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2024

Journal of Diagnostic Medical Sonography
2024, Vol. 40(1) 79–99

DOI: 10.1177/87564793231198521
journals.sagepub.com/home/jdm


Exploring the Use of Lung Ultrasonography to Assess Cardiac Surgery Patients: A Scoping Review

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Abstract

Objective: Lung ultrasonography (LUS) is a safe, quick, and portable diagnostic tool, which can accurately detect postoperative pulmonary complications, postsurgically, without ionizing radiation. The aim of this scoping review was to map the evidence base regarding the use of LUS to assess cardiac surgery patients.

Materials and Methods: The JBI methodology was used to conduct this particular scoping review.

Results: In total, 90 publications were identified and of those, 73 were research studies, six were narrative reviews, and 11 were narrative, opinion, and text articles. The studies that were included were predominantly observational cohorts and aimed to determine or compare LUS diagnostic ability, prognostic ability, or both. The LUS methods used with patients were heterogeneous and variably reported.

Conclusion: Despite an increasing number of studies since 2014, standardized protocols for the use of LUS are yet to be widely adopted and remain an important area for further work. Future research should consider exploring perceptions and experiences of LUS, the use of LUS in treatment outcome measurement, and use by nonphysician health care professionals.

Keywords

Lung ultrasonography, chest ultrasound, thoracic ultrasound, point-of-care ultrasound, POCUS, postoperative pulmonary complications, cardiac surgery, cardiothoracic surgery, and scoping review

Patients undergoing cardiac surgery are subjected to prolonged anesthesia, supine position, ventilation, and compression, which increases their susceptibility to developing postoperative pulmonary complications (PPCs), such as atelectasis, pleural effusion, and pneumothorax.[1–4] Up to 30% of patients who develop PPCs die within 30 days of major surgery, a considerably higher mortality rate than those without such complications (0.2%–3.0%).[3] Consequently, timely identification of PPCs is crucial for effective management and improved patient outcomes.

A chest radiograph (CXR) and auscultation are commonly used to assess for PPCs following cardiac surgery, yet these common diagnostic assessment tools have limitations. For instance, while an erect CXR has a sensitivity of 92% for pneumothorax, a supine CXR (which is common postoperatively) has only 50% sensitivity.[5] Furthermore, a "white-out" on a CXR could indicate pleural effusion or one of 15 other causes.[6] Studies indicate that the intrarater reliability of auscultation can be as low as 28%.[7] Using CXR, auscultation, or both, to differentiate between pulmonary pathologies can be difficult and result in misdiagnosis. This can decrease confidence in the management plan and may result in delayed recovery.

In recent years, point-of-care ultrasound (PoCUS) has become increasingly popular due to its high accuracy, portability, and lack of radiation emissions.[2,8,9] Lung ultrasonography (LUS) is a type of PoCUS, which focuses on the pleura and parenchyma, and has been studied globally in the medical field. Lung ultrasonography has the ability to detect common pulmonary pathologies, such as pneumothorax,

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Received June 5, 2023, and accepted for publication August 8, 2023.

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pleural effusion, lung consolidation, atelectasis, and pneumonia,[2,10,11] making it a valuable tool to identify PPCs. Lung ultrasonography compares well with the standard tools used in the cardiac surgery population. Senniappan et al[12] found LUS to be comparable with CXR both immediately postoperatively ($k = 0.652$) and 1-day postoperatively ($k = 0.740$) with a near-perfect agreement for pneumothorax ($k = 0.931$). Several other studies have tested the sensitivity and specificity of LUS against computed tomography (CT), the gold standard for identifying pulmonary pathology, and demonstrated high sensitivity, specificity, and diagnostic accuracy of LUS.[13–15]

There is a growing body of evidence on the use of LUS within cardiac surgery patients. Lung ultrasonography's comparability to both CXR and CT in addition to its lack of ionizing radiation has made it a diagnostic tool of interest, within cardiac surgery research. It will be useful to both the clinical and research community to map that body of evidence, to identify what is currently known about LUS, when used with cardiac patients, and to guide future research investment in the field. A preliminary search of the International Prospective Register of Systematic Reviews (PROSPERO), Open Science Framework (OSF), the Cochrane Database of Systematic Reviews, JBI Evidence Synthesis, Medline, and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) was conducted, and no planned, underway, or completed systematic reviews or scoping reviews on the topic were identified. Systematic and scoping reviews conduct a more comprehensive search of the literature than literature reviews, using a systematic approach. While systematic reviews have a more focused research question and are explanatory or analytical in nature, scoping reviews broaden the research question and are more exploratory or descriptive in nature. Scoping reviews aim to assess and understand the extent of the knowledge in an emerging field, often identifying, mapping, reporting, or discussing literature characteristics using a systematic and methodologic approach.[16]

Review Questions

The objective of this scoping review was to map the evidence base on the use of LUS within cardiac surgery patients. The primary review question was: *What has been reported on the use of LUS within cardiac surgery patients?*

The following sub-questions were explored:

- What types of studies have been published on LUS and cardiac surgery?
- How and why has LUS been used with cardiac surgery patients?
- What anatomic structures and artifacts have been investigated with LUS with cardiac surgery patients?
- Which professionals are reportedly using LUS with cardiac surgery patients?
- What LUS protocols are reportedly being used by professionals undertaking LUS with cardiac surgery patients?

Inclusion Criteria

This scoping review considered literature including or concerning both adult and pediatric patients undergoing cardiac surgery irrespective of participants' demographic profile. Types of cardiac surgery included, but were not limited to:

- Coronary artery bypass grafting
- Heart valve repair or replacement
- Coronary angioplasty and stenting
- Atherectomy
- Cardiomyoplasty
- Heart transplant
- Catheter ablation

Literature that included a mixed demographic was considered if cardiac surgery patients contributed 75% or more of the total cohort or the cardiac surgery patient outcomes could be extracted separately.

Concept

This scoping review considered literature concerning LUS use by any qualified health care professional on a cardiac surgery patient. Lung ultrasonography could have been used as a diagnostic assessment tool, outcome measure, during treatment, or for any other purpose. For this review, LUS is defined as a tool for investigating the pleura and parenchyma ultrasonically. For this reason, literature sources investigating the diaphragm were excluded.

Context

This scoping review considered literature from any health care setting where cardiac surgery is conducted. Studies were not limited by geographical location. Non-English records were considered if they could be reliably translated using Google Translate.

Type of Sources

This scoping review considered: primary research of any type (e.g., qualitative, quantitative, case reports); literature reviews of any type (e.g., systematic, narrative); narrative, opinion and text (e.g., editorials, opinion pieces, commentaries); and conference abstracts reporting any of these types. Trial registrations and protocols were

excluded; however, they were retrieved to identify additional published studies from their reference lists.

Materials and Methods

This scoping review was conducted in accordance with JBI methodology for scoping reviews[17] and followed an a priori open access protocol registered on OSF in March 2022.[18] This methodology was chosen as the research team has expertise in and experience with the methodology. JBI, a global organization, supports and promotes evidence-based health care decision-making, which considers feasibility, appropriateness, meaningfulness, and effectiveness.[19] The JBI methodology is a well-known and accepted methodology within health care.

Search Strategy and Information Sources

The search strategy aimed to locate both published and unpublished studies. An initial limited search of Medline and CINAHL (EBSCOhost) was undertaken using the keywords (TX lung ultrasound) AND (TX cardiac surgery) to identify articles on the topic. The text words contained in the titles and abstracts of relevant articles, and the index terms used to describe the articles were used to develop a full search strategy for Medline. The search strategy, including all identified keywords and index terms, was adapted for each included database and information source (See Supplemental Appendix 1). A second search for all databases was undertaken on April 6, 2022 and for gray and unpublished literature on August 3, 2022.

The databases searched included: Medline and CINAHL (via EBSCOhost), Embase (via Ovid), Cochrane Reviews and Trials, Scopus, and Web of Science. Sources of unpublished studies and gray literature included: Google Scholar and university repositories. The full search strategy including the search terms and hits from each database and gray literature source are provided in Supplemental Appendix 1.

The reference list of all included reports was then searched for additional eligible reports.

Source of Evidence Selection

Following the searches, all identified records were collated and uploaded into the reference manager Zotero (v6.0.13; Roy Rosenzweig Center for History and New Media, Fairfax, VA, USA) and duplicates removed. Remaining records were uploaded into Covidence (Veritas Health Innovation, Melbourne, Australia) with further duplicates detected and removed. Titles and abstracts were initially screened independently by two reviewers (two of CF, CW, KC) against the inclusion criteria for the scoping review. Excellent agreement (90%) was demonstrated after 10% of title and abstract screening, and as this scoping review formed part of an unfunded doctoral research program, one reviewer (CF) conducted the remainder of title and abstract screening, with regular review and discussion with members of the review team (CW and KC). This process was repeated for full-text screening, with 90% agreement following screening of 20% full texts.

Data Extraction

A data extraction form was constructed prior to database searching[18] based on the Covidence Data Extraction Form 2.0 and extraction from 10% of reports was piloted independently by two reviewers (CF and KC). Minor amendments were made to the data extraction form to focus more on LUS methods and characteristics. After good agreement was reached on independent screening by two reviewers (85%), one reviewer (CF) extracted data from the remaining reports, with regular review and discussion with the review team (CW and KC). Data were extracted on the aim, study design, setting, participant characteristics, and key findings. LUS methods were also extracted regarding the profession of the operator, the number of operators, the reason for use, time of use in relation to surgery, anatomic features or artifacts of interest, LUS findings, and any protocols used.

Results

Study Inclusion

Initial screening of databases retrieved 10 806 records, with an additional 172 records identified from other sources. After the removal of duplicates, 9626 records remained for title and abstract screening. Three hundred and seventeen records proceeded to full-text screening. Ninety reports met the inclusion criteria and were included in the review. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (See Figure 1) illustrates the number of records and reports at each of these stages and the distribution of reasons for exclusion.

