Lung ultrasound at the department of anesthesiology and intensive care for pediatric cardiac surgery: a narrative review

A.I. Gritsan, A.A. Pfeifer, S.A. Gurchenko, K.A. Ilinykh, V.A. Sakovich

1 Voino-Yasenetsky Krasnoyarsk State Medical University, Krasnoyarsk, Russia
2 Federal Center for Cardiovascular Surgery, Krasnoyarsk, Russia

Abstract

INTRODUCTION: Pediatric cardiac surgery is associated with a high risk of developing acute respiratory failure in the early postoperative period. An anesthesia and intensive care specialist has to make effective and quick decisions of the intensive care tactics considering the severity of the children’s condition, limited capacity of transporting and radiation exposure. As a result, there is the demand for a simple, quick, safe and highly sensitive method available to the anesthesia and intensive care specialist at the bedside, which may be met through implementation of routine lung ultrasound.

OBJECTIVE: To combine, organize and analyze the data on application of lung ultrasound as a bedside diagnostic method in pediatric cardiac surgery.

MATERIALS AND METHODS: Two independent researchers conducted a systematic review of articles published within the period from 2013 to 2023 in English (PubMed, Google Scholar) and Russian (eLibrary, Google Scholar) databases according to the PRISMA protocols. The search was based on the queries: “lung ultrasound”, “children”, “cardiac surgery”, “respiratory failure” in both English and Russian. The overall search result was 528 articles in English with 494 excluded from search after title and abstract reading. A total of 34 articles were considered for inclusion with 20 falling under at least one exclusion criterion. The final selection for detailed analysis was 14 articles. In Russian, a total of 897 articles were found, all of which were considered inappropriate for a systematic review.

RESULTS: A total of 14 articles were studied to reveal information on the role of lung ultrasound in pediatric cardiac surgery as a method for diagnosis and assessment of interstitial syndrome, atelectasis, pneumothorax, diaphragmatic function.

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and complex combined lung diseases. The utility of perioperative lung ultrasound and the effect of recruitment maneuver under ultrasound guidance as well as ultrasound predictors of successful tracheal extubation were assessed in children after cardiac surgery. CONCLUSIONS: The literature analysis has revealed that this bedside diagnostic method makes it possible to diagnose pulmonary edema, atelectasis, pneumothorax, to assess the diaphragmatic function, to perform visually guided recruitment maneuver as well as to predict successful tracheal extubation in pediatric cardiac surgery.

KEYWORDS: lung ultrasound, ultrasound, congenital heart defects, children, cardiac surgery, systematic review

Introduction

There is increasing evidence that ultrasound imaging contributes to the timely detection of pulmonary pathology in intensive care departments and is highly sensitive for the verification of many pathological processes including alveolar consolidations, interstitial syndrome [1, 2], hydrothorax [3, 4] and pneumothorax [5–8].

Year 2012 was an important stage in the adoption and improvement of lung ultrasound. It was this year that the International Liaison Committee on Lung Ultrasound, which included more than 30 leading international experts,
compiled evidence-based guidelines demonstrating this method’s greater sensitivity in the diagnosis of pneumothorax, pulmonary edema, foci of pulmonary consolidation and effusion in the pleural cavity in comparison with chest X-ray [8].

The advantages of bedside ultrasound examination of the lungs are the speed of diagnosis (may be performed within 2–3 minutes), absence of ionizing load and of the need to transport the patient to the diagnostic room, the possibility of multiple scans with dynamics assess and the response to etiotropic treatment, as well as conducting all studies using one universal linear sensor.

The method is based on several basic principles: 1) most pathological processes occurring in the lungs are associated with changes in the morphology of the pleural line and the lung parenchyma; 2) all causes of acute respiratory failure have their own characteristic ultrasound sign, as well as a number of indirect signs for more accurate differentiation of the type of pathological process from the ultrasound syndrome [7].

There is a large amount of data on the use of lung ultrasound in different areas of medicine, including pediatric surgery. However, there is very little data on the potential of the method and the features of its use in pediatric cardiac surgery.

Objective

To combine and systemically analyze the data on application of lung ultrasound for bedside diagnosis and its specifics in pediatric cardiac surgery.

Materials and methods

Data sources and search strategies

This systematic review has been performed in compliance with the PRISMA protocols [9].

Two independent researchers conducted a search for articles in English published in PubMed and Google Scholar and in Russian published in eLibrary within the period from the 1st of September 2013 to the 1st of September 2023. Then, the compliance of the full text with the inclusion criteria was assessed. The search was performed based on the queries “lung ultrasound”, “children”, “cardiac surgery”, “respiratory failure” in both English and Russian.

Study selection criteria

The assessment of the works’ compliance with the inclusion criteria was performed in three stages: based on the title, based on the abstract and based on the full text of the article.

Inclusion criteria:

- Original research articles, clinical cases.
- Studies including assessment of the lung ultrasound method.
- Only pediatric cardiac surgery patients.
- Full-text articles published no earlier than in 2013.

Exclusion criteria:

- Review articles, abstracts only, incomplete texts, talk abstracts.
- Studies that did not include lung ultrasound.
- Presence of adult patients in the sample.

Results

Selection of studies

Upon search in the English language, a total of 443 articles were found in Google Scholar and 85 articles were found in PubMed. The overall result was 528 articles in English with 494 excluded from search after title and abstract reading. A total of 34 articles were considered for inclusion with 20 falling under at least one exclusion criterion. The final selection for detailed analysis comprised 14 articles (see Table 1). A total of 14 articles were included into this systematic review [2, 6, 10–21].

In Russian, 83 potentially relevant studies were found in the eLibrary database, among which there was no single article compliant with the inclusion criteria. In this connection, additional search was conducted in Russian in the Google Scholar reference base using the keywords meaning “ultrasound”, “lungs”, “children” and “cardiac surgery” respectively. The search provided 814 additional articles, none of which complied with the inclusion criteria. In total, 897 articles were found, all of which were considered inappropriate for a systematic review (see Figure 1).

