Live teleultrasound for evaluation of the chest: a systematic review

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Live teleultrasound is an emerging technology. Using this approach to image the chest appears to be feasible; however, more research is needed to confirm that it does not sacrifice diagnostic accuracy. https://bit.ly/4bpsk8p

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Abstract

Background Innovation in ultrasound technology has led to the development of portable devices which can transmit images in real time to a remotely located expert, known as live teleultrasound. This allows immediate feedback on image acquisition, assistance with interpretation and subsequent clinical decision-making.

Aim We performed a systematic review of the literature to examine outcomes related to live teleultrasound of the chest.

Methods A systematic search for studies reporting outcomes from live teleultrasound of the chest (excluding cardiac) in adults was performed in PubMed, MEDLINE, Embase, CINAHL and Cochrane CENTRAL. At least two independent reviewers were involved in screening, data extraction and critical appraisal.

Results In total, 1855 eligible studies were identified. Of those, 106 studies progressed to full-text screening and 43 studies were included for data extraction. Case reports and feasibility studies were most prevalent, and study quality was low overall. Commonly reported outcomes included 1) image quality rated by a remote clinician; 2) remote clinician's comfort in making management decisions; and 3) comparison of teleultrasound image acquisition with images acquired at the bedside by an expert. Three diagnostic accuracy studies demonstrated a high accuracy of teleultrasound for the identification of signs such as lung sliding, the interstitial syndrome and pleural effusion. Consolidation was less reliably identified. Eight studies collected qualitative data on attitudes of remote and face-to-face clinicians, which were consistently positive.

Conclusion Low-quality evidence suggests that live teleultrasound can be used to assess the lungs and pleural space; however, further study is required to ensure its diagnostic accuracy.

Introduction

Diagnostic ultrasound is a key imaging modality with widespread uses across virtually every field of medicine [1]. Its features include portability, low cost, lack of ionising radiation and the ability to produce real-time visualisation of body tissues and structures [2]. It is used by clinicians to acquire images at the bedside, or point of care, and then immediately integrate the information into clinical decision-making [3]. Chest, or thoracic ultrasound, refers to imaging of the lungs and pleural space using ultrasound [4].

Chest ultrasound has been demonstrated to be more sensitive than chest radiography for the diagnosis of pneumonia, pulmonary oedema, pneumothorax and pleural effusions [5–9]. For the latter condition, ultrasound has also shown superior specificity [9]. Additionally, it can be used to assess pleural effusion characteristics, parietal pleural abnormalities and diaphragm function [3]. Ultrasound is superior to computed tomography in the detection of fibrinous septations within pleural effusions [10, 11], and ultrasound guidance prior to thoracentesis is recommended practice to optimise procedural safety [12, 13].

An introduction to chest ultrasound and discussion of commonly encountered findings is covered in a previous review article [14]. The uptake of chest ultrasound has expanded in recent years, particularly among pulmonologists, emergency and intensive care physicians [14, 15]. Its utility in rapid bedside patient evaluation has led to its incorporation into the Extended Focused Assessment with Sonography in Trauma (E-FAST) [16] and the development of the Bedside Lung Ultrasound in Emergency (BLUE) [17]. Recently, point-of-care lung ultrasound has also emerged as a valuable adjunct to the assessment and monitoring of patients diagnosed with coronavirus disease 2019 (COVID-19) infection [18].

Traditional ultrasound machines are bulky, limiting their use to the hospital or clinic setting. Improvements to ultrasound technology have led to the development of small, "ultra-portable" handheld devices which can fit into a pocket and are a fraction of the cost of their larger counterparts [19]. This enables wider uptake of point-of-care ultrasound (POCUS), particularly in healthcare settings outside of hospitals. Supported by advancements in telecommunications, a field known as teleultrasound, or teleultrasonography has been developed. Teleultrasound refers to the process of performing bedside ultrasound at one location, with the acquired images being transmitted and interpreted by a provider located in a geographically different location [20]. This can be performed in an asynchronous manner, or in a real-time ("live") or synchronous fashion. Asynchronous teleultrasound is noninteractive, and involves images from the examination being stored and forwarded using teleradiology systems to a specialist for later interpretation [21]. Live teleultrasound involves data transmission taking place at the time of ultrasound, allowing the remote clinician to interact directly with the patient, but also for the supervision, instruction and interpretation of the ultrasound examination. Less is known about the utility of live teleultrasound, which, unlike asynchronous ultrasound, requires established telecommunications infrastructure due to relying on real-time data transmission [22]. Despite this, a recent systematic review has shown encouraging results in multiple fields including in the intensive care setting, trauma, musculoskeletal, cardiac and austere or remote environments [23]. To date, there has not been a systematic evaluation of live teleultrasound for assessment of the chest.

This systematic review aimed to evaluate the existing literature specifically reporting the use of live teleultrasound in evaluation of noncardiac structures in the chest, to gain an understanding of its applicability to real-world practice, accuracy in diagnosis and potential pitfalls.