Characteristics of Included Reports

A summary of general characteristics of all included reports is reported in Table 1. The scoping review included 90 reports: 73 research studies, six narrative reviews, and 11 narrative, opinion and text. The reports were published between 1994 and 2022, with a sharp increase in publication rates from 2014, peaking in 2020 ($n = 16$) (See Figure 2). Reports were published in 27 different countries but most originated from Italy ($n =$

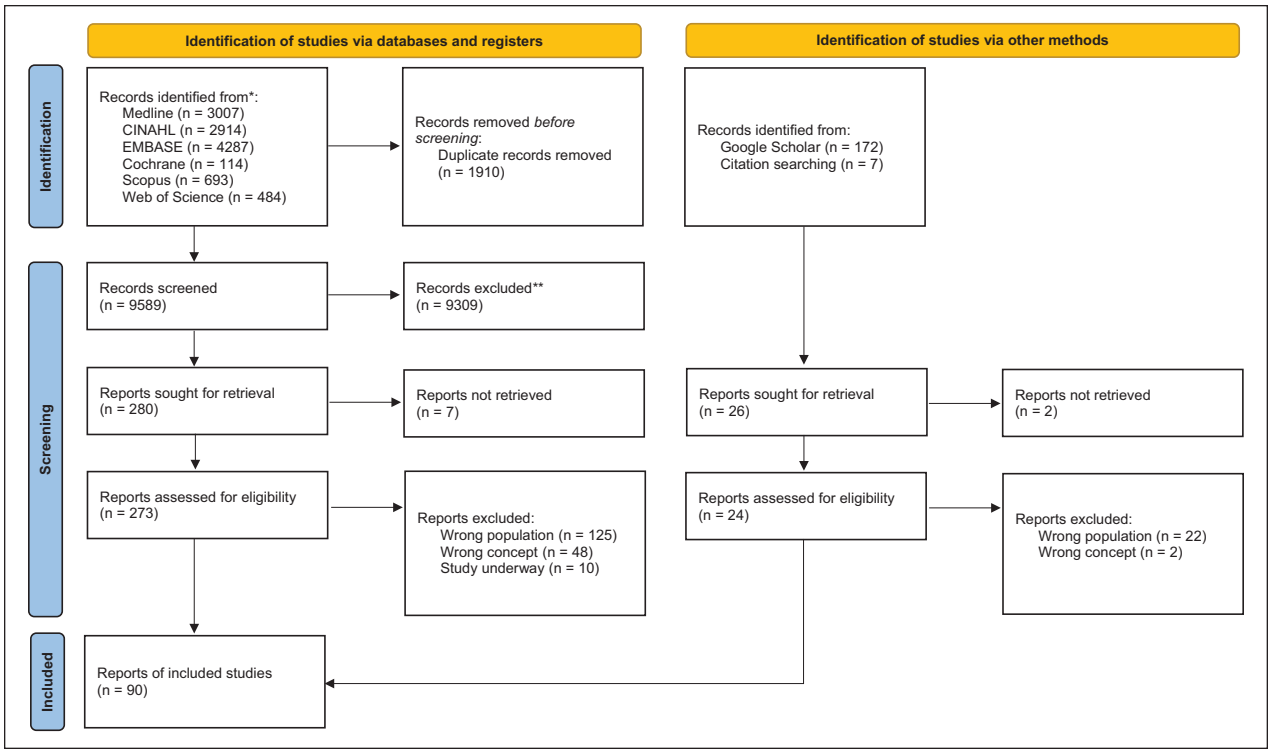

Figure 1. The PRISMA flow chart for the search results and the study inclusion process. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

29, 32.6%) followed by China (n = 7, 7.9%). Five reports were translated successfully by Google Translate.[15,20–23]

Empirical Research Studies

Most of the included literature in this scoping review comprised empirical research (n = 73, 81.1%). This included 64 observational studies (71.1%), six randomized controlled trials (RCTs) (6.7%), and three secondary analyses (3.3%). Of the observational studies, the most common sub-type was cohort study (n = 43, 67.2%). Twenty of the studies were in the form of conference abstracts (22.2%). The most common setting that studies were conducted in was intensive care (n = 48, 88.9%). All studies included patients, with a large range in sample size (n = 1–351). Age was well-balanced between pediatric (n = 34, 51.5%) and adult patients (n = 32, 48.5%). Of the 55 primary studies that reported patients' sex, 38 included mostly male patients (52%) while seven studies included only males (12.7%). Many primary studies included a mixed surgical population. Of the 55 primary studies, which reported type of surgery, the most common were congenital cardiac surgery (n = 31, 56.4%) followed by coronary artery bypass grafts (n = 19, 34.5%) and valve repairs or replacements (n = 19, 34.5%).

Narrative Reviews

This review included six narrative reviews (6.7%). All narrative reviews aimed to summarize LUS applications in cardiac surgery, with half focusing on the pediatric population (3.3%). The specific focus of the reviews varied from improving awareness of LUS among other specialists[98] to discussing the need for a new LUS protocol[99] to highlighting the role of LUS in weaning and extubation in pediatric cardiac patients.[100] The earliest narrative review was published in 2016.[2] Countries of origin included Italy[2,92,94] (n = 3), Russia[98] (n = 1), Mexico[99] (n = 1), and Saudi Arabia[100] (n = 1).

Narrative, Opinion and Text

Other evidence types (n = 11, 12.2%) included in the scoping review consisted of letters to the editor (n = 6, 6.7%), editorials (n = 3, 3.3%), editorial commentary (n = 1, 1.1%), and a scientific letter (n = 1, 1.1%). Some reports underlined cases in which LUS played an important role in pathology identification and treatment.[91,95,102] Other reports carried a discussion between researchers regarding studies conducted using LUS,[96,105] including one letter to the editor[104] in which use of LUS in another included study[33] was questioned.

Table 1. The characteristics of the included studies for this review.

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
Alsaddique et al,[24] Australia	To determine whether both repeated postoperative TTE and LUS revealed or excluded clinically important cardiac and respiratory disorders compared with conventional monitoring and CXR	Observational—cohort	General ICU/ITU, general ward	Patients older than 18 receiving cardiac surgery; mean (*SD*): 57.3 years (13.1); majority male; $n = 91$	CABG, valve repair/ replacement, thoracic aorta, LV aneurysmectomy	Routine repeated monitoring with cardiac and LUS after cardiac surgery is feasible and frequently alters diagnosis of clinically important cardiac and respiratory pathology
Bajracharya et al,[25] Nepal	To compare diagnostic performance of LUS with CXR to detect pulmonary complication after cardiac surgery in children	Observational—cohort	CICU/CITU	All consecutive pediatric patients aged less than 14 years scheduled for cardiac surgery; mean: 6.3 ± 4.7 years; majority male; $n = 141$	Congenital cardiac surgery, valve repair/ replacement	LUS done routinely is an alternative noninvasive, reliable and accurate tool for diagnosing common pulmonary complications in pediatric patient postcardiac surgery as compared with CXR with acceptable diagnostic accuracy thereby decreasing exposure to ionizing radiation, time, and costs
Beerepoot et al,[26] Netherlands	To compare the rates of PPCs detected by LUS and CXR in patients after cardiac surgery admitted to ICU	Observational—cohort	General ICU/ITU	Cardiac surgery patients; mean: 68 ± 9.5 years; majority male; $n = 134$	NR	LUS detects more PPCs than CXR in patients after cardiac surgery and with good interobserver agreement. In addition, time to perform LUS is significantly shorter. However, most PPCs detected by LUS come with little clinical consequence. Therefore, we suggest in further studies to quantify the extent of the PPC detected by LUS to improve its value in clinical decision-making
Bianco et al,[27] Italy	To assess the diagnostic performance and the predictive value of ultrasound lung comets compared with CXR and NT-proBNP, for the early diagnosis of postoperative AHF in a cohort of patients admitted to the CSICU of our hospital	Observational—cohort	CICU/CITU	Cardiac surgery patients; mean: 69.7 ± 10.1 years; $n = 55$	NR	LUS allows a prompt and reliable ruling out of AHF, but with lower specificity compared with supine CXR and NT-proBNP assay
Biasucci et al,[28] Italy	To report a case in which LUS was used as an effective lung monitoring tool during treatment of a child suffering from severe and complex lung injury after heart surgery	Observational—case study/report	NR	A 1-year-old male with hypoplastic left heart syndrome underwent bidirectional Glenn procedure and systemic to-left pulmonary artery shunt for heart palliation due to severe hypoplasia of left pulmonary artery	Bidirectional Glenn procedure and systemic-to-left pulmonary artery shunt	The decision for extracorporeal membrane oxygenation weaning was also supported by the documentation of the bilateral sonographic improvement of the perfused lobes
Bucciarelli et al,[29] Italy	To assess the additional diagnostic performance of NLR and PLR along with CPUS for early rule-in and rule-out diagnosis of PHF	Observational—cohort	CICU/CITU	Admitted to the cardiac surgery ICU after elective cardiac surgery with a CPUS available before and after surgery; mean: 68.9 ± 9.8 years; majority male, $n = 81$	CABG, NR	Elevated preoperative NLR and PLR well correlate with elevated B-lines, reduced echocardiographic myocardial performance indexes and pulmonary arterial pressure in early diagnosis of PHF in elective patients after cardiac surgery
Cantinotti et al,[30] Italy	To test the feasibility of LUS following pediatric cardiac surgery and to compare LUS and CXR findings, assessing whether LUS may provide additional information	Observational—cohort	General ICU/ITU	All children and adolescent (< 20 years old) undergoing corrective or palliative CHD surgery; median: 9.3 months; IQR: 1 month–6 years; majority male; $n = 79$	Congenital cardiac surgery	In 81 cases, LUS allowed reclassification of CXR findings, including 40 new diagnoses (diagnosis of effusion/atelectasis with negative CXR reports) and 41 changes in diagnosis (effusions reclassified as atelectasis/severe congestion or vice versa)
Cantinotti et al,[31] Italy	To assess LUS ability to evaluate common pulmonary complications after cardiac surgery	Observational—cohort	NR	Pediatric cardiac surgery patients; mean: 24.8 ± 73 months; $n = 85$	Congenital cardiac surgery	LUS may lead to a new diagnosis of unknown retro-sternal clots as well as a better definition of those incidentally detached at echocardiography, potentially leading to less need for more complex, ionizing and expensive examinations
Cantinotti et al,[32] Italy	To test the feasibility of LUS in pediatric cardiac surgery	Observational—cohort	NR	Pediatric cardiac surgery patients; median: 6 months; range: 1 day–16.7 years; $n = 62$	NR	LUS allows differential diagnosis and severity estimation of effusion/atelectasis, and the posterior approach is much more accurate than anterior/lateral for this setting
Cantinotti et al,[33] Italy	To investigate the prognostic potential of a new LUS score in children undergoing surgery for CHD, and to compare LUS score with traditional markers of Outcome, including age, body surface area, the STAT score, Aristotle score, and CPB time and established prognostic biomarkers, such as BNP and cystatin-C	Observational—cohort	General ICU/ITU	All children and adolescents (< 18 years old) undergoing corrective or palliative CHD surgery between June 2015 and May 2018 at the Department of Pediatric Cardiac Surgery of Fondazione CNR–Regione Toscana G. Monasterio; median age: 0.55 years; IQR: 0.09–4.15 years; $n = 237$	Congenital cardiac surgery	The LUS score, when added as continuous predictor to a conventional risk model (age, STAT score, and cardiopulmonary bypass time) emerged significant both for intensive care unit length of stay (beta = 0.145, $P = .047$) and extubation time (beta = 1.644; $P = .024$)
Chatzivasiloglou et al,[34] Greece	To report the respiratory complications in the immediate postoperative period following cardiac surgery and to highlight the importance of LUS in the cardiac surgery ICU	Observational—cohort	CICU/CITU	Cardiac surgery patients; $n = 170$	NR	Atelectasis was detected in 71% of the patients, pleural effusion in 94%, alveolar-interstitial syndrome in 26% and consolidation in 14%. Prompt diagnosis of postoperative complications following cardiac surgery is of paramount importance and it may be made reliably, quickly and safely with LUS
Compton et al,[35] Canada	To report the use of ultrasound to diagnose PL in newborn	Observational—case study/report	NR	Newborn male with suspected pulmonary lymphangiectasia	NR	This report represents the first description of the use of ultrasound to diagnose PL. The abnormal ultrasound appearances are easily detectable using a high-frequency linear probe in an intercostal scanning approach
Corradi et al,[36] Italy	To investigate whether Q-LUS can provide estimates of pulmonary edema, which are better correlated with PCWP and EVLW than V-LUS	Observational—cohort	General ICU/ITU	Patients requiring invasive hemodynamic monitoring after cardiac surgery; EVLW: 69 ± 8 years; PCWP: 70 ± 8 years; majority male, $n = 48$	CABG, valve repair/ replacement, aortic surgery	Both V-LUS and Q-LUS are acceptable indicators of pulmonary edema in mechanically ventilated patients. However, at high PEEP, only Q-LUS provides data that are significantly correlated with PCWP and EVLW. Computer-aided Q-LUS has the advantages of being not only independent of operator perception but also of PEEP