Lung ultrasound and interstitial syndrome

Three articles were devoted to ultrasound examination of interstitial syndrome in children with congenital heart defects (CHD).

In a study by Kaskinen A.K. et al., the feasibility of using six-point lung ultrasound to assess extravascular lung water in children after cardiac surgery was studied.

61 children (aged from 3 days to 7.4 years) were included in the study. The authors assessed the correlation of the number of B-lines with the volume of extravascular lung water, with the data of frontal chest X-ray, with static compliance, with postoperative fluid balance, with comprehensive assessment of the complexity of CHD correction according to the Aristotle score, with the duration of cardiopulmonary bypass (CPB), as well as with short-term clinical outcome according to the following criteria: duration of mechanical ventilation, length of stay in the intensive care unit, delayed sternal closure.
Table 1. Analysis results

<table>
<thead>
<tr>
<th>Sources</th>
<th>Article type</th>
<th>Aim of study</th>
<th>Materials and methods</th>
<th>Results</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Song I.K. et al., 2018</td>
<td>Randomized controlled study</td>
<td>To assess the utility of perioperative lung ultrasound examination and the effect of ultrasound-guided recruitment maneuver in pediatric cardiac surgery</td>
<td>Children (5 yr old or younger) undergoing cardiac surgery were allocated into a control (n = 61) or intervention (n = 61) group. The control group received only lung ultrasound examinations at the end of surgery and 6 to 12 hours after surgery. The intervention group received lung ultrasound examinations and an ultrasound-guided recruitment maneuver depending on ultrasound findings after inducing anesthesia, at the end of surgery, and 6 to 12 hours after surgery.</td>
<td>The incidences of intraoperative desaturation and postoperative pulmonary complications were similar between the groups. Lung ultrasound scores were better in the intervention group than in the control group. Duration of mechanical ventilation was longer in the control group than in the intervention group.</td>
<td>The use of lung ultrasound for optimization of alveolar recruitment maneuver improves clinical outcomes in children undergoing cardiac surgery.</td>
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<tr>
<td>Hammadah H.K. et al., 2017</td>
<td>Retrospective cohort study</td>
<td>To evaluate the role of bedside ultrasound performed by an intensivist to diagnose diaphragmatic dysfunction and the need for plication after pediatric cardiac surgery</td>
<td>A total of 32 children participated in the study out of the 344 operated throughout the research period. Mean age and body weight amounted to 9.7 ± 3.2 months and 5.3 ± 0.7 kg, respectively. Ultrasound examination was performed on children with suspected diaphragmatic dysfunction in the postoperative period.</td>
<td>Ultrasound studies confirmed diaphragmatic dysfunction in 17/32 (53%) patients. The incidence rate of diaphragmatic dysfunction was 4.9% in relation to the whole population. Diaphragmatic plication was needed in 9/17 cases (53%).</td>
<td>Ultrasound examination of the diaphragm in intensive care may serve as a basis for further therapeutic and surgical treatment.</td>
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<tr>
<td>Gil-Juanmi-quel L. et al., 2017</td>
<td>Prospective observational study</td>
<td>To assess the utility of bedside ultrasound combining B- and M-mode in the diagnosis of abnormal diaphragmatic movement (ADM) in children after heart surgery</td>
<td>A total of 47 children (aged 0–16 years) with suspected abnormal diaphragmatic motion after cardiac or thoracic surgery. The patients with suspected ADM underwent double-blind examinations: chest ultrasound, radioscopy and electromyography.</td>
<td>Ultrasound examination performed by an intensive care specialist has a high level of compliance with the results of electromyography thus being a safe and accessible tool for diagnosis of ADM in pediatric cardiac surgery. Apart from that, ultrasound was found to be more effective than radioscopy.</td>
<td>Chest ultrasound in combination of B- and M-mode is a valid tool for the diagnosis of ADM. The method has higher sensitivity and specificity in comparison to electromyography and radioscopy of the chest for patients with clinically suspected ADM.</td>
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<td>Results</td>
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<td>Zhang Y.B. et al., 2013</td>
<td>Retrospective</td>
<td>The authors did not state the aim</td>
<td>The study was conducted from April 2001 to December 2010. Postoperative diaphragmatic</td>
<td>Confirmation of diaphragmatic paralysis was achieved by ultrasound in 23/47 (48.9 %)</td>
<td>Diaphragmatic paralysis caused by phrenic nerve injury during surgical intervention for CHD is an important risk factor for respiratory failure during the postoperative period</td>
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<td></td>
<td>observational study</td>
<td></td>
<td>paralysis was diagnosed in 47/10 200 (0.46 %) children with congenital heart disease (CHD) after cardiac surgery. Confirmation of diaphragmatic paralysis was achieved by ultrasound and radioscopy</td>
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<td>Nozaki Y. et al., 2018</td>
<td>Clinical case</td>
<td>The authors did not state the aim</td>
<td>A male neonate (body weight 4065 g, 40 weeks of gestation) with coarctation of the aorta and ventricular septal defect, after plastic surgery of the aortic arch using a modified end-to-end anastomosis in combination with subclavian flap aortoplasty and narrowing of the pulmonary artery trunk. The percentage change in diaphragm thickness was calculated as ([End-inspiratory thickness − End-expiratory thickness]/[End-expiratory thickness]) × 100, with diaphragmatic dysfunction detected in patients with a value of &lt; 17 %</td>
<td>For three breathing cycles, mean values of change in the diaphragm thickness fraction amounted to 31 % on the right and 0.2 % on the left, which attested to the paralysis of the left dome of the diaphragm</td>
<td>The diaphragm thickness fraction can be evaluated in children during mechanical ventilation, while echographic diagnosis of diaphragmatic dysfunction may be supplemented by the excursion method</td>
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<tr>
<td>Polito A. et al., 2016</td>
<td>Clinical case</td>
<td>The authors did not state the aim</td>
<td>A 12-day-old newborn affected by coarctation of the aorta and intraventricular defect who underwent coarctectomy and pulmonary artery banding. On post-operative day 7, the patient suffered from clinical death due to tension pneumothorax. Emergency ultrasound was performed during cardiopulmonary resuscitation</td>
<td>In patients with hemodynamic shock or cardiac arrest, the complete absence of pleural line movement — pulmonary pulse, pleural slide, associated with the absence of B-lines — makes it possible to diagnose pneumothorax</td>
<td>The authors suggest including point-of-care ultrasound into the pediatric advanced life support algorithm during each pause to assess cardiac function, if necessary. In newborns and children, ultrasound may effectively assess the pleural line and the condition of the lungs</td>
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<td>Kaskinen A.K. et al., 2017</td>
<td>Prospective observational study</td>
<td>To evaluate the efficacy of ultrasound in assessment of extravascular lung water after surgery for CHD</td>
<td>A total of 61 children (age range 3 days to 7.4 years) undergoing congenital cardiac surgery. The authors compared postoperative extravascular water (B-line) scores from lung ultrasounds with postoperative chest X-ray, static compliance, duration of mechanical ventilation and the term of stay in the intensive care unit</td>
<td>B-lines according to ultrasound and signs of pulmonary edema on the radiograph correlate 1-6 hours after surgery as well as on the first and fourth days after surgery. B-lines on the ultrasonogram and signs of pulmonary edema according to chest X-ray showed no correlation with pulmonary compliance</td>
<td>Lung ultrasound, when assessing extravascular lung water in the postoperative period, was a reliable predictor of duration of mechanical ventilation and intensive care unit stay and had less interobserver variability than chest X-ray. Lung ultrasound may complement radiography in the assessment of pulmonary edema after surgery for CHD</td>
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<td>Li M. et al., 2022</td>
<td>Prospective observational study</td>
<td>To identify ultrasound predictors of successful extubation in children who underwent cardiac surgery</td>
