pediatric lung ultrasound imaging modes include two-dimensional imaging (level of evidence A), color Doppler (level of evidence A), contrast enhance ultrasound [15–17] (level of evidence B), and elastography [18,19] (level of evidence C). Color Doppler ultrasound is mainly used to identify the presence or lack of blood flow and arteriovenous fistula, while contrast enhanced ultrasound is used to identify tumor, abscess, contusion, and laceration.

Qualifications and Skills

Training

The operator should understand the basic knowledge of the anatomy and physiology of the lungs, thoracic cavity, and mediastinum. After the mandatory training, the operator should be able to accurately identify basic normal and abnormal sonograms, correctly apply ultrasound-guided thoracentesis [20–22], and perform at least 30 cases of lung and pleural effusion under the guidance of professional physicians, including at least 20 positive cases.

Operation method

Position Supine and lateral positions are applied in newborns and infants. Children are examined in a sitting position, and severely ill children were placed in supine

or semi-recumbent positions (Fig. 1) (Recommended level A). Ultrasound examination should be conducted in a quiet environment.

Figure 1 Position and body surface partition. (A) Supine position; (B) Semi-recumbent position; (C ~ D) Sitting position. a, anterior axillary line; b, posterior axillary line; c, the connecting line between the two nipples. Named by L/R-A/L/P-U/L method: the chest surface is divided into left (L) and right (R), which are divided into anterior (A), lateral (L) and posterior (P) zones by four lines, and the above three parts are divided into upper (U) and lower (L) parts by horizontal line connecting nipples.

The body surface partitions of lung scan are shown in Figure 1 (Recommended level A). The areas need to be examined including trans-thoracic wall, subcostal, parasternal, and suprasternal. Subcostal scan shows the image of the lung diaphragmatic surface, and scan through the superior sternal fossa and parasternal scan can show an image of the mediastinal surface. Most critically ill children require a comprehensive evaluation of cardiac and lung ultrasound. Transthoracic scans use the longitudinal section to move the probe horizontally and the intercostal transverse section to move up and down and swing the probe. The operation method is shown in Figure 2 (Recommended level A).

Basic image identification

A-Line (Recommended level A): It is a complete

reflection (repetition artifacts) formed by a highly reflective surface. It is found in normal lungs, emphysema, pneumothorax, and intestinal gas (e.g., intestinal canal in diaphragmatic hernia) (Fig. 3).

B-Line (Recommended level A): It is a ring-down artifact generated by mixing of small-diameter gas with surrounding water and tissues. The exudation and hyperplasia of alveoli and interstitial tissue mixes with gas to form the B-line (Fig. 4), which is also happen in the mixtures of intestinal gas and fecal fluid. B-Line is a pathological phenomenon caused by the increase in the proportion of fluid or exudations from tissue in the lungs (“wet changes” of the lungs). B-Line occurs in diseases such as pneumonia, cardiogenic and non-cardiogenic pulmonary edema, respiratory distress syndrome, lung trauma, and pulmonary interstitial hyperplasia, etc.

Figure 2 Schematic diagram of the body surface partition of the lung scan. (A) Transthoracic lung surface scan (blue), subcostal scan (green), parasternal precordial area scan (red), and trans sternal scan (yellow); (B) Transthoracic scan technique: The probe is vertical to the chest wall surface, moving and swinging the probe, the longitudinal section moves laterally (orange arrow), and the transverse section moves up and down (blue arrow).

Figure 3 A-lines. (A ~ B) Normal pulmonary sonogram; (C ~ D) pneumothorax. (A) Transthoracic transverse section, the arrow is shown as A-line; (B) Transthoracic longitudinal section, the arrow is shown as A-line; (C) A-line of gas formation in pleural cavity (arrow); (D) Sporadic B line (arrow) indicates that A-line originates from the lung.

Pulmonary consolidation (Recommended level A): Pulmonary consolidation is a non-gas expansion of alveoli, occurs in inflammation, atelectasis, pulmonary

embolism, tumors and congenital malformations. The manifestation of diffuse and widely distributed lung consolidation does not have specific pathological

significance (Fig. 5), because many diseases can present the similar lung consolidation image. Abnormal "pleural line" is not formed by pleural tissue but a small

consolidation caused by increased fluid in the sub-pleural interstitial lung or alveoli.

Figure 4 B-lines. (A ~ D) B-line scan of Transthoracic lung surface; (E ~ H) B-line scan of subcostal; (I ~ L) B-line scan of parasternal precordial area. Scattered B-lines, sparse B-lines, dense B-lines and fused B-lines are displayed respectively.

Lung abscess (Recommended level A): It is a local anechoic or hypoechoic of lung tissue due to infection

and necrosis, and color Doppler flow image shows no blood flow within mass [23] (Fig. 6).

Figure 5 Lung consolidation sonograms. (A) Small fragment-like consolidation scattered under the pleural line (long arrow); (B ~ C) Pulmonary consolidation was accompanied by bronchial inflation echo (long arrow) and peripheral pulmonary B-line echo (short arrow); (D) Local atelectasis with pleural effusion; (E) Pulmonary consolidation after ECMO; (F) Pulmonary embolism showed wedge-shaped consolidation; (G) Necrotizing granuloma of lung; (H) Consolidation of lung with fluid bronchogram (arrow); (I) Pleuropulmonary blastoma.