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
de Souza et al,[37] Brazil	To describe the presence of a pneumothorax, identified by point-of-care ultrasound in a 4-month-old infant in postoperative care after cardiac surgery	Observational—case study/report	PICU	A 4-month-old infant (weighing 5 kg) diagnosed with endocarditis	Removal of a right atrial vegetative lesion	This case report describes the successful use of CUS to diagnosis a pneumothorax in an infant.
Dureau et al,[38] France	To investigate the clinical relevance of LUS diagnosis of pneumonia in cardiac postoperative patients with ARF	Observational—cohort	CICU/CITU	Adult patients with ARF less than 3 days after a cardiac surgery with CPB; mean: 65 ± 12 years; majority male; $n = 51$	NR	LUS combined with a clinical score can be a reliable tool for early diagnosis of pneumonia in a cardiac ICU population after cardiac surgery with cardiopulmonary bypass
Edrich et al,[39] Austria	To describe a case where intraoperative transthoracic cardiac and pulmonary ultrasound played a key role in the timely management of sudden cardiopulmonary decompensation	Observational—case study/report	OR	An 81-year-old male brought via ambulance to the emergency room with the complaint of sudden onset of pain, pallor, and weakness in the right leg	AAA repair	The present report demonstrates the value that anesthesiologists can bring to an operative team when they have basic competency in cardiac and pulmonary ultrasonography
Elayashy et al,[40] Egypt	To study the effect of ultrafiltration during cardiopulmonary bypass on postbypass EVLW using LUS and its effect on oxygenation	RCT	General ICU/ITU	CHD patients between 1 and 48 months with body weight > 3 kg; Ultrafiltration group: 15.5 ± 14 months; nonfiltration group: 19 ± 14.8 months; majority female; $n = 60$	Congenital cardiac surgery	Conventional ultrafiltration did not alter EVLW when assessed by LUS and the oxygenation state
Elwakeel et al,[41] Egypt	To study the use of LUS to evaluate EVLW and predict PPCs	Observational—cohort	Pediatric cardiac ICU	Pediatric patients with acyanotic CHD, scheduled for elective cardiac surgery; 6 months–5 years; mean: 1.48; majority female; $n = 80$	Congenital cardiac surgery	LUS score in patients complicated by PPC showed a significant difference from noncomplicated patients; in all LUS scans
Emperador et al,[42] Saudi Arabia	To assess EVLW before and after cardiac surgery by scoring B-lines using LUS. The primary outcomes were to assess the relationship between B-lines and the effect on oxygenation and time of extubation	Observational—cohort	General ICU/ITU	Patients older than 18 years who were scheduled for elective cardiac surgery using CPB; mean (range): 56 (18–87) years; majority male; $n = 73$	CABG, valve repair/replacement, excision of tumor	We found three significant correlations that support the use of LUS in cardiac surgery: (1) the more B-lines, the lower the oxygenation; (2) the more B-lines, the longer the period of ventilation; and (3) the more B-lines, the more positive the fluid balance
Fot et al,[20] Russia	To evaluate the effectiveness of ultrasonic monitoring of the lungs in detecting PPCs in patients after cardiosurgical interventions under cardiopulmonary bypass	Observational—cohort	CICU/CITU	Patients who had cardiosurgical intervention under cardiopulmonary bypass with subsequent hospitalization in a cardiac ICU; mean (range): 63 (53–69) years; majority male; $n = 39$	Valve repair/replacement, congenital cardiac surgery, AAA	Lung ultrasonography monitoring accelerates the diagnosis of respiratory problems after cardiac surgery and allows timely identification of the patients requiring prolonged respiratory support and ICU stay
Terra et al,[43] Brazil	To analyze whether the evaluation of pulmonary aeration by LUS for the indication of NIV in patients undergoing cardiac surgery caused an impact on the length of stay in the ICU and in the hospital	Observational—cross-sectional	CICU/CITU	Patients undergoing elective CS from January 2016 to August 2020 and who were admitted to the cardiac ICU; mean: 59.9 ± 11.7 years; majority male; $n = 111$	Valve repair/replacement, myocardial revascularization	Results of this study suggest that LUS makes it possible to early identify pulmonary complications and facilitate indication of NIV to reverse dysfunctions of the respiratory system in patients undergoing cardiac surgery
Ghotra et al,[44] India	To assess whether the addition of LUS to the usual practice of clinico-radiologic examination would result in earlier or better detection of PPC in pediatric patients undergoing cardiac surgery under cardiopulmonary bypass	Observational—cohort	General ICU/ITU	Pediatric patients aged between 1 month and 14 years with left-to-right shunt and a history of congestive heart failure and/or history of respiratory tract infection in the last 4 weeks; no PPCs: 2 (1–5.75) years; PPCs: 1 (0.5–1) years; majority male; $n = 100$	Congenital cardiac surgery	LUS improves identification of PPC over clinico-radiologic examination in the early postoperative period. Preoperative LUS scores have better predictive ability than CXR scores for the occurrence of PPC
Girona-Alarcon et al,[45] Spain	To compare the sensitivity, specificity, and positive and negative predictive values of LUS (using a quantitative score) with respect to CXR, to assess pulmonary edema in children prior to cardiopulmonary bypass	Observational—cohort	PICU	< 2 months old with CHD that required CPB; median age: 12.5 days; IQR: 9–17.5 days; majority male; $n = 17$	NR	LUS detected pulmonary edema better than CXR, with greater sensitivity and negative predictive value. LUCAS score was useful to predict more inotropic support and longer mechanical ventilation
Hasan et al,[46] Italy	To compare the use of bedside CXR with LUS in pediatric patients undergoing cardiac surgery, identifying the presence of pneumothorax, pulmonary effusion, and pulmonary congestion and to demonstrate the noninferiority of LUS compared with CXR in the detection of lung lesions	Observational—cohort	Pediatric cardiac ICU	Pediatric patients affected by a congenital cardiovascular disease who underwent cardiac surgery; median (range): 11 months (12 days–15 years); majority male, $n = 52$	Congenital cardiac surgery	LUS showed a good agreement for pneumothorax and a moderate agreement for both pleural effusion and pulmonary congestion. LUS also showed a significantly superior relative sensitivity than CXR for pulmonary congestion and pleural effusion and a significantly inferior relative sensitivity for pneumothorax
Hayward and Hayward,[47] UK	To highlight the impact of thoracic ultrasound on physiotherapy practice	Observational—case study/report	CICU/CITU	63-year-old postoperative male patient who underwent cardiac surgery for mitral and tricuspid valves' repair, and three coronary bypass grafts	CABG, valve repair/replacement	When patients are referred to physiotherapy thoracic ultrasound can highlight pathologies not amenable to physiotherapy treatment

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
He et al,[48] China	To investigate the effectiveness of postural lung recruitment maneuver in improving postoperative atelectasis evaluated by LUS scans in children undergoing right lateral thoracotomy cardiac surgery with cardiopulmonary bypass	RCT	CICU/CITU	Pediatric patients aged 3 years or younger, with American Society of Anesthesiology physical status 2 or 3, scheduled for right lateral thoracotomy cardiac surgery (ventricular septal defect or atrial septal defect closure) with CPB were included in; Group C: 1.6 years; Group P: 1.7 years; majority female; $n = 84$	Congenital cardiac surgery	More significant reduction of the left LUS scores and sizes of atelectatic areas were found in the postural lung recruitment group than those in the control group
He et al,[21] China	To study the effect of PEEP on perioperative atelectasis in these children evaluated by lung ultrasonography, and the rationality and effectiveness of PEEP in lateral thoracotomy with small incision surgery	RCT	OR	Children who underwent thoracotomy in lateral decubitus by the same group of surgeons under CPB; Group C: 1.8 ± 0.5 years Group P: 1.7 ± 0.6 years; majority female, $n = 57$	Congenital cardiac surgery	LUS was used to assess for atelectasis
Hui et al,[22] China	To investigate the correlation between LUS images and postoperative pulmonary complications in patients after cardiac surgery	Observational—cohort	General ICU/ITU	Cardiac and major vascular surgery patients newly admitted to the ICU; mean: 60.50±10.43 years; majority male; $n = 52$	Valve repair/replacement, left atrium myxoma	Bedside LUS is an effective method for clinical monitoring of pulmonary complications
Ibrahim et al,[49] Egypt	To evaluate the efficacy of transalveolar pressure measurement (PTA) using esophageal manometer as a monitoring parameter during a modified stepwise staircase lung recruitment employing AVM in postcardiac surgery hypoxic patients	Observational—case series	General ICU/ITU	Adult patients who were undergone on-pump cardiac surgeries; 20–30 years ($n = 9$), 30–40 ($n = 18$), 40–50 ($n = 10$), 50–60 ($n = 15$) and 60–70 ($n = 10$); majority male; $n = 62$	CABG, valve repair/replacement, congenital cardiac surgery	Hypoxic index and ultrasound lung aeration score could be used to detect atelectatic and the effectiveness of the lung recruitment maneuver
Kaskinen et al,[50] Finland	To investigate whether LUS could estimate EVLW after congenital cardiac surgery	Observational—cohort	PICU	Children scheduled for surgery for different types of CHD; median age: 4.43 months; IQR: 0.4–21; $n = 61$	Congenital cardiac surgery	In this observational study, we found a significant positive correlation between LUS and CXR in assessing EVLW in children undergoing surgery for CHD
Larson[51], South Africa	To assess the prevalence of LIS due to EVLW in pediatric patients with high pulmonary flow congenital cardiac lesions	Observational—cross-sectional	CICU/CITU	Pediatric cardiac surgery patients, previously diagnosed with high pulmonary flow lesions scheduled for palliative or corrective surgery; median (range): 17.0 (6.0–108.0) months; equal split; $n = 20$	Congenital cardiac surgery	This is the first study that uses LUS to assess the prevalence of LIS due to EVLW in pediatric cardiac surgical patients undergoing cardiopulmonary bypass
Cantinotti et al,[52] Italy	To describe a case of manual recruitment of atelectasis under LUS guidance in a child after surgical ligation of patent ductus arteriosus	Observational—case study/report	Pediatric cardiac ICU	An 11-month-old female baby underwent a surgical ligation of a large patent ductus arteriosus	Congenital cardiac surgery	LUS may help to follow rapid and dynamic pulmonary changes occurring postcardiac surgery and to actively monitor invasive/noninvasive maneuvers, such as one we have described
Menzel et al,[53] Germany	To find out whether the number of x-ray images and thus radiation exposure to the patients may be reduced by the use of ultrasound	Observational—case study/report	OR	A 13-year-old girl with restrictive cardiomyopathy was admitted in OR for heart transplant	Heart transplant	In emergency, CXR is not mandatory to perform the diagnosis since pneumothorax is a thoracic pathology of surface and can be detected quickly by ultrasound
Mohammed et al,[54] Egypt	To evaluate furosemide on attempting lung injury and/or edema during coarctation repair surgery and to evaluate dynamic lung compliance	RCT	General ICU/ITU	Patients with simple coarctation of the aorta aged 1–18 months who required coarctation repair surgery; Group C: 4.642 ± 2.617 months Group F: 3.853 ± 3.289 months; majority male; $n = 56$	Coarctation of the aorta	LUS was used as an outcome measure for the study
Moshavegh et al,[55] Denmark	To propose an automatic method for accurate detection and visualization of B-lines in ultrasound lung scans, which provides a quantitative measure for the number of B-lines present	Observational—case-control	NR	Four healthy subjects and four patients with pulmonary edema were scanned. The patients had undergone major cardiac surgery; 32, 42, 31, and 28 years; majority male	CABG, left atrium myxoma, heart implantation	The results indicated the proposed technique was able to detect the B-lines and was able to differentiate the ultrasound scans acquired from the patients after cardiac surgery and those acquired from healthy subjects
Myszkowski,[56] Poland	To assess the effectiveness and the possible use of diagnostic transthoracic ultrasound of the respiratory tract to qualify patients for therapy and to monitor the effectiveness of physiotherapy in children after cardiac surgeries	Observational—cohort	General ICU/ITU	Patients between 1 and 12 months after a series of congenital heart surgeries using cardiopulmonary bypass; median (*SD*): 5.24 months (2.94); $n = 103$	Congenital cardiac surgery	A tailored protocol for ultrasonographic assessment of the respiratory tract is an optimal tool for determining therapeutic goals, as well as for the assessment of the efficacy of pulmonary physiotherapy in pediatric patients after cardiac corrections. The diagnostic value of ultrasonographic assessment of the respiratory tract and standard radiography in the study group depends on the location of the investigated lung segment