<td>A total of 83 children with CHD aged 3 months to 6 years who underwent cardiac surgery (if they were intubated for &gt; 6 hours and underwent a trial of spontaneous breathing through the intubation tube). Transthoracic echocardiography and lung ultrasound were performed immediately before spontaneous breathing trials</td>
<td>In the multivariate regression analysis, a lung ultrasound score ≥ 12 and ejection fraction ≥ 40 % immediately before spontaneous breathing trials were the only independent predictors of successful extubation</td>
<td>The combination of lung ultrasound and transthoracic echocardiography immediately before the spontaneous breathing trial effectively predicts extubation outcomes in children after cardiac surgery</td>
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<td>Avneet S. et al., 2020</td>
<td>Prospective observational study</td>
<td>To determine, whether ultrasound measurement of EVLW and diaphragm function may predict weaning failure defined as reintubation within 48 hours of endotracheal extubation</td>
<td>Fifty patients aged (1 month to 18 years) undergoing congenital cardiac surgeries were enrolled in the study. The ultrasound measurement of B-line of lung, diaphragm excursion amplitude and diaphragm thickening fraction were done preoperatively, on pressure support ventilation (PSV), during weaning from mechanical ventilation and 4 hours after extubation. There were 2 groups: group 1 with unsuccessful weaning from mechanical ventilation, group 2 with successful tracheal extubation</td>
<td>7 out of 50 patients had weaning failure. The patients with weaning failure (group 1, n = 7) were younger, with median age of 1 year (0.25–7) compared to those who tolerated weaning (group 2, n = 43), median age of 3 years. The B-line score in group 1 increased from a preoperative score of 0 to post-extubation period score of 2, the score being significantly higher than the patients of group 2. The left diaphragm thickening fraction of &lt; 17.15 % predicted weaning failure with a sensitivity of 85 % and a specificity of 51.4 %</td>
<td>Lung ultrasound cannot predict weaning failure</td>
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<table>
<thead>
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<tbody>
<tr>
<td>Wu L. et al., 2019</td>
<td>Randomized controlled prospective study</td>
<td>To determine the most indicative area of the lungs for assessing lung atelectasis in children with CHD under general anesthesia, as well as the effect of pressure-controlled ventilation with positive end-expiratory pressure (PEEP) on lung aeration</td>
<td>40 children between 3 months and 3 years old, scheduled for CHD surgery under general anesthesia. The patients were randomly allocated to either the 5 cm H₂O positive end-expiratory pressure group or the control group without PEEP. Preoperative lung ultrasound was performed twice in each patient-after 1 and 15 minutes of mechanical ventilation. Atelectatic areas and B-lines were compared between two examinations</td>
<td>The incidence of atelectasis was much higher in the inferoposterior regions of the lungs than in the anterior and anterolateral regions. The median of lung ultrasound parameters was lower in the PEEP group than in the control group after treatment</td>
<td>Lung ultrasound in inferoposterior lung regions may be more likely to reflect changes in atelectasis and save examination time. Positive end-expiratory pressure may be useful in lung reaeration and can reduce, but not eliminate, atelectasis in children with congenital heart disease</td>
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<td>Biasucci D. et al., 2014</td>
<td>Clinical case</td>
<td>To report a case of using lung ultrasound for clinical monitoring of complex and severe lung disease during the treatment of a child with CHD</td>
<td>A 1-year-old male with hypoplastic left heart syndrome underwent bidirectional cavopulmonary anastomosis by Glenn and systemic left pulmonary artery shunt. After surgery, he developed a severe acute respiratory distress syndrome that required extracorporeal membrane oxygenation treatment. Lung ultrasound was performed daily to monitor the disease’s progression and response to treatment during lung rest</td>
<td>In the process of treatment, B-lines were decreasing and A-lines were becoming visible; therefore, the authors were able to monitor the improving aeration of the injured lung. The ultrasound showed high consistency with traditional imaging</td>
<td>This case makes it possible to suggest that lung ultrasound may be a successful and useful tool for monitoring lung diseases in children with CHD and severe post-operative complex lung injury</td>
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<td>Mohammam A.K. et al., 2019</td>
<td>Randomized prospective study</td>
<td>To evaluate the efficacy of furosemide in attenuating lung injury and edema during surgery for coarctation of the aorta</td>
<td>The study involved 56 children aged 1-18 months. Patients were divided into two groups: control group (Group C) which did not receive furosemide and furosemide group (Group F) at a dose of 1 mg/kg at induction of anesthesia. At induction and at the end of the surgery, dynamic compliance (Cdyn) evaluation</td>
<td>Administering furosemide attenuated the lung injury/edema and other pulmonary complications, Cdyn and increased the PaO/FiO ratio in Group F in comparison with Group C. Lung ultrasound scale values were lower in the F Group compared to the C Group. There was also less mechanical ventilation days in Group F.</td>
<td>The use of furosemide was accompanied by improved lung injury/edema profile as indicated by a much lower drop in Cdyn, better oxygenation, (according to the increased PaO/FiO ratio), a more favorable score on the ultrasound scale with less parenchymal lung affection.</td>
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<th>Aim of study</th>
<th>Materials and methods</th>
<th>Results</th>
<th>Conclusion</th>
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<tr>
<td>Rodríguez-Fanjul J. et al., 2016</td>
<td>Prospective observational study</td>
<td>To explore the pattern of lung ultrasound in newborns with CHD</td>
<td>Lung ultrasound was performed in 51 newborns during the first days of life; the newborns were classified in two groups depending on the predisposition to develop hypervolemia of the pulmonary circulation as evaluated by the abundance of B-lines. The results were compared to the physical examination, chest X-ray, and echocardiography</td>
<td>In both groups there were no differences in abundance of B-lines during the first days of life; however, CHD children with hypervolemia of the pulmonary circulation were observed to have a higher B-lines score after 72 hours with a good correlation with echocardiography findings and with a better sensibility than physical examination and chest X-ray</td>
<td>Lung ultrasound is a reliable tool for the diagnosis of CHD patients with hypervolemia of the pulmonary circulation in comparison to radiography and echocardiography and may be useful to monitor the lungs and optimize the therapy</td>
</tr>
<tr>
<td>Bajracharya S.M. et al., 2020</td>
<td>Prospective observational study</td>
<td>To compare diagnostic performance of lung ultrasound in comparison to chest X-ray to detect pulmonary complication after cardiac surgery in children</td>
<td>A total of 141 children aged less than 14 years were enrolled in the study. Ultrasound was done on the first post-operative day of cardiac surgery and compared to chest X-ray done on the same day to detect pleural effusion, consolidation, atelectasis and pneumothorax</td>
<td>Lung ultrasound had overall sensitivity of 60 % and specificity of 72.4 % for diagnosing consolidation; sensitivity of 90 %, specificity of 82.6 % for diagnosing pleural effusion. For atelectasis diagnosis, ultrasound had sensitivity of 50 % and specificity of 76.9 %. No pneumothorax cases were detected during our study period</td>
<td>Lung ultrasound is an alternative non-invasive technique which is able to diagnose pulmonary complications after cardiac surgery with acceptable diagnostic accuracy with no proven complications</td>
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B-lines were assessed as follows: 1 point: B-lines at < 25 % of the intercostal space, 2 points: 25–50 % of B-lines, 3 points: 50–75 % of B-lines, 4 points: > 75 % of B-lines. Frontal chest radiographs were assessed by an experienced radiologist. The results showed that B-line indicators according to ultrasound and the X-ray picture of the lungs correlated with the duration of CPB and aortic compression, the patient’s age, comprehensive assessment of the complexity of CHD correction according to the Aristotle score as well as with the duration of mechanical ventilation and the length of stay in the intensive care unit.