Figure 6 Pulmonary abscess sonograms. (A) Consolidated lung tissue showed a liquid dark area echo; (B) There was no blood flow signal in CDFI.

Pneumothorax (Recommended level A): Pneumothorax presents with a fixed A-line does not move with the breath, and there is no B-line displays. A small amount of pneumothorax can be found in the "lung point" between

the fixed A-lines when the moving with the breath [4]. Traumatic pneumothorax is usually combined with pleural effusion (hemorrhage) and lung contusion.

Pulmonary infarction (Recommended level B): The sonogram shows pulmonary consolidation without blood flow. Contrast enhanced ultrasound shows no enhancement [24].

Pleural effusion (Recommended level A): Ultrasound images of pleural effusion have various manifestations due to different causes.

Interventional ultrasound (Recommended level A): Ultrasound-guided thoracentesis biopsy, aspiration, or catheter drainage increase the accuracy and safety of clinical procedures in pediatric [12].

Measurement

Quantification of pleural effusion (Recommended

level A): The amount of pleural effusion in pediatrics is semi-quantitative. While the patients lie in the supine position, the range of fluid dark areas will be evaluated at intercostal level in the anterior axillary line, mid-axillary line, and posterior axillary line or subscapular line. Healthcare providers should measure the maximum depth from the pleural wall layer to the visceral layer perpendicular and further to the chest wall.

Line semi-quantitative counting (Recommended level C): If necessary, use B-line counting method to evaluate the degree of increase in lung interstitial or lung lobular water [25-32].

Lung consolidation (Recommended level A): It is recommended to measure the location, size, air and fluid bronchograms, and color Doppler blood flow.

Application Recommendations

Pleural effusion (Level A I)

Due to the different composition of the effusion, such as transudate, pus, blood, and chyle, etc., pleural effusion usually presents with varies images including the thickening of the pleura, the presence or absence of multiple separations, and wrapped effusions [33,34]. Ultrasound examination is used to assess the severity, evaluate the dynamic changes of the lesion, and guide the puncture [1].

Severe pneumonia (Level A I)

Pneumonia is an inflammatory disease of the terminal airway, alveoli, and the surrounding pulmonary interstitial tissue. Because of different etiology and pathological type, the severity and complications of pneumonia varies, which are reflected by different imaging manifestations. Common ultrasound manifestations are A-lines (survival area), B-lines, and lung consolidations. Color Doppler usually shows localized rich blood flow within the consolidation [35-37]. Ultrasound examination focuses on identifying the size, range and symmetry of the B-line, and consolidation on both lungs. Mild pneumonia may have no abnormal ultrasound findings, or only the B-lines show up under the pleura. Severe pneumonia patients have obvious lung consolidation and may present with pulmonary complications, such as pleurisy, pleural effusion, empyema, bronchopleural fistula, and lung abscess, etc. (Fig. 7), and those are the main indications for performing ultrasound examination in children with pneumonia. Clinicians should also pay particular attention to the extra-pulmonary complications of pediatric severe pneumonia, e.g., myocarditis, pericardial effusion, kidney injury, abdominal compartment syndrome [38]. In addition, lung ultrasound is helpful to show the dynamic changes of B-lines and consolidations during the recovery period [39].

Figure 7 Pneumonia sonograms. (A) Large patchy pulmonary consolidation with massive pleural effusion; (B) The pleura is thickened, and there are effusions in the pleural cavity, with dense point echoes in the effusions; (C) Bronchial pleural fistula, the arrow shows the gas at the fistula; (D) Pulmonary abscess.

Atelectasis (Level A I)

There are two types of atelectasis: compressive atelectasis and obstructive atelectasis. Compressive atelectasis is caused by extra-pulmonary compression, which is more commonly seen in pediatric patients with pleural effusions. The typical ultrasound presentation is lung consolidation connecting to the hilum combined with removable bronchial gas. Obstructive atelectasis is caused by bronchial obstruction (e.g., inflammation, hematoma, tumor, and foreign body, etc.), and images will show that the lungs are evenly parenchymal. The

bronchus is full of gas or fluids but does not move, and rarely shows obstructive pathological masses (Fig. 8) [40]. Color Doppler often shows branched blood flow signals in local lung tissue [4].

Cardiogenic pulmonary edema (Level A I)

Pulmonary edema is caused by various causes of abnormal fluid quickly extravasates from capillaries and accumulates in the alveoli and/or interstitial lung, forming alveolar pulmonary edema and/or interstitial pulmonary edema, which could further cause severe

respiratory failure. Based on different etiology, there are two types of pulmonary edema: cardiogenic pulmonary edema and non-cardiogenic pulmonary edema. Cardiac pulmonary edema is characterized by bilateral, symmetric, gravity-dependent distribution of B-lines [27], and the distribution is related to the severity of the disease.