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
Nguyen et al,[57] Vietnam	To report a case of severe systolic anterior movement of the anterior mitral leaflet after CABG with low LVEF, which was promptly diagnosed and successfully treated based on echocardiography and LUS	Observational—case study/report	CICU/CITU	A 72-year-old Vietnamese woman presented to a community hospital due to chest pain for the previous 3 days	CABG	All these interventions were carried out under close hemodynamic monitoring, echocardiography, and LUS
Niyogi et al,[58] India	To investigate the correlation of LUS B-line scoring with EVLWI, thresholds indicating elevated EVLWI, and its outcome following pediatric cardiac surgery	Observational—cohort	CICU/CITU	Children aged younger than 12 years undergoing elective cardiac surgery for complete correction of cyanotic or acyanotic CHD; median (IQR): 28 (13–72) months; majority male; $n = 25$	Congenital cardiac surgery	LUS B-line scoring has limited utility in semiquantitative estimation of EVLWI at lower thresholds of EVLWI in pediatric cardiac surgical patients
Ozturk et al,[59] Turkey	To evaluate the efficacy of thoracic ultrasonography during echocardiography in newborns	Observational—cohort	General ICU/ITU	Sixty newborns who had undergone pediatric cardiac surgery; median (range): 14 days (2–30 days); majority male, $n = 60$	Congenital cardiac surgery	Except for one of the cases determined by both methods, five of the cases were diagnosed by ultrasonography. There was a moderate correlation when all pathologies evaluated together ($k = 0.51$)
Paczkowski et al,[60] Poland	To assess usefulness of transthoracic ultrasound in monitoring pediatric patients after cardiac surgery with ECC	Observational—cohort	NR	Pediatric patients who were qualified to cardiac surgery with ECC; average (range): 13.7 months (5 days–6 years); $n = 33$	NR	Our early data suggest that transthoracic ultrasound brings extra information during intensive care for pediatric patients after cardiac surgery with ECC
Paczkowski et al,[23] Poland	To present the possibility of using transthoracic ultrasound of the lungs during postoperative monitoring in children with CHD after cardiac surgery under ECC conditions	Observational—cohort	NR	Children who underwent cardiac surgery; mean (range): 15.7 months (5 days–11.8 years); majority male; $n = 126$	Congenital cardiac surgery	Ultrasound images of lungs were entirely correct in all cases before surgery and no abnormalities were observed, whereas on the first or the second day after surgery several ultrasound findings were observed
Palamattam et al,[61] India	To study the degree of agreement between CUS studies and CXR studies in postoperative pediatric cardiac surgical patients regarding diagnosis of thoracic abnormalities and also to compare the diagnostic performance of CUS in reference to CXR for the detection of thoracic abnormalities	Observational—cohort	General ICU/ITU	Patients who were in the age group of 2 months–18 years and were undergoing elective cardiothoracic surgery; mean: 6.04 $\pm$ 4.68 years; majority male; $n = 160$	Congenital cardiac surgery	The degree of agreement between CUS and CXR studies was substantial for atelectasis, interstitial edema and diaphragmatic weakness. The degree of agreement between CUS and CXR studies was almost perfect for pneumothorax and fair for pleural effusion
Parlevliet et al,[62] Netherlands	To assess whether routine LUS can detect cr-PPCs earlier than routine CXR in patients after cardiac surgery	Observational—cohort	Tertiary ICU	Cardiac surgical patients, $n = 40$	NR	LUS detects the more PPCs and cr-PPCs than CXR and in an earlier stage
Phillips et al,[63] USA	To describe a case where handheld ultrasound was used to assess a deteriorating woman in her 90s	Observational—case study/report	NR	A woman in her 90s	Valve repair/replacement, pacemaker implantation	This case illustrates the versatility of handheld ultrasound in augmenting the physical examination to rapidly assess potentially malignant causes of dyspnoea and reinforces the notion that complicated does not exclude the common
Piccoli et al,[64] Italy	To assess the potential value of HCU devices in the diagnosis and follow-up of patients with pleural effusion after cardiac surgery	Observational—cohort	NR	Patients admitted to a center to participate in a cardiac rehabilitation program after cardiac surgery; mean: 68 $\pm$ 9 years; majority male; $n = 70$	CABG, valve repair/replacement, vascular replacement	The correlation between ultrasound and radiographic scores was statistically significant
Polito et al,[65] Italy	To report the case of a 12-day-old newborn affected by coarctation of the aorta and intraventricular defect who underwent coarctectomy and pulmonary artery banding	Observational—case study/report	CICU/CITU	A 12-day-old newborn affected by coarctation of the aorta and intraventricular defect who underwent coarctectomy and pulmonary artery banding	Congenital cardiac surgery	Our case and published evidence suggest that ultrasound assists in early diagnosis and prompt treatment of reversible causes of asystole/pulseless electric activity obtaining rapid return of spontaneous circulation
Ramelli et al,[66] Italy	To evaluate whether physiotherapy treatment was able to induce changing in LUS pattern in the postoperative patients	Observational—cohort	NR	Cardiac surgery patients; majority male; $n = 19$	NR	Physiotherapy may induce increase of reaeration when evaluated with LUS even though it is not able to reduce consolidation
Ricci et al,[67] Italy	To evaluate the diagnostic performance of CPUS for early rule-in and rule-out diagnosis of PHF	Observational—cohort	CICU/CITU	Elective cardiac surgery patients; mean: 69.6 $\pm$ 2.7 years; $n = 81$	NR	CPUS provides unique opportunity for early rule-in and rule-out of PHF in cardiac surgery ICU
Ricci et al,[68] Italy	To evaluate the prognostic value of pulmonary and hemodynamic congestion, as assessed by CPUS, for the prediction of the 1-year composite outcome of cardiac death, cardiovascular hospitalizations and worsening NYHA functional status, in a cohort of patients admitted to the CSICU of our hospital	Observational—cohort	CICU/CITU	Cardiac surgery patients; Mean: 69.6 $\pm$ 2.7 years; $n = 55$	NR	CPUS provides unique opportunity for early detection and noninvasive bedside monitoring of pulmonary and hemodynamic congestion
Ricci et al,[69] Italy	To assess the diagnostic performance of ULCs, alone or in combination with TTE, compared with CXR and NT-proBNP, for the early diagnosis of AHF in a cohort of patients admitted to the CSICU of our hospital	Observational—cohort	CICU/CITU	Cardiac surgery patients; mean: 71.1 $\pm$ 8.8 years; $n = 42$	NR	In postcardiac surgery LUS allows rapid and reliable ruling out of AHF. LUS represents an attractive, radiation-free, bedside, noninvasive tool for early detection of EVLW
Ricci et al,[70] Italy	To investigate accuracy of LUS in assessing lung water in critically ill children with pulmonary overflow	Observational—case-control	NR	Critically ill children with pulmonary overflow, $n = 10$	NR	LUS B-lines are correlated with EVLW in neonates and children with CHDs characterized by pulmonary overflow