The authors noted that lung ultrasound has advantages in assessment of extravascular lung water after surgical correction of CHD in children for a number of reasons:

1. Lung ultrasound results are easy to interpret.
2. Ultrasound results have low interobserver variability.
3. Ultrasound may be performed at the patient’s bedside, and the results are immediately available to the doctor.
4. B-lines may appear early and precede radiological signs of the increase in extravascular lung water volume [2].

In a study by Mohammed A.K., et al., which included 56 children aged 1–18 months, lung ultrasound was performed within the framework of analysis of the efficacy of
furosemide before induction of anesthesia in children with surgical resection of coarctation of the aorta. After induction of anesthesia and at the end of the surgery, B-lines were assessed in 12 sections of the lungs and the results were displayed on a scale from 0 to 36. The physician performing the research did not know which group the patient belonged to. When comparing sonographic scores at the beginning and end of surgery, it was found that the score at the end of surgery (LUS 2) was higher than after induction of anesthesia (LUS 1), which was caused by the development of edema and/or consolidation. Additionally, despite the fact that LUS 2 was higher than LUS 1 in both groups, LUS 2 was significantly lower in the furosemide group before induction of anesthesia than in the control group indicating less pronounced development of pulmonary edema and consolidation after the surgical intervention. The results of lung ultrasound were confirmed by chest X-ray upon admission to the intensive care unit [10].

Rodriguez-Fanjul J. et al. performed lung ultrasound on 51 newborns with CHD in the first days of life. All patients were divided into two groups depending on their predisposition to the development of hypervolemia of the pulmonary circulation, assessed by the abundance of B-lines. The results were compared with physical examination, chest X-ray and echocardiography.