Figure 8 Atelectasis sonograms. (A) Air bronchogram (arrow); (B) Fluid bronchogram (arrow).

Acute respiratory distress syndrome (Level B I)

Acute respiratory distress syndrome (ARDS) is a diffuse injury of pulmonary capillaries resulting

in increased capillary permeability and decreased lung compliance, followed by alveolar collapse, and ventilation-perfusion imbalance. The basic pathology is diffuse alveolar exudation and lung consolidation.

Ultrasound findings of ARDS often consist of small or massive consolidations under the pleura of the anterior chest wall, thickened hyperechoic area on the lung surface, weakened or disappeared lung sliding signs, and unevenly distributed B-lines [4,41]. For those who improves after treatment, the diffused B-lines will change to localized B-lines, and the lungs will return to the A-lines eventually.

Pulmonary trauma (Level A I)

Pediatric lung injury is most commonly from blunt trauma, which usually resulting in hemothorax, pneumothorax, lung contusion, lung laceration, pericardial effusion, and rupture of the heart [42]. Lung contusion can lead to potential ARDS. Lung ultrasound can quickly assess pleural effusion, pneumothorax and B-line distribution, and lung consolidation (Fig. 9). Since chest trauma is usually combined with abdominal injury, using rapid ultrasound is helpful in emergency settings to guide further treatment [43, 44].

Figure 9 Pulmonary contusion and laceration sonograms. (A) Fusion B-line; (B ~ C) Patchy consolidation; (D) Massive consolidation with B-line of peripheral lung tissue; (E) Pulmonary consolidation with massive pleural effusion; (F) There was blood flow signal in CDFI.

Congenital pulmonary airway malformation (Level C III)

The pathological mechanism of congenital pulmonary airway malformation is the occlusion of bronchial

lumen by hamartomatous tissue or stenosis during embryonic development. There are 5 main types of congenital pulmonary airway malformation: type 0 (alveolar dysplasia or underdevelopment), type 1 (large

cyst), type 2 (medium cyst), type 3 (mini cyst)), type 4 (peripheral alveolar cyst). All cysts are not connected to the bronchus [45]. Types 1, 2, and 4 are cystic with ultrasound showing cystic lesions in different sizes. Type 1 can cause spontaneous pneumothorax. Type 3 is similar to substantive, with ultrasound showing a homogeneous iso-hyperechoic mass [46].

Pulmonary sequestration (Level C III)

Pulmonary sequestration is a non-functioning lung tissue formed by the partial ectopic separation of the lung buds from the bronchial tree during the embryonic development. The lung tissue is not connected to the bronchus, and the arterial supplies come from the thoracic or abdominal aorta. Ultrasound appears as a fusiform or triangular-shaped mass in the pleural cavity with bronchial fluid. Color Doppler shows blood flow signal. Pulse wave Doppler shows high-speed and high-resistance blood flow, suggesting that blood flow originated from the systemic circulation [47]. Affected by the gas in the adjacent lung, it is often difficult to visualize the origin of the artery.

Pleuropulmonary blastoma (Level C III)

Pleuropulmonary blastoma usually occurs in infants. There are three types: purely cystic, cystic and solid, and purely solid [48], presenting monocystic or thinly divided polycystic, cystic solid, and solid mass, respectively [45,49,50]. When the tumor involves the pleura, pleural thickening and pleural effusion will be shown. Besides, tumor compression leads to atelectasis, and big tumors can further cause mediastinal displacement.

Extra-corporeal membrane oxygenation (Level A I)

Extra-corporeal membrane oxygenation (ECMO) can be used for cardiopulmonary support in patients with severe heart failure or respiratory failure. Patients often need a comprehensive ultrasound evaluation of the heart and lungs. The contents of lung ultrasound for patients with ECMO including the assessment of pulmonary edema, pulmonary consolidation, atelectasis, pleural effusion, pneumothorax, hemothorax, etc., and their outcomes [51,52].

Records and Reports

The pediatric lung ultrasound reports should describe normal and abnormal imaging findings (location, size, range), e.g., the presence and degree of A-lines and B-lines, consolidation location, size, lung sliding, and changes in pleural cavity and mediastinum and its Doppler results. All results and their interpretations should be recorded in the PACS files.

Limitation

In lung ultrasound, the B-lines from the lung surface are caused by changes in the sub-pleural pulmonary interstitial tissue and alveolar fluid. When the deep lung tissue lesion is covered by the surface inflatable lung, the sub-pleural pulmonary interstitial tissue cannot be displayed using the ultrasound image [53]. Therefore, lung ultrasound is more suitable for the follow-up of known lung diseases, which can appropriately reduce the radiation exposure of children under X-ray.

In summary, lung ultrasound is useful in the preliminary diagnostic work-up of pediatric patients with suspected lung diseases before more invasive tests are performed. Furthermore, its most important application is the follow-up of patients with a previous diagnosis of cardiopulmonary lesions to assess the extent of disease involvement and identify early complications.

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Conflicts of Interest

The authors declare no conflict of interests.

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