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
Richard et al,[71] Canada	To assess whether increased preoperative semiquantitative assessment of B-lines with LUS was associated with prolonged ICU and hospital LOS after heart surgery	Secondary analysis	General ICU/ITU	Adults undergoing nonemergent cardiac surgery; mean: 63.7 ± 10.4 years; majority male; $n = 115$	CABG, valve repair/ replacement, ascending aorta repair	The presence of preoperative pulmonary edema identified with semiquantitative assessment of B-lines with LUS is associated with a longer hospital and ICU LOS
Sausse et al,[72] France	To describe the incidence and severity of the alteration of the TELUS imaging before and after CPB in adult cardiac surgery and the relation of these changes to the occurrence of PORE	Observational—cohort	General ICU/ITU	Patients with cardiac surgery and cardiopulmonary bypass and TEE monitoring; $n = 72$	NR	Patients with PORE have a significantly higher TELUS post-CPB suggesting that structural changes and lung de-aeration captured by TELUS occur during CPB
Sengel et al,[73] Turkey	To identify pulmonary interstitial edema with lung ultrasonography after open-heart surgery and searching the reasons of edema	Observational—case-control	General ICU/ITU	Patients with or without interstitial edema after open-heart surgery	NR	Because of noninvasiveness and bedside usage, we thought that the use of LUS should be generalized
Senniappan et al,[12] India	To compare the diagnosis predicted from LUS to the diagnosis made from routine bedside CXR and to find the degree of agreement in diagnosis made by both modalities in different cardiopulmonary pathologies in ICUs	Observational—cohort	CICU/CITU	Patient between 18 and 75 years of age, undergoing elective cardiothoracic and vascular surgery; mean: 55.45 ± 13.81 years; majority male; $n = 250$	CABG, valve repair/ replacement, congenital cardiac surgery	For specific cardiopulmonary pathologies, the degree of agreement was moderate for pleural effusion ($\kappa = 0.561$), substantial for atelectasis ($\kappa = 0.673$), interstitial edema ($\kappa = 0.707$), and perfect for pneumothorax ($\kappa = 0.931$)
Singh et al,[74] India	To observe the correlation between weaning failure, which we defined as reintubation within 24–48 hours of extubation and ultrasonic assessment of EVLW and diaphragm function in pediatric patients on mechanical ventilation after cardiac surgery	Observational—cohort	Cardiothoracic surgical ICU	Patients aged 1 month–18 years undergoing cardiac surgery under CPB; mean (range); Group 1: 1 (0.25–7) years; Group 2: 3 (0.25–17) years; majority male; $n = 50$	Congenital cardiac surgery	LUS cannot predict weaning failure. The diaphragmatic thickening fraction < 17.15% was found to be a predictor of weaning failure in our patients
Song et al,[75] South Korea	To assess the utility of perioperative LUS and effect of ultrasound-guided recruitment maneuver in pediatric cardiac surgery	RCT	PICU, OR	Pediatric patients aged 5 years old or younger who were scheduled for cardiac surgery of acyanotic CHD; control group: 10 months ± 14; intervention: 15 months ± 16; majority male; $n = 122$	Congenital cardiac surgery	Perioperative LUS examination followed by ultrasound-guided recruitment maneuver helped decrease postoperative desaturation events and shorten the duration of mechanical ventilation in pediatric cardiac patients
Steenvoorden et al,[76] Netherlands	To present a unique case of the presence of lung point in the absence of pneumothorax in a 75-year-old man admitted after CABG	Observational—case study/report	NR	A 75-year-old man admitted after CABG	CABG	Absent lung sliding and lung point can be observed in cases of pleural thickening and adhesion and may thus warrant revision of the perception that lung point is pathognomonic for pneumothorax
Sun et al,[77] China	To explore the effect of iPEEPRM in children with CHDs using LUS	Observational—cohort	NR	Children aged between 3 months and 5 years old with CHD who were scheduled for elective cardiac surgery under general anesthesia; mean (range): 12 (5.3–34.5) months; majority male; $n = 36$	Congenital cardiac surgery	LUS was used as an outcome measure for incremental PEEP recruitment maneuver in children undergoing cardiac surgery
Thuraisingam et al,[78] Australia	To compare the accuracy of LUS to CXR when assessing postoperative cardiac surgery patients	Observational—cohort	NR	Postoperative cardiac surgery patients; mean: 61 ± 18.7 (range: 31–82); majority male; $n = 28$	NR	These pilot data suggest neither clinical examination nor CXR have high accuracy for three common postoperative chest complications in postoperative cardiac surgery patients when compared with LUS
Touw et al,[79] Netherlands	To compare the performance of LUS with CXR in detecting PPCs and clinically relevant PPCs, defined as PPCs that required treatment, after cardiothoracic surgery	Observational—cohort	General ICU/ITU	Cardiothoracic surgery patients; mean (*SD*): 68 (10) years; majority male; $n = 177$	CABG, valve repair/ replacement	Overall interobserver agreement for LUS was excellent ($k = 0.907$, $P < .001$)
Ueda et al,[80] USA	To describe two cases in which intraoperative transthoracic ultrasound rapidly established a diagnosis of pneumothorax and facilitated timely utilization of resources for definitive treatment	Observational—case study/report	OR	A 58-year-old male with multiple psychiatric disorders, including schizophrenia, was brought to the emergency treatment center after jumping from the second story of a building	Endovascular repair of the aorta dissection	Transthoracic ultrasound can provide critical information pertaining to diagnosis of a pneumothorax in the operation room setting
Usta et al,[81] Germany	To establish a practical simplified formula to facilitate the management of a frequently occurring postoperative complication, pleural effusion	Observational—cohort	NR	Spontaneous breathing cardiac surgery patients requiring thoracentesis performed under ultrasound guidance; median (range): 60 (45–67) years; majority male; $n = 150$	CABG, valve repair/ replacement	With our simplified formula we could easily quantify pleural effusion and could decide cost and time effectively whether or not to perform a thoracentesis
Vargas et al,[82] NR	To prospectively analyze the relationship between pericardial effusion and pleural effusion in patients undergoing CABG	Observational—case-control	NR	Patients undergoing elective myocardial revascularization for treatment of their coronary artery disease; mean (years) SVG group: 62.10 ± 10.12; IMA group: 59.72 ± 7.73; majority male; $n = 47$	CABG	LUS was used to assess for pleural effusions after different grafts
Vergara Sanchez et al,[83] Spain	To study the correlation between the number of B-lines at the time of discharge from the CCU and the rate of readmission and mortality in cardiac surgery patients	Observational—cohort	CCU	Patients undergoing valvular surgery, coronary revascularization surgery with and without CPB, transcatheter aortic valve implantation and combined surgeries; majority male; $n = 104$	CABG, valve repair/ replacement, transcatheter aortic valve implantation	Patients who were readmitted to the CCU or hospital ward usually have more number of B-lines at discharge, without being this difference statistically significant

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
Vezzani et al,[84] Italy	To evaluate whether CUS could be able to identify early abnormalities after cardiac surgery in comparison with chest auscultation and chest x-ray	Observational—cohort	Cardiac surgery ICU	Adult patients undergoing cardiac surgery; mean: 70 ± 10 years; majority male; $n = 151$	CABG, valve repair/ replacement	There was a highly significant correlation between abnormalities detected by CUS and x-ray ($k = 0.90$), but a poor correlation between chest auscultation and x-ray abnormalities ($k = 0.15$)
Vitale et al,[85] Italy	To describe five pediatric cardiac patients who had postoperative lung complications	Observational—case series	Pediatric cardiac ICU	Pediatric cardiac patients who had postoperative lung complications; 2 years, 30 days, 15 days, 5 months, 4 years; $n = 5$	Congenital cardiac surgery	LUS provides a noninvasive way to diagnose perioperative lung complications (pleural effusion, pneumothorax, atelectasis, and pneumonia) of children affected by CHDs with real-time monitoring, complementing radiographic images, and potentially decreasing the total number of radiographs made in the pediatric intensive care unit
Vitale et al,[86] Italy	To explore the association between LUS and clinical variables in children undergoing CPB	Secondary analysis	Pediatric cardiac ICU	Children whose body weight was < 20 kg and who had an Aristotle score ≤ 9 who required elective cardiac surgery on CPB; median (IQR): 3.25 (3.0–7.25) months; majority male; $n = 20$	Congenital cardiac surgery	In a small cohort of children undergoing CPB, the LUS profile on POD1 was associated with CPB time, aortic cross-clamp time and mechanical ventilation duration
Vitomskyi et al,[87] Ukraine	To determine the impact of implementing an extra early mobilization protocol and other factors on effusion in patients undergoing cardiac surgical procedures	Secondary analysis	General ICU/ITU	Adult cardiac surgery patients; Median (upper; lower quartile); EEM group: 58 (65; 71) years; EM group: 56 (63.5; 71) years; majority male; $n = 351$	CABG, valve repair/ replacement, ventricular aneurysm	LUS was used as an outcome measure for the study
Wang et al,[15] China	To investigate the value of LUS in the diagnosis and treatment of atelectasis after cardiac surgery	Observational—cohort	NR	Patients with secondary respiratory failure within 1 week after cardiac surgery; range: 32–67 years; mean: 47±5 years; majority male; $n = 45$	CABG, valve repair/ replacement, aortic dissection	The accuracy of LUS in evaluating atelectasis after cardiovascular surgery is consistent with that of chest CT
Wu et al,[88] China	To determine the most efficient region to assess changes in atelectasis in children with CHD under general anesthesia	RCT	OR	Pediatric patients scheduled for elective CHD surgery under general anesthesia; median (IQR) months; PEEP group: 9.5 (4.3–16.8); control: 11.5 (8.3–25.8); equal split; $n = 40$	Congenital cardiac surgery	LUS in inferoposterior lung regions may be more likely to reflect changes in atelectasis and save examination time
Wu et al,[89] China	To explore the feasibility of using LUS to assess pulmonary overcirculation in CHD children and compare the diagnostic performance of LUS and CXR for the detection of pulmonary overcirculation	Observational—cohort	NR	Children aged between 3 months and 7 years, and scheduled for elective congenital heart surgeries under general anesthesia; median (IQR): 10 (5–26) months; majority male; $n = 59$	Congenital cardiac surgery	The sensitivity, specificity, and diagnostic accuracy of PO were 96%, 94%, and 95% for LUS and 74%, 50%, and 63% for CXR. The percentage of mild, moderate, and severe PO diagnosed via LUS was 31% (18/59), 19% (11/59), and 2% (1/59), respectively
Young et al,[90] USA	To present a rare case of PCIS with atypical features following RFCA	Observational—case study/report	NR	A 58-year-old male with atrial fibrillation underwent RFCA	Catheter ablation	CXR revealed minimal pleural effusions. Pleural ultrasonography showed trivial effusions not amenable to thoracentesis. PCIS went unnoticed
Narrative reviews; narrative, opinion, and text						
Lead author, country	Aim	Type	Setting	Participant description	Type of surgery	Author's description of key findings
Antonella et al,[91] Italy	To evaluate the usefulness and therapeutic efficacy of auscultation, ultrasound, and CXR for identifying clinically significant findings in cardiac surgery patients	Letter to the Editor	General ICU/ITU	Cardiac surgery ICU patients; $n = 151$	NR	Chest ultrasound identified all abnormalities requiring interventions and showed a good agreement with CXR
Bertolone et al,[92] Italy	To summarize LUS applications for the evaluation and management of patients admitted to Cardiac Rehabilitation Unit	Narrative review	Cardiac rehab unit	Patients admitted to the cardiac rehab unit; $n = NR$	NR	LUS should be performed in six scan each hemithorax, covering 12 imagine regions. For each scan will be noted a specific physiologic or pathological pattern. Furthermore, we suggest for each patient, the use of the LUS score to obtain a global view of lung aeration and to monitor any changes during the hospitalization
Cantinotti et al,[93] Italy	To review the different ways of exploring the entire chest before and after cardiac surgery	Editorial Commentary	NR	NA	NR	Chest radiography is a fundamental tool in cardiac surgery, but it may be replaced by CT preoperatively, at least in selected cases, and by LUS to monitor common postoperative pulmonary complications
Cantinotti et al,[94] Italy	To provide a comprehensive overview and list of current potential applications for LUS in children with CHD, postsurgery, with the hope of encouraging its use for this important patient population	Narrative review	General ICU/ITU, NICU, PICU	Cardiac surgery patients	NR	LUS is an easy, accurate, fast, cheap, and radiation-free tool for the diagnosis and follow-up of major pulmonary complications in pediatric cardiac surgery, and we strongly encourage its use in routine practice
Cantinotti et al,[95] Italy	To discuss the use of LUS to reduce radiographic examinations in pediatric cardiac surgery patients	Letter to the Editor	General ICU/ITU	Pediatric cardiac surgery patients; Study 1 mean: 7.09 ± 12.34 years; range: 0–17 years; $n = 1487$; Study 2 median age: 9.3 months; $n = 79$	NR	Judicious use of LUS in pediatric cardiac surgery (1) significantly reduced the amount of chest radiographic examinations without any adverse patient outcome and (2) was associated with substantial cost benefit

(continued)

Table 1. (continued)