Pulmonary edema was established based on the number of B-lines, where the absence of B-lines was considered normal, mild pulmonary edema was characterized by the presence of < 3 B-lines in one intercostal space (this group included children with the pattern of transient tachypnea of the newborn), moderate pulmonary edema was characterized by the presence of 3 to 7 B-lines, while severe edema was characterized by the presence of > 7 B-lines in one intercostal space or confluent B-lines without retained normal areas.

The ultrasound picture of the lungs at birth was abnormal in 86.3 % of the cases; in 50 % of these cases, mild pulmonary edema was diagnosed occurring in the first 48 hours.

The authors found that newborns with CHD with hypervolemic pulmonary circulation had a significant increase in the number of B-lines on lung ultrasound assessment at all analyzed time points before it was detected on radiological examination, on clinical examination or even on echocardiography.

Patients with moderate to severe edema showed no improvement in ultrasound picture over time but rather a progressive deterioration of the findings compared with patients with normal pulmonary blood flow. The authors explain this by the fact that pulmonary vascular resistance is still high at birth, which prevents hypervolemia of the pulmonary circulation, but as resistance decreases in the first days of life, the left-to-right shunt increases, which later leads to clinically significant tachypnea, ARF and developmental delay.

In conclusion, the authors stated that lung ultrasound is a more useful tool for assessing the severity of hypervolemia of the pulmonary circulation in patients with CHD compared with traditional studies such as radiography and echocardiography [11].

Lung ultrasound and atelectasis

One article was devoted to lung ultrasound in atelectasis.

Wu L. et al. conducted a study to determine the most indicative area of the lungs for assessing atelectasis in children with surgical correction of CHD under general anesthesia, as well as to evaluate the effect of pressure-controlled mechanical ventilation with positive end-expiratory pressure (PEEP) on lung aeration.

The study included CHD patients aged between 3 months and 3 years, scheduled for surgery under general anesthesia. A total of 40 children were randomly assigned to a group with mechanical ventilation with PEEP +5 cm H₂O, or to a control group with standard therapy without PEEP. Preoperative lung ultrasound was performed for each child twice: after 1 and 15 minutes of mechanical ventila-
tion. The incidence of atelectasis was 82.5% 1 minute after mechanical ventilation, and the occurrence of atelectasis in the same scanning areas did not differ between the groups. However, the occurrence of atelectasis on ultrasound scans in the posterior sections of the lungs (in the fifth, sixth and seventh intercostal spaces along the posterior axillary line) was much higher than in the anterior sections, where almost no atelectasis was detected.

Pressure-controlled ventilation with PEEP + 5 cm H₂O after 15 minutes significantly reduced the occurrence of atelectasis while pressure-controlled ventilation without PEEP did not affect the dynamics of atelectasis in the same scanning areas after 15 minutes compared with scans obtained 1 minute after its initiation.

It is noted that atelectatic areas in the left lung were larger than in the right one before treatment, both in the PEEP group and in the control group.

The incidence of atelectasis in the posteroinferior sections was significantly higher than in the anterior and anterolateral sections. Thus, the choice of ultrasound scanning area may influence the detection of atelectasis and the assessment of the use of PEEP.

Perioperative lung ultrasound has shown that PEEP + 5 cm H₂O is beneficial in reaeration of the lungs and reducing atelectasis [12].

**Lung ultrasound and pneumothorax**

The article by Polito A. et al. describes a clinical case of successful urgent diagnosis of pneumothorax during cardiopulmonary resuscitation in a newborn with coarctation of the aorta and ventricular septal defect after resection of the coarctation and narrowing of the pulmonary artery trunk. The ultrasound was completed in less than 10 seconds; the following signs of left-sided pneumothorax were identified:

- no lung sliding in B-mode;
- absence of B-lines;
- “barcode” in M-mode;
- the lung point was found.

The on-duty surgeon performed emergency drainage of the left pleural cavity. Cardiac activity recovery was achieved approximately 30 minutes after the initiation of cardiopulmonary resuscitation. A chest X-ray image obtained immediately before pleural drainage placement confirmed the presence of massive left-sided pneumothorax [6].

**Diaphragm ultrasound: paralysis, paresis, paradoxical movement**

Four articles were devoted to ultrasound diagnosis of diaphragm function. Ultrasound criteria for normal diaphragmatic function, weakness, paralysis, and paradoxical movement were presented and described.

Hamadah H.K. et al. performed ultrasound of the diaphragm if its dysfunction was suspected in the following cases:

- difficulties in weaning from invasive or non-invasive lung ventilation with PEEP: increasing shortness of breath or the appearance of laboratory signs of ineffective gas exchange (decreased SaO₂, tissue hypoxia or respiratory acidosis);
- reintubation within 24 hours of extubation;
- high position of the diaphragm on serial chest radiographs in the absence of abdominal distension and/or atelectasis.

A microconvex sensor was located in the subxiphoid ultrasound window in an inclined transverse plane, with a marker directed at the 9 o’clock position, to obtain comparative simultaneous visualization of the right and left domes of the diaphragm.

The second sensor position was perpendicular to the chest wall, with the marker pointing at the 12 o’clock position in the eighth or ninth intercostal space, between the anterior and middle axillary lines.

It has been noted that during inhalation, the diaphragm normally moves caudally, resulting in an elevation of the M-mode curve. During the screening process, the authors analyzed two parameters: the direction of movement and the amplitude of the excursion. Diaphragmatic dysfunction indicates either weakness or paralysis. Diaphragmatic movement is classified as follows: normal, diaphragmatic weakness, diaphragmatic paralysis, paradoxical movement of the diaphragm (see Table 2).