Empirical research studies

Lead author, country	Aim	Study type	Setting	Participant description	Type of surgery	Author's description of key findings
Cantinotti et al,[96] Italy	Responding to a comment by Sperandeo regarding an article	Letter to the Editor	NR	NA	NR	LUS is a valuable test in pediatric cardiac surgery that complements traditional chest radiography and could also have prognostic potential. When performing LUS, it is important to keep limitations in mind, particularly the difficulty to understand the etiologies of B-lines
Cantinotti et al,[97] Italy	To discuss research concerning the use of LUS in the pediatric cardiac surgery setting	Editorial	General ICU/ITU, NICU	Children undergoing pediatric cardiac surgery	NR	LUS may provide not only diagnostic but also prognostic information in pediatric cardiac surgery setting. LUS should become a basic diagnostic tool for multiple professional skills involved in the care of the children undergoing cardiac surgery for CHD, including cardiologist, anesthetists, surgeons, physiotherapists, and nurses
Cantinotti et al,[2] Italy	To review the existing scientific literature about applications of LUS in cardiac surgery, with special attention to the pediatric population	Narrative review	NR	Cardiac surgery patients with a focus on pediatrics	NR	Implementation of LUS in clinical practice may help to reduce excessive and unnecessary radiology tools, thereby decreasing radiation exposure, time, and costs. Up to now, the use of LUS in cardiac surgery has been mainly limited to the evaluation of pleural effusion and more recently to the assessment of diaphragmatic mobility in children
Efremov et al,[98] Russia	To improve the awareness of LUS among specialists involved in the treatment of cardiac patients	Narrative review	General ICU/ITU	NA	NR	The authors believe that the following points must be addressed urgently to successfully implement LUS in routine practice: (1) standardized LUS protocols, (2) educational standards and training programs focused on LUS, and (3) studies regarding the effects of LUS-guided interventions on clinically relevant outcomes
Garduno-Lopez et al,[99] Mexico	To lay out the need for the creation of a new ultrasonographic protocol focused on the initial assessment of cardiac surgery postoperative patients	Narrative review	CICU/CITU	Cardiac surgery postoperative patients	NR	Ultrasound is a highly useful tool for approach and decision-making in patients in critical conditions
Hamadah et al,[100] Saudi Arabia	To highlight the role of US in detecting the most common causes of respiratory weaning difficulties and extubation failure in postoperative cardiac children through proposed illustration and algorithm	Narrative review	Pediatric cardiac ICU	The first group consists of patients who failed an extubation trial postsurgery and required reintubation; the second group is those patients who experienced respiratory weaning difficulties after pediatric cardiac surgery	NR	PCICU ultrasound (US) stands as a simple, basic bedside tool that can be performed by trained intensivists for the diagnosis with immediate implication on therapeutic decisions in multiple scenarios that physicians may face in PCICU
Santos-Martinez et al,[101] Mexico	To discuss the use of pulmonary ultrasound to evaluate hemodynamic status of postcardiac surgery patients	Scientific Letter	CICU/CITU	Cardiac surgery patients	NR	LUS can be used to assess hemodynamic evaluation in the early postoperative period of cardiac surgery
Saranteas et al,[102] Greece	To underline a case where the role of ultrasound examination as an important diagnostic tool in the ICU setting	Letter to the Editor	General ICU/ITU	A 79-year-old man who underwent CABG cardiac surgery	CABG	This case underlines the role of ultrasound examination as an important diagnostic tool in the ICU setting
Saranteas et al,[103] Greece	To present an interesting case in which both TTE and LUS aided in the differentiation between pericardial and left pleural effusion in a cardiac surgery patient	Letter to the Editor	General ICU/ITU	A 52-year-old woman underwent tricuspid valve repair and was referred to the intensive care unit	Valve repair/replacement	Our case shows that ultrasound monitoring not only aided in the diagnosis of pericardial tamponade but also contributed to the suitable therapeutic management
Sperandeo et al,[104] Italy	To comment on research done by Cantinotti et al (2020)[33]	Letter to the Editor	NR	NA	NA	Limitations of thoracic US and complementarity to standard radiology should be kept in mind to avoid fatal errors
Steppan et al,[105] USA	To discuss LUS use in the US PICU and discuss Cantinotti's contribution	Editorial	PICU	Pediatric population	NR	It is on the community to participate in the design and implementation of prospective RCTs to assess its feasibility and utility
Townsley et al,[106] USA	To discuss the use of LUS in pediatric cardiac surgery	Editorial	NR	Pediatric cardiac surgery patients	NR	Both applications of LUS in the domain of pediatric cardiac surgery offer exciting potential for more widespread adoption of this modality in the immediate future

Abbreviations: AAA, abdominal aortic aneurysm; AHF, acute heart failure; ARF, acute respiratory failure; AVM, adaptive ventilation mode; BNP, brain natriuretic peptide; CABG, coronary artery bypass grafting; CCU, critical care unit; CHD, congenital heart disease; CICU, cardiac intensive care unit; CITU, cardiac intensive treatment unit; CPB, cardiopulmonary bypass; CPUS, cardiopulmonary ultrasound; CSICU, cardiac surgery intensive care unit; CUS, chest ultrasound; CS, cardiac surgery; CXR, chest radiograph; EEM, extra early mobilization; ECC, extracorporeal circulation; EVLW, extravascular lung water; EVLWI, extravascular lung water index; HCU, hand-carried ultrasound; IMA, internal mammary artery graft; ICU, intensive care unit; iPEEPRM, incremental positive end-expiratory pressure recruitment maneuver; IQR, interquartile range; ITU, intensive treatment unit; LIS, lung interstitial syndrome; LOS, length of stay; LUCAS, lung ultrasonography in cardiac surgery; LUS, lung ultrasound; LV, left ventricular; LVEF, left ventricular ejection fraction; NIV, noninvasive ventilation; NA, not applicable; NICU, neonatal intensive care unit; NLR, neutrophil-to-lymphocyte ratio; NR, not reported; NYHA, New York Heart Association; OR, odds ratio; PCICU, pediatric cardiac intensive care unit; PCIS, postcardiac injury syndrome; PCWP, pulmonary capillary wedge pressure; PEEP, positive-end expiratory pressure; PHF, postoperative heart failure; PICU, pediatric intensive care unit; POD, postoperative day; PO, Pulmonary overflow; PL, pulmonary lymphangiectasia; PLR, platelet-to-lymphocyte ratio; PORE, postoperative respiratory events; PPC, postoperative pulmonary complication; Q-LUS, quantitative LUS; RCT, randomized controlled trials; RFCA, radiofrequency catheter ablation; SD, standard deviation; SVG, saphenous vein graft; STAT, Society of Thoracic Surgeons/European Association of Cardio-Thoracic Surgery; TTE, transthoracic echocardiography; TELUS, transesophageal lung ultrasound; V-LUS, visual LUS; ULC, ultrasound lung comets.
This table is divided into two sections: empirical research studies and narrative reviews; narrative, opinion, and text.

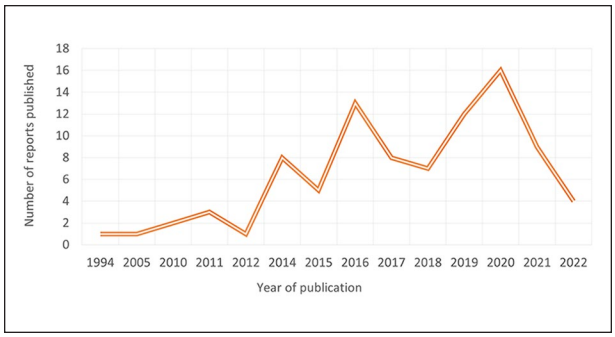

Figure 2. A graph of the publications by year, based on all included 90 reports.

Table 2. The reported LUS methods.

Profession of LUS operator (n = 24)	
Medical consultant	16
Anesthesiologist	10
Physiotherapist	5
Medical resident	2
Nurse	2
Ultrasonographer	2
Anesthetist	2
Radiographer	1
NR	66
LUS protocols (n = 54)	
Previously reported protocols (n = 25)	
Volpicelli 2012[107]	9
The BLUE-protocol[8]	7
Acosta 2014[108]	4
Lichtenstein 2012[109]	2
Cantinotti 2018[30]	1
Monastesse 2017[110]	1
Bouhemad 2015[111]	1
Volpicelli 2006[112]	1
Lichtenstein 2004[113]	1
Coiro 2015[114]	1
Targhetta 1994[115]	1
The FALLS protocol[8]	1
Cattarossi 2013[116]	1
Picano 2006[117]	1
CCROSS[99]	1
eFAST[118]	1
FAST[118]	1
Author-modified protocols (n = 26)	
12 regions	15
6 regions	7
8 regions	3
28 regions	2
4 regions	3
NR	36

(continued)

Table 2. (continued)

Reason for using LUS (n = 90)	
Compare diagnostic ability	30
Feasibility of a new prognostic tool	22
Monitor pathology progression	18
Assess a deteriorating patient	16
Confirm or rule out suspected pathology	16
Feasibility of new protocol	13
Standard protocol	12
Prognostic tool	10
Outcome measure	8
Question diagnostic ability	1
NA	1
Number of LUS operators in primary studies (n = 25)	
1 operator	19
2 operators	2
3 operators	3
NR	51
NA	14
Time windows in relation to cardiac surgery (n = 86)	
Preoperative	21
Perioperative	4
Immediately after surgery	6
Postoperative not specified	28
On admission	4
Postoperative day 0	44
Postoperative day 1	18
Postoperative day 2	11
Postoperative day 3	7
Postoperative day 4	3
Postoperative day 5	5
Postoperative day 6	2
Postoperative day 7	4
Before/after intervention	6
Before discharge	7
Other	11
NR	4

Abbreviations: LUS, lung ultrasonography; NA, not applicable; NR, not reported; FALLS, fluid administration limited by lung sonography; CROSS, Cardiac, cerebral, renal, optic nerve, and lung ultrasound study; eFAST, extended Focused Assessment with Sonography for Trauma; FAST, Focused Assessment with Sonography for Trauma. This tables shows the number of reports which reported certain aspects of the LUS methods. Some reports have reported more than one type within each category.

How and Why has LUS Been Used With Cardiac Surgery Patients?

Ten reasons for using or discussing LUS were identified from included reports (Table 2). Primary studies most commonly aimed to compare or determine the diagnostic (n = 27, 37%) or prognostic (n = 22, 30.1%) ability of

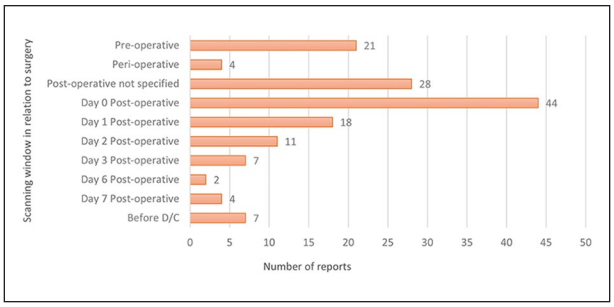

Figure 3. The scanning windows, used for lung ultrasonographer, in relation to cardiac surgery from preoperative to 1 week and D/C. D/C, discharge.

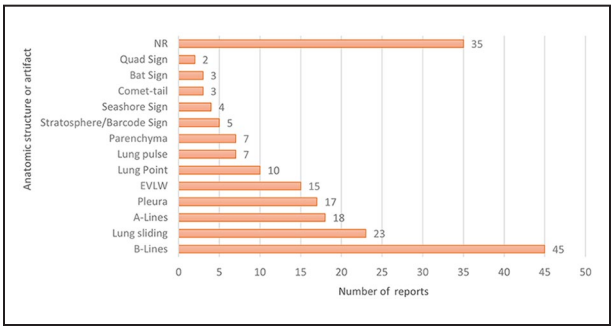

Figure 4. The anatomic features and artifacts found or sought, using lung ultrasonography (LUS), across all included 90 reports. EVLW, extravascular lung water; NR, not reported.

LUS. In narrative reviews and within narrative, opinion, and text, LUS was most commonly suggested to be a prognostic tool ($n = 8$, 47.1%) or used as a standard protocol ($n = 8$, 47.1%) for cardiac surgery patients. Other suggested reasons for use across all included reports were using LUS to monitor pathology progression ($n = 18$, 20.2%), to assess a deteriorating patient ($n = 16$, 18%), and either to confirm or rule out a suspected pathology ($n = 16$, 18%).

Within primary studies, LUS was most commonly performed on postoperative day (POD) 0 ($n = 40$, 55.6%) followed by preoperatively ($n = 20$, 27.8%), POD1 ($n = 17$, 23.6%) and POD2 ($n = 10$, 13.9%). In the narrative reviews and narrative, opinion, and text, most reports suggested that LUS should be used postoperatively, but did not specify a day or time ($n = 9$, 64.3%). The frequency of scanning windows for up to POD7 and discharge can be seen in Figure 3 while a more extensive list can be seen in Table 2.

Which Anatomic Structures, Artifacts, and Pathologies Were Investigated?

The included reports found, sought, or discussed several anatomic structures, artifacts, and pathologies that can be investigated with LUS with many reporting more than one

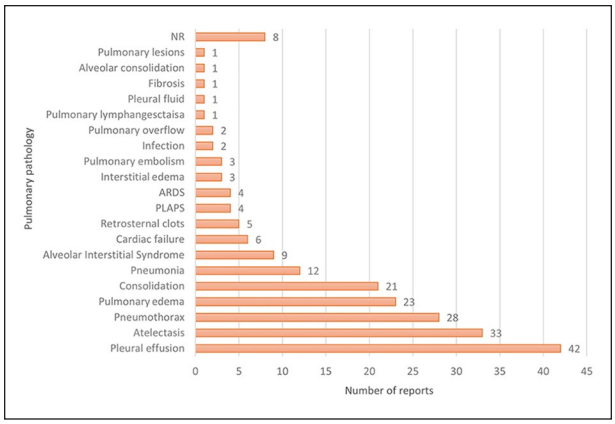

Figure 5. The pulmonary pathologies found or sought, using lung ultrasonography (LUS), across all included 90 reports. ARDS, acute respiratory distress syndrome; NR, not reported; PLAPS, posterolateral alveolar and/or pleural syndrome.

of each. Across all reports, B-lines were the most identified and sought artifact ($n = 45$, 81.8%) followed by lung sliding ($n = 23$, 41.8%) and A-lines ($n = 18$, 32.7%) (See Figure 4). Narrative reviews and narrative, opinion, and text discussed using B-lines to assess for extravascular lung water (EVLW) ($n = 7$, 63.6%). Eight primary studies used B-lines for this purpose (18.2%). Of the 82 reports, which reported pulmonary pathologies (91%), the most common pathologies of focus were pleural effusion ($n = 42$, 51.2%), atelectasis ($n = 33$, 40.2%), pneumothorax ($n = 28$, 34.1%), pulmonary edema ($n = 23$, 28%), and consolidation ($n = 21$, 25.6%) (See Figure 5).

Who is Conducting LUS?

The profession of the LUS operators in primary studies was underreported with only 23 studies reporting a profession (31.5%). Of those 23 studies, the most common professions were anesthesiologists ($n = 9$, 39.1%) and medical consultants ($n = 9$, 39.1%). In the narrative reviews ($n = 4$, 4.4%) and editorials ($n = 2$, 2.2%), which discussed operator profession, physiotherapists ($n = 3$, 50%), and nurses ($n = 2$, 33.3%) were the most common nonphysician health care professions. Nonphysician LUS operators were first identified in an editorial in 2017,[97] with the first primary study involving a nonphysician LUS operator being published in 2019 and featuring a physiotherapist in a single patient case study.[47] An observational cross-sectional study included a physiotherapist as one of the two LUS operators along with a cardiologist in a study the following year.[43] Of the 25 primary studies that reported the number of LUS operators, it was most common to have one LUS operator for the study ($n = 19$, 76%). There were never more than three operators involved.

What LUS Methods Were Utilized?

There was a lack of reporting regarding LUS methods and protocols. Only 25 of all reports, where applicable, reported how many LUS operators were involved (43%), only 24 reports (26.7%) mentioned the profession of the LUS operator, and only 25 (27.8%) reported a previously reported LUS protocol. Of the primary studies, only 20 reported using a previously reported LUS protocol (27.4%).

There was a large variety of protocols used or discussed across all reports; a total of 18 different previously reported protocols were mentioned. Twenty-five primary studies used an author-modified protocol—a protocol which involved scanning either 4, 6, 8 12, or 28 regions of the chest, but did not cite a protocol previously reported (34.2%). The specific regions scanned varied across all author-modified protocols. The most commonly reported protocol was the international evidence-based recommendations for LUS by Volpicelli et al[107] ($n = 7$, 35%) followed by Acosta et al[108] ($n = 4$, 20%) for the pediatric population. Protocols were infrequently discussed in narrative reviews or narrative, opinion, and text ($n = 5$, 29.4%). Nonetheless, the most commonly reported protocol in these five reports was the BLUE-protocol[8] ($n = 3$, 60%).

This review also found a wide variety and combinations of scanning windows. While it was most common for patients to be scanned in the combination of preoperatively and POD0 ($n = 6$, 6.7%), there were a total of 69 unique combinations for when LUS was performed in relation to cardiac surgery. The most common scanning windows have been synthesized and reported individually by number of reports in Table 2 with several unique time windows grouped as "other," for example, after 1 week of birth, before or after imaging, or POD18.

Discussion

In this scoping review, literature concerning the use of LUS with cardiac surgery patients was identified and explored, providing a comprehensive map of the evidence base to date. Lung ultrasonography has gained significant traction over the last decade, with a growing number of publications since 2014 exploring its use in this patient group. The reporting of LUS methods, however, was found to be inconsistent; this needs to be addressed in future research to better interpret and generalize findings to be applied in clinical practice.

Types of Sources

A total of 90 reports were included, none of which were systematic reviews. The reporting of LUS methods in primary studies, however, was variable and heterogeneous, which makes formal synthesis of the current evidence base challenging. Evidence syntheses are valuable resources for clinicians and are used to inform clinical practice guidelines. Therefore, there is a need for further high-quality research to be conducted and adequately reported to better facilitate future synthesis of the evidence base to provide robust practice recommendations. Moreover, no qualitative studies were identified with the search strategy, highlighting the need for further research to investigate the facilitators, barriers, and perspectives of patients and clinicians regarding the use of LUS in the cardiac surgery population. While it is vital to conduct quantitative research, it is equally valuable to investigate how best to integrate LUS into practice through qualitative exploration of patients' and clinicians' experiences.

The Pediatric Population

Just over half of the reports were centered on the pediatric patients, with the most prevalent surgery type being congenital cardiac surgery. Lung ultrasonography has become popular in this patient group, due to its noninvasive and nonionizing nature and is being used more often for the diagnosis and surveillance of pediatric pulmonary conditions.[119]

The Uses of LUS

The use of LUS as a diagnostic tool has been extensively studied in both cardiac surgery patients and other groups. Lung ultrasonography use to identify PPCs has been seen in this review as monitoring pathology progression, assessing deteriorating patients, and confirming or ruling out suspected pathologies. Furthermore, LUS has also gained popularity as a prognostic tool. Pulmonary edema became a pathology of interest within the included reports in 2012,[23] and in 2014, B-lines began to be used to assess for EVLW to predict and diagnose pulmonary edema.[70] Another way LUS is used as a prognostic tool is using a LUS score to attempt to predict a variety of conditions. Lung ultrasonography score can be used to predict death, intensive care unit (ICU) admission, endotracheal intubation, and weaning failure with moderate accuracy.[120] Some authors have described the potential for LUS to go beyond its role as a diagnostic tool, specifically as a way of measuring the effectiveness of recruitment maneuvers.[121,122] Only eight studies in this review (8.9%) explored using LUS as an outcome measure for intervention. This potential ability of LUS therefore requires more exploration through further high-quality research.

The Use of LUS by Nonphysician Health Care Professions

The evidence base regarding nonphysician health care professionals using LUS, with cardiac surgery patients is limited. Studies with noncardiac patients have explored

this concept: Le Neindre et al[123] explored the influence of LUS on physiotherapists; for example, clinical decision-making when managing critical care patients. Further studies have begun to assess the ability of nurses to operate traditional[124,125] and handheld LUS[126] following surgery or to assess cardiogenic dyspnoea. In addition, several narrative reviews have discussed the potential for nonphysician health care professionals to use LUS within their scope of practice.[10,127] Considering the rate of mortality in postcardiac surgery patients, it is important to detect PPCs early on; Increasing the accessibility of LUS for other professions within the multidisciplinary team may aid in detecting PPCs earlier and allow for more appropriate treatment sooner. Further primary research involving these professional groups is required if this potential is to be realized.

LUS Techniques and Methods

This review found a lack of reporting regarding LUS techniques and methods. This is consistent with other LUS evidence syntheses: Heldeweg et al[128] raised the same concern for methodological inconsistencies in a systematic review evaluating the impact of LUS on clinical decision-making in the emergency department, intensive care, and in the general ward; Hayward and Janssen[129] found it difficult to compare studies with the numerous different scanning techniques in their scoping review exploring the use of thoracic ultrasound by physiotherapists; new international recommendations by Demi et al[130] suggest extensive studies to define the optimal imaging settings for LUS. At most, only nine reports cited the same previously reported protocol. This could be attributed to the lack of available protocols to replicate in research. The protocols most cited, Volpicelli et al[107] international recommendations and the BLUE-protocol,[8] were not introduced until 2012 and 2014, respectively. The first instance of a protocol cited in the included primary studies was in 2014 with the BLUE-protocol.[53] It is possible the sudden rise in the popularity of LUS has not allowed time for more standardized protocols to be developed and evaluated, which may be contributing to the inconsistent reporting.

The methodological inconsistency among studies could have an impact on the advancement of LUS research. For instance, the 27 primary studies assessing the diagnostic ability of LUS contained a variety of eight different protocols with a mix of previously reported protocols and protocols unique to the study. The diversity in scanning techniques and time windows may introduce confounding variables, making it difficult to generalize findings. In addition, this can pose challenges to clinicians looking to incorporate evidence-based LUS practice.

Furthermore, the protocols which have been previously reported and replicated vary in purpose and technique. The recommendations by Volpicelli et al[107] include a variety of methods. While an eight-region LUS examination is recommended for general patients with interstitial syndrome, a two-region approach is recommended for the critically ill. Other recommendations suggest what region to begin scanning and which direction to travel in without specifying a number of zones, for example, the technique for lung consolidation should begin at the area of interest and progress to the entire lung as needed. The BLUE-protocol[8] is specifically for patients with acute respiratory failure and consists of six regions, or "points." Literature in other populations suggest otherwise: a prospective cohort study evaluating the impact of different LUS protocols in the assessment of lung lesions in COVID-19 patients found a 12-region method to improve diagnostic power compared with a 10- or an eight-region method;[131] a retrospective cohort found similar results in their secondary analysis finding a 12-region method to be superior to an eight- or six-region method.[132] The protocol used by Acosta et al[108] does consist of a 12-region method for children with anesthesia-induced atelectasis; this method was used solely by studies with a pediatric population in this review, but only two were assessing for atelectasis.[21,48]

Challenges for Clinical Practice

With so many variations in protocols for varying patient groups and pathologies, conducting research with consistent LUS methods and selecting the most appropriate protocol to use clinically remains a challenge. Standardizing protocols and methods will improve consistency in the research, facilitating more effective evidence synthesis. This, in turn, can improve generalization of diagnostic findings to cardiac surgery patients. Once best practices for LUS is established, future research can more effectively investigate other queries, such as the indications for LUS, effective scanning windows, alternative LUS applications, and who may be able to use LUS in other fields. Improving clinical practice and the ability to detect PPCs in a timely and efficient manner begins with improving consistency of LUS methods in the research.