<table>
<thead>
<tr>
<th>Categories of diaphragm movements</th>
<th>Description of movements during inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>The diaphragm moves caudally toward the liver or spleen with an upward M-mode flexion wave. The excursion is ≥ 4 mm and the difference between the amplitude of movement of the diaphragm domes is &lt; 50 %</td>
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<tr>
<td>Diaphragmatic weakness (paresis)</td>
<td>The movement is directed caudally. The difference between the amplitude of movement of the diaphragm domes is &gt; 50 %. The excursion is &lt; 4 mm</td>
</tr>
<tr>
<td>Diaphragmatic paralysis</td>
<td>Even line in M-mode, diaphragmatic movement is absent</td>
</tr>
<tr>
<td>Paradoxical movement of the diaphragm</td>
<td>During inhalation, the diaphragm shifts cranially with deviation of the wave downward in M-mode (inverted wave)</td>
</tr>
</tbody>
</table>
Bilateral paresis of the diaphragm was diagnosed in 1 patient (5.9 %), paresis of the right dome of the diaphragm — in one case (5.9 %), paresis of the left dome of the diaphragm — in five patients (29.4 %).

Left-sided diaphragmatic dysfunction was predominant in 12 of 17 patients (70.5 %).

The authors noted that with the increasing use of ultrasound in intensive care units, bedside ultrasound is becoming a simple and practical non-invasive method for assessing diaphragmatic movement in various diseases. It was noted that since 2012, bedside ultrasound of the diaphragm has replaced fluoroscopy in diagnostics in the researchers’ in-patient facility [13].

Zhang Y.B. et al. studied diaphragmatic paralysis in 47 children after surgical correction of CHD. Confirmation of diaphragmatic paralysis was achieved in 48.9 % of the cases using ultrasound alone, in 40.4 % of the cases using radioscopy alone and in 10.6 % of the cases using both methods simultaneously. The authors noted the high promise of ultrasound as the main diagnostic method since ultrasound has diagnostic capabilities similar to radioscopy, facilitates early diagnosis at the patient’s bedside, does not cause discomfort in the patient, and the study can be easily repeated the required number of times. It was noted that in the authors’ department, all children undergo routine testing of diaphragm function using ultrasound before transfer from the intensive care unit [14].

An analogical study was conducted by Gil-Juanmiquel L. et al. Two pediatric intensivists trained in ultrasound participated in the study. Diaphragmatic movement was classified as normal or abnormal (including paretic, akinetic, and paradoxical). At each examination, images were obtained in B- and M-modes.

Chest X-ray was performed for 16 patients (61.5 %), electromyography for 25 patients (96.1 %), and chest ultrasound for all 26 patients with suspected atypical diaphragm movement (ADM). One of the intensivists (intensivist 1) examined a total of 25 patients (96.1 %), and the other (intensivist 2) examined 24 patients (92.3 %). Chest ultrasound performed by intensivist 1 had a sensitivity of 91 % and a specificity of 91 % for diagnosing ADM compared with electromyography. The results obtained by intensivist 2 provided a sensitivity of 92 % and a specificity of 95 % for the diagnosis of ADM compared with electromyography.

The authors came to the conclusion that chest ultrasound combined with B- and M-modes is an effective method for diagnosing ADM. The technique is harmless, available, easy to learn and has higher sensitivity and specificity than chest radioscopy in patients with clinically suspected ADM [15].

Nozaki Y. et al. noted the fact that the method of ultrasound diagnosis assessing the excursion of the diaphragm is unsuitable for assessing its function in patients receiving mandatory mechanical ventilation. In the category of patients for whom it is impossible to interrupt mechanical breathing, the authors proposed assessing the diaphragm thickening fraction. The mechanical ventilation was switched to the CPAP ventilation mode, after which an ultrasound examination was performed. Diaphragm function was assessed by scanning along the midaxillary line between the 8th and 10th ribs.

Diaphragm thickening fraction = ([End-inspiratory thickness − End-expiratory thickness]/[End-expiratory thickness]) × 100.

Thereat, the value of < 17 % was considered to indicate diaphragmatic dysfunction.

Over three respiratory cycles, the mean diaphragmatic thickening fraction was 31 % on the right and 0.2 % on the left, which indicated the paralysis of the left dome of the diaphragm [16].

**Lung ultrasound and recruitment maneuver**

One article was devoted to the use of lung ultrasound in assessing the recruitment maneuver. Song IK et al. assessed the efficacy of perioperative pulmonary ultrasound, including its application as a tool for visual guidance of the recruitment maneuver, in pediatric cardiac surgery patients. The study included 122 children aged 5 years and younger, who were divided into the intervention and control groups.

Patients were scanned in the lying position. Each hemithorax was divided into six regions using three longitudinal lines (parasternal, anterior and posterior axillary) and two axial lines (one above the diaphragm, the other 1 cm above the nipples).

In the intervention group, recruitment maneuver was performed after each lung ultrasound examination in the presence of significant atelectasis, defined as a consolidation score of 2 or higher in any area. The recruitment maneuver was carried out by stepwise pressure increase by 5 cm H2O from 10 cm H2O during inhalation with a 5-second delay at each level until the collapsed areas of the lungs are straightened according to ultrasound data or until the pressure in the respiratory tract reaches 40 cm H2O. The degree of consolidation and B-lines was graded from 0 to 3 points.

This randomized trial showed that perioperative lung ultrasound, including that for visual guidance during the recruitment maneuver, was useful in reducing postoperative desaturation, improving lung condition and shortening the duration of mechanical ventilation.

The occurrence of intraoperative desaturation was 36 % in the control group and 19 % in the intervention group; the occurrence of postoperative desaturation was 64 % in the control group and 27 % in the intervention group. The occurrence of intra- and postoperative desaturation in the intervention group was reduced by more than two times due to perioperative lung ultrasound and ultrasound-guided recruitment maneuvers. The duration of mechanical ventilation was also significantly shorter in the intervention group than in the control group.

Apart from that, it was noted that preoperative lung ultrasound revealed abnormal position of the endotrache-
al tube in the intervention group, while postoperative lung ultrasound revealed significant pleural effusion requiring drainage and insignificant pneumothorax in the control group. The investigators indicated that the recruitment maneuver did not lead to any complications such as hypotension, arrhythmia, or lung injury.

The authors conclude that perioperative pulmonary ultrasound, including that for visual guidance of the recruitment maneuver, turned out to be effective and beneficial for children undergoing cardiac surgery. The described method reduced the frequency of postoperative desaturation and shortened the duration of mechanical ventilation, which contributed to its more active use in pediatric cardiac surgery [17].

Lung ultrasound and weaning from mechanical ventilation

Two articles were devoted to the use of lung ultrasound when weaning pediatric cardiac surgical patients from mechanical ventilation. The two studies brought controversial results.

Li M. et al. determined ultrasound predictors of successful extubation in children undergoing cardiac surgery. When performing lung ultrasound, four categories were identified corresponding to the different degrees of lung aeration decrease:

- 0 — normal aeration: A-lines and 1 or 2 B-lines;
- 1 — moderate decrease in lung aeration: multiple clearly defined B-lines;
- 2 — severe decrease in lung aeration: multiple confluent B-lines;
- 3 — complete loss of aeration leading to consolidation of the lungs.

The ultrasound score was calculated as the sum of points based on the results of scanning 12 sections of the lungs (from 0 to 36). Left ventricular ejection fraction (LVEF) was assessed using the Simpson method. Two-dimensional fractional change in the area was used for quantitative assessment of the right ventricular function. Pulmonary hypertension (PH) and severe PH were defined as pulmonary artery systolic pressure greater than 50 % and 75 % of systemic systolic pressure, respectively.

Of the 83 included patients aged 3 months to 6 years, 57 (68.7 %) were successfully extubated.

The authors noted that children after successful extubation were significantly older and weighed more than children who failed to extubate; additionally, in cases of the latter, there was a shorter time of aortic compression and cardiopulmonary bypass. In children who could not be extubated (26 patients), the duration of mechanical ventilation and stay in the intensive care unit increased. The causes of failed extubation included heart failure (n = 10), pulmonary disease (n = 9), airway edema (n = 6), and diaphragmatic paralysis (n = 1).

In this study, in multivariate regression analysis, lung ultrasound score ≤ 12 and LVEF ≥ 40 % immediately before attempting spontaneous breathing were the only independent predictors of successful extubation [18].

Avneet S. et al., on the contrary, came to the conclusion that lung ultrasound cannot reliably predict failure in weaning from mechanical ventilation, which is explained by the multifactorial nature of pulmonary edema after cardiac surgery in children. At the same time, the authors managed to establish the significance of the thickening fraction of the left dome of the diaphragm at less than 17.15 % (sensitivity 85 %) during assisted ventilation for predicting failure of tracheal extubation [19].

Ultrasound and complex lung diseases

The article by Biasucci D et al. describes the use of ultrasound imaging in complex combined lung diseases has been described.

The paper presented a case of successful lung ultrasound in a 1-year-old male child with hypoplastic left heart syndrome after bidirectional cavopulmonary anastomosis by Glenn and systemic a shunt of the hypoplastic left pulmonary artery from the left subclavian artery. The shunt was placed between the left subclavian artery and the distal collateral left pulmonary vessel. The arterial branches of the upper lobe of the left lung were excluded from the circulation, therefore the apical region of the left lung and the anterior surface of the lingula were not perfused. After the surgery, the patient experienced a sharp decrease in lung compliance due to reperfusion syndrome (Pplat > 32 cmHg and auto-PEEP > 3 cmHg) accompanied by respiratory acidosis (pH = 7.13, PaCO2 = 107 mmHg) and a decrease in the PaO2/FiO2 ratio < 100. The left upper lobe was completely ischemic with localized pulmonary infarction. Computed tomography findings showed parenchymal consolidation in gravity-dependent areas of the lungs with ground-glass opacities and a large area of consolidation in the left upper lobe and anterior surface of the lingula. Extracorporeal membrane oxygenation (ECMO) was initiated.

Lung ultrasound was performed daily to monitor disease dynamics. Prior to ECMO initiation, an area of consolidation in the apical region of the left lung, while the rest of the left and the entire right lung presented a picture of a bright hyperechoic image combined with thickening of the pleural line. On the 5th day, when the patient’s condition began to improve, lung ultrasound showed heterogeneous distribution of B-lines, the number of which was reduced in dynamics. On the 12th day, in the X-ray surgical operating room, a vascular collateral was discovered and occluded that was shunting blood from the superior vena cava to the left atrium, which led to significant desaturation as a result of mixing venous and arterial portions of blood and a decrease in blood flow along the formed cavopulmonary circuit. At this stage, the B-lines began to become less noticeable while A-lines became visible. The patient was weaned from ECMO on day 13. With mechanical ventilation, gas exchange improved significantly. Both chest X-ray and lung
ultrasound showed that the zone of consolidation in the apical region of the left lung remained unchanged throughout the clinical course of the patient’s condition.

According to the authors, this case attests to the fact that lung ultrasound is a useful tool for monitoring the progression of lung diseases in children and visually assessing the effectiveness of therapy, helping physicians provide appropriate treatment. In this particular case, the decision to withdraw ECMO was also made based on sonographic evidence of improvement in the perfused lobes. In addition, non-invasive bedside lung ultrasound can help physicians limit the number of chest X-ray and CT imaging procedures thereby minimizing radiation exposure to the organism. Based on the above characteristics, pulmonary ultrasound appears to be particularly useful in unstable pediatric patients [20].

Bajracharya S.M. et al. conducted a study on the efficacy of the ultrasound method for diagnosing lung damage in children after cardiac surgery compared to chest radiography.

The study involved 141 children under the age of 14 years. Ultrasound was performed on the first day after surgery. The authors assessed the lung parenchyma in the anterior, lateral and posterior parts of the lungs, and also assessed the presence of liquid in the pleural cavities and ruled out pneumothorax.