Criticism

Despite its growing popularity, there is some remaining doubt and skepticism regarding the use of LUS. One letter to the editor by Sperandeo[104] questioned the diagnostic capability of LUS when using B-lines as a pathognomonic marker of lung disease. Owing to the growing interest in LUS over the past decade, there remains a significant amount of research to be conducted

on both its established and novel applications, making it a challenging task to comprehensively investigate all aspects of the tool. As further research is needed to fully understand the potential of LUS, researchers and clinicians may continue to approach its use with caution and in conjunction with other tools.

Recommendations

Standardizing LUS protocols would be advantageous for future research, and qualitative studies could shed light on the facilitators, barriers, and perspectives of LUS operators in this population, as well as the experience of patients themselves. Once LUS best practice is established, exploring alternative applications of LUS, such as its potential as a measure of treatment effectiveness, would be beneficial. Further investigation of the use of LUS by other health care professionals, including physiotherapists and nurses, is encouraged before any recommendations for scope of practice can be made.

Limitations

This review involved a comprehensive search strategy and protocol which was developed by an experienced review team. Despite the rigorous approach, it is possible that some relevant articles may have been missed. This scoping review was limited to records which were either in English or could be translated by Google Translate. Nonetheless, the five included reports translated using Google may have a degree of inaccuracy. Illegible or untranslatable reports were excluded; therefore, mapping the entire evidence base was not possible. While the methodological quality of the literature was not assessed, this was in keeping with methodological guidance for scoping reviews,[16] which aim to map available literature rather than assess the quality.

Conclusion

This scoping review has comprehensively mapped the current literature exploring the use of LUS with cardiac surgery patients. While LUS has garnered significant attention in the field of cardiac surgery, this scoping review has identified areas requiring further investigation to fully harness its potential. Further research is needed to establish best practices for LUS, including standardizing methods, exploring its use by other professions, and conducting qualitative studies. Lung ultrasonography has the potential to improve patient outcomes by enabling early identification of PPCs. With continued research, LUS may prove to be a valuable tool for clinicians and researchers to assess cardiac surgery patients.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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Supplemental Material

Supplemental material for this article is available online. Scan the QR code with your smart device to view the online supplemental materials available at https://journals.sagepub.com/doi/suppl/10.1177/87564793231198521

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Appendix 1 Search Strategies

Medline (via EBSCOhost)

Search conducted April 6, 2022

Search	Query
#1	(MH “Lung”) OR (TX “lung”) OR (MH “Lung Diseases”) OR (TX “lung diseas*”)
#2	(MH “Ultrasonography”) OR (TX “ultraso*”)
#3	#1 AND #2
#4	(TX “lung ultraso*”) OR (TX “chest ultraso*”) OR (TX “pulmonary ultraso*”)
#5	#3 OR #4
#6	(MH "Thoracic Surgery") OR (TX “thoracic surgery”) OR (TX "cardi* surgery") OR (TX “heart surgery”) OR (TX “Coronary artery bypass *”) OR (TX "CABG") OR (TX “Heart valve repair”) OR (TX “Heart valve replacement”) OR (TX “Coronary angioplasty”) OR (TX “Coronary stenting”) OR (TX “Atherectomy”) OR (TX “Cardiomyoplasty”) OR (TX “Heart transplant”) OR (TX “Catheter ablation”)
#7	#5 AND #6
Records Retrieved: 3,007	

CINAHL (via EBSCOhost)

Search conducted April 6, 2022

Search	Query
#1	(MH “Lung+”) OR (TX “lung”) OR (MH “Lung Diseases+”) OR (TX “lung diseas*”)
#2	(MH “Ultrasonography+”) OR (TX “ultraso*”)
#3	S1 AND S2
#4	(TX “lung ultraso*”) OR (TX “chest ultraso*”) OR (TX “pulmonary ultraso*”)
#5	S3 OR S4
#6	(MH “Surgery, Cardiovascular+”) OR (TX “cardi* surgery”) OR (MH “Heart Surgery+”) OR (TX “heart surgery”) OR (TX "thoracic surgery") OR (TX “Coronary artery bypass *”) OR (TX "CABG") OR (TX “Heart valve repair”) OR (TX “Heart valve replacement”) OR (TX “Coronary angioplasty”) OR (TX “Coronary stenting”) OR (TX “Atherectomy”) OR (TX “Cardiomyoplasty”) OR (TX “Heart transplant”) OR (TX “Catheter ablation”)
#7	S5 AND S6
Records Retrieved: 2,914	

Web of Science

Search conducted April 6, 2022

Search	Query
#1	ALL=Lung OR ALL="Lung Diseases" OR (TI="Lung disease*" OR AB="Lung diseas*") OR (TI=Lung OR AB=Lung)
#2	ALL=Ultrasonography OR (TI=ultraso* OR AB=ultraso*)
#3	#1 AND #2
#4	(TI="lung ultraso*" OR AB="lung ultraso*") OR (TI="chest ultraso*" OR AB="chest ultraso*") OR (TI="pulmonary ultraso*" OR AB="pulmonary ultraso*")
#5	#3 OR #4
#6	(TI="thoracic surgery" OR AB="thoracic surgery") OR (TI="cardi* surgery" OR AB="cardi* surgery") OR (TI="heart surgery" OR AB="heart surgery") OR (TI="coronary artery bypass *" OR AB="coronary artery bypass *") OR (TI=cabg OR AB=cabg) OR (TI="heart valve repair" OR AB="heart valve repair") OR (TI="heart valve replacement" OR AB="heart valve replacement") OR (TI="coronary angioplasty" OR AB="coronary angioplasty") OR (TI="coronary stenting" OR AB="coronary stenting") OR (TI=atherectomy OR AB=atherectomy) OR (TI=cardiomyoplasty OR AB=cardiomyoplasty) OR (TI="heart transplant" OR AB="heart transplant") OR (TI="catheter ablation" OR AB="catheter ablation")
#7	#5 AND #6
Records Retrieved: 484	

Scopus

Search conducted April 6, 2022

Search	Query
#1	INDEXTERMS(Lung) OR INDEXTERMS("Lung Diseases") OR TITLE-ABS("Lung diseas*") OR TITLE-ABS(Lung)
#2	INDEXTERMS(Ultrasonography) OR TITLE-ABS(ultraso*)
#3	#1 AND #2
#4	TITLE-ABS("lung ultraso*") OR TITLE-ABS("chest ultraso*") OR TITLE-ABS("pulmonary ultraso*")
#5	#3 OR #4
#6	TITLE-ABS("thoracic surgery") OR TITLE-ABS("cardi* surgery") OR TITLE-ABS("heart surgery") OR TITLE-ABS("coronary artery bypass *") OR TITLE-ABS(cabg) OR TITLE-ABS("heart valve repair") OR TITLE-ABS("heart valve replacement") OR TITLE-ABS("coronary angioplasty") OR TITLE-ABS("coronary stenting") OR TITLE-ABS(atherectomy) OR TITLE-ABS(cardiomyoplasty) OR TITLE-ABS("heart transplant") OR TITLE-ABS("catheter ablation")
#7	#5 AND #6
Records Retrieved: 693	

Cochrane Trials and Reviews

Search conducted April 6, 2022

Search	Query
#1	[mh Lung] OR [mh "Lung Diseases"] OR ("Lung" NEXT diseas*):ti,ab OR Lung:ti,ab
#2	[mh Ultrasonography] OR ultraso*:ti,ab
#3	#1 AND #2
#4	("lung" NEXT ultraso*):ti,ab OR ("chest" NEXT ultraso*):ti,ab OR ("pulmonary" NEXT ultraso*):ti,ab
#5	#3 OR #4
#6	"thoracic surgery":ti,ab OR (cardi* NEXT "surgery"):ti,ab OR "heart surgery":ti,ab OR ("coronary artery bypass" NEXT *):ti,ab OR cabg:ti,ab OR "heart valve repair":ti,ab OR "heart valve replacement":ti,ab OR "coronary angioplasty":ti,ab OR "coronary stenting":ti,ab OR atherectomy:ti,ab OR cardiomyoplasty:ti,ab OR "heart transplant":ti,ab OR "catheter ablation":ti,ab
#7	#5 AND #6
Records Retrieved: 114	

EMBASE (via OVID)

Search conducted April 6, 2022

Search	Query
#1	exp Lung/ OR exp Lung Diseases/ OR Lung diseas*.tw. OR Lung.tw.
#2	exp Ultrasonography/ OR ultraso*.tw.
#3	1 AND 2
#4	lung ultraso*.tw. OR chest ultraso*.tw. OR pulmonary ultraso*.tw.
#5	3 OR 4
#6	thoracic surgery.tw. OR cardi* surgery.tw. OR heart surgery.tw. OR coronary artery bypass *.tw. OR cabg.tw. OR heart valve repair.tw. OR heart valve replacement.tw. OR coronary angioplasty.tw. OR coronary stenting.tw. OR atherectomy.tw. OR cardiomyoplasty.tw. OR heart transplant.tw. OR catheter ablation.tw.
#7	5 AND 6
Records Retrieved: 4,287	

EBSCO Open Dissertation

Searched August 3, 2022

Search	Query	Records Retrieved
#1	"lung ultrasound" AND "cardiac surgery"	0
#2	"lung ultrasound" AND "heart surgery"	0
#3	"thoracic ultrasound" AND "cardiac surgery"	0
#4	"thoracic ultrasound" AND "heart surgery"	0
#5	"chest ultrasound" AND "cardiac surgery"	0
#6	"chest ultrasound" AND "heart surgery"	0

Networked Digital Library of Theses and Dissertations – Global ETD Search

Search conducted August 3, 2022

Search	Query	Records Retrieved
#1	"lung ultrasound" AND "cardiac surgery"	0
#2	"lung ultrasound" AND "heart surgery"	0
#3	"thoracic ultrasound" AND "cardiac surgery"	0
#4	"thoracic ultrasound" AND "heart surgery"	0
#5	"chest ultrasound" AND "cardiac surgery"	0
#6	"chest ultrasound" AND "heart surgery"	0
#7	“lung ultrasound” AND “surgery”	0
#8	"thoracic ultrasound" AND "surgery"	0
#9	"chest ultrasound" AND "surgery"	0

Google Scholar

Search conducted August 3, 2022

Search	Query	Records Retrieved
#1	"lung ultrasound" AND "cardiac surgery"	85
#2	"lung ultrasound" AND "heart surgery"	29
#3	"thoracic ultrasound" AND "cardiac surgery"	18

Google Scholar

Search conducted August 4, 2022

Search	Query	Records Retrieved
#1	"thoracic ultrasound" AND "heart surgery"	8
#2	"chest ultrasound" AND "cardiac surgery"	25
#3	"chest ultrasound" AND "heart surgery"	7