Compared with chest X-ray, lung ultrasound had overall sensitivity of 60 %, specificity of 72.4 %, positive predictive value of 31.9 % and negative predictive value of 89.3 %, as well as diagnostic accuracy of 70.2 % for the diagnosis of consolidation; for atelectasis, ultrasound had sensitivity of 50 %, specificity of 76.9 %, positive predictive value of 30.7 %, negative predictive value of 88.2 %, and diagnostic accuracy of 72.3 %.

It is worth noting that this division of pulmonary tissue compression syndrome (alveolar consolidation syndrome) into “consolidation” and atelectasis was carried out by the authors of the study based on an analysis of air bronchograms. In the presence of dynamic bronchograms, the authors stated the presence of “consolidation,” and in the presence of static bronchograms or in their complete absence, atelectasis was assumed.

For pleural effusion diagnosis, lung ultrasound showed sensitivity of 90 %, specificity of 82.6 %, positive predictive value of 46.1 %, negative predictive value of 98 % and diagnostic accuracy of 83.6 %. The authors did not detect pneumothorax during the study period [21].

**Discussion**

The data obtained by the authors when analyzing interstitial syndrome and the degree of severity of B-lines in children undergoing cardiac surgery are consistent with data from other areas of medicine [8, 22–26]. It has been shown that analysis of the severity of interstitial syndrome can be carried out both by assessing the number of B-lines and by the method of the percentage ratio of B-lines to the length of the intercostal space. It was also revealed that the use of furosemide reduces the number of B-lines, which seems logical in the pathophysiological sense.

There is a limitation in the study conducted by Wu L. et al. [12]. The authors searched for atelectasis in children in the supine position, without turning on the side and without scanning the posterior parts of the lungs, in which foci of consolidation potentially occur more often due to more pronounced hypoventilation of these sections.

The tension pneumothorax described in the case report had the classic ultrasound findings outlined in the blue protocol.

It is worth noting that most of the authors included in the systematic review indicate that they assessed diaphragm function only when switching to spontaneous breathing, interrupting mechanical ventilation, Hamadah H.K. et al. [13], Gil-Juanmiqul L. et al. [15], which is a major limitation of the method for unstable patients with severe lung damage. However, Nozaki Y. et al. [16] proposed assessing diaphragm function in this category of patients based on measuring the diaphragm thickening fraction, although they were drawing upon the data obtained from one clinical case, which is certainly unrepresentative and requires further research. Zhang Y.B. et al. did not indicate whether the switch to spontaneous breathing during the ultrasound examination of the diaphragm function was carried out or not [14].

The article by Bajracharya S.M. et al. [21], in which they assessed the efficacy of the ultrasound method for diagnosing pulmonary lesions in children after cardiac surgery in comparison with chest X-ray, describes rather ambiguous results that contradict the literature data. As a reference method, the authors chose the direct projection chest X-ray method, the results of which were assessed by different doctors (intensivists). Considering the large amount of data that lung ultrasound is superior in sensitivity to radiography in diagnosing alveolar consolidation syndrome [26–30], the correctness of such an efficacy assessment method seems doubtful.

Analysis of the lung ultrasound efficacy in weaning from mechanical ventilation was carried out in two studies, where opposite results were obtained. It is worth noting that the results obtained by Arneet S. et al. [19] may have been influenced by the fact that the study included heterogeneous age groups: from 1 month to 18 years. In the unsuccessful weaning group, the age of patients was significantly lower than in the group with successful tracheal extubation, and the sample size was too small (the group with unsuccessful weaning was only 7 people). The study by Li M. et al. [18] involved children of a more homogeneous age group: from 3 months to 6 years, while the group with unsuccessful tracheal extubation consisted of 26 people.

In the study of recruitment maneuver efficacy under lung ultrasound guidance, it should be noted that the anesthesia and intensive care specialist who performed the ultrasound examination of the lungs and the recruitment maneuver was not “blinded”, which could affect the study results.
Systematic analysis of the literature revealed that research devoted to this issue is very fragmentary. Not a single Russian-language article was found even after a repeated and broader search. These facts indicate an extremely low degree of elaboration of the topic and the need for further research in this category of patients with the formation of clinical guidelines for practical healthcare.

In our opinion, it is worth noting separately the main problems when performing lung ultrasound in children, especially newborns and infants: narrow intercostal spaces that limit the visualization window, difficulties in adequate assessment of the volume of pleural effusion, lack of patient compliance, which complicates the already difficult visualization of the necessary structures, the need for high-frequency linear sensors and high-class ultrasound devices for adequate assessment of the pleural line and tissues located at shallow depths, as well as a convex sensor for assessing the diaphragm function. In addition, the assessment should be carried out by an anesthesia and intensive care specialist experienced in lung ultrasound and with a certificate of completion of advanced training course in the respective area.

Conclusion

The literature analysis has revealed that this promising method for bedside diagnosis of the condition of the lungs and the thoracic cavity tissues makes it possible to diagnose pulmonary edema, atelectasis, pneumothorax, to assess the diaphragmatic function, to perform visually guided recruitment maneuver as well as to predict successful tracheal extubation in pediatric cardiac surgery.

Disclosure. The authors declare that they have no competing interests.

Author contribution. All authors according to the ICMJE criteria participated in the development of the concept of the article, obtaining and analyzing factual data, writing and editing the text of the article, checking and approving the text of the article.

Ethics approval. Not required.

Funding source. This study was not supported by any external sources of funding.

Data Availability Statement. Data available within the article.

Authors’ ORCID:

Gritsan A.I. — 0000-0002-0500-2887
Pfeifer A.A. — 0009-0008-4028-0533
Gurchenko S.A. — 0009-0001-6894-7749
Ilinykh K.A. — 0000-0002-8068-3088
Sakovich V.A. — 0000-0001-7743-8770

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Lung ultrasound at the department of anesthesiology and intensive care for pediatric cardiac surgery: a narrative review