Methods

The protocol for this systematic review was registered on PROSPERO (www.crd.york.ac.uk/PROSPERO/, registration number CRD42023463574). The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were adhered to [24]. Eligibility criteria included any study performed on adults and written in English that reported outcomes on live teleultrasound and included

TABLE 1 Study exclusion and inclusion criteria

	Inclusion	Exclusion
Participants	Adults aged ⩾18 years: real or simulated scenarios	Children aged <18 years
Ultrasound operator	Ultrasound expert or experienced operator Nonexpert healthcare professional Nonhealthcare professional Patient Robot	NA
Intervention	Live teleultrasound involving assessment of the chest (excluding cardiac)	Asynchronous teleultrasound
Comparators	No comparator or any comparator including bedside ultrasound, plain radiograph, computed tomography, magnetic resonance imaging	NA
Outcomes	All clinically relevant outcomes: diagnostic accuracy, image quality/readability, suitability for decision-making, time to perform examination, operator attitudes, patient attitudes, cost, limitations including adverse effects and technical difficulties	NA
Setting	All healthcare settings: hospital (inpatient and outpatient), patient's home, external environment or field studies, simulation environments or training facilities	NA
Study type	All study designs: randomised controlled trials, observational studies (all types), cohort (longitudinal) studies, case–control studies, before–after studies, cross-sectional studies, case reports, case series and conference abstracts	Reviews, letters and book chapters not reporting original data

NA: not applicable.

examination of the chest (table 1). Studies involving chest ultrasound as part of a broader systemic or whole-body scanning protocol were included, provided chest-specific outcomes were reported. Cardiac ultrasound was specifically excluded, as the focus of this study is on the lungs and pleura. Paediatric studies were similarly excluded, in order to retrieve studies relevant to adult pulmonary medicine. Live teleultrasound was defined as ultrasound performed at the point of care, with images transmitted in real-time to a different location for feedback, guidance and/or interpretation by an expert reviewer. All original studies or cases were included, regardless of publication status. All reported outcomes were of interest, with a particular focus on outcomes related to real-time instruction of a novice operator and diagnostic accuracy.

Search strategy

Structured search strategies were run in PubMed, MEDLINE *via* Ovid, Embase *via* Ovid, CINAHL *via* EBSCO, and Cochrane Central Register of Controlled Trials (CENTRAL). Databases were searched from inception. The final search was performed on 11 September 2024.

The full search strategy was developed by V. Duong and E. Hateley, a clinical librarian, and included keywords and controlled vocabulary terms for each major concept as per the following logic: ((telemedicine AND ultrasound) OR teleultrasound) AND (pleura OR lungs) (supplementary table S1).

To supplement the database searches, forwards and backwards citation analysis was performed on included studies.

Study selection, screening and data extraction

Citations acquired from the search were managed using EndNote Version 21 (Clarivate, Philadelphia, PA, USA). Screening and data extraction were performed using Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia). References were screened independently against the eligibility criteria by V. Duong, L.M. Hannan, K. Tirant and S. Muruganandan. Once the initial title/abstract screening was completed, the full texts of the included studies were reviewed by two authors (V. Duong, S. Muruganandan or K. Tirant) to determine if they should be included. The citation search was screened by V. Duong. Discrepancies were resolved by consensus.

A specifically designed data extraction form was used (supplementary table S2) and data extraction was performed by V. Duong, K. Tirant and Y.X. Choe. A minimum of two reviewers independently extracted data from each study and discrepancies were resolved by consensus.

Critical appraisal

Critical appraisal was performed using relevant checklists from the Joanna Briggs Institute (JBI; https://jbi.global/critical-appraisal-tools). The JBI provides a wide range of checklists for critically appraising almost any study type, each usually containing between eight and 10 items which a high-quality study of that type should possess. Each study was allocated to the checklist determined to be the most suitable, despite often having multiple nonapplicable fields. For instance, although many studies were strictly not diagnostic accuracy studies, the checklist for diagnostic accuracy studies was chosen as the most appropriate tool for assessing 28 of the studies, as many reported on image quality in the context of diagnosis or clinical decision-making. Other checklists used included the checklist for case series (four studies), the checklist for case reports (seven studies) and the checklist for qualitative research (four studies). Two reviewers independently scored each study according to the provided checklist and disagreements were resolved by consensus.

Data synthesis

Due to the wide variability in study design, quality and reported outcomes, meta-analysis was not possible. In addition, many reporting items in the Synthesis Without Meta-analysis guideline were not applicable [25]. Descriptive summaries were generated instead.

Results

The database search identified 1855 references (the PRISMA flowchart is presented in figure 1). After initially selecting 36 articles for inclusion, backwards and forwards citation analysis of those papers identified another 909 references for screening. Of these, seven articles were assessed as relevant and included in the review, producing a total of 43 studies. The earliest study was published in 2008, with a trend toward an increasing number of new publications in later years (figure 2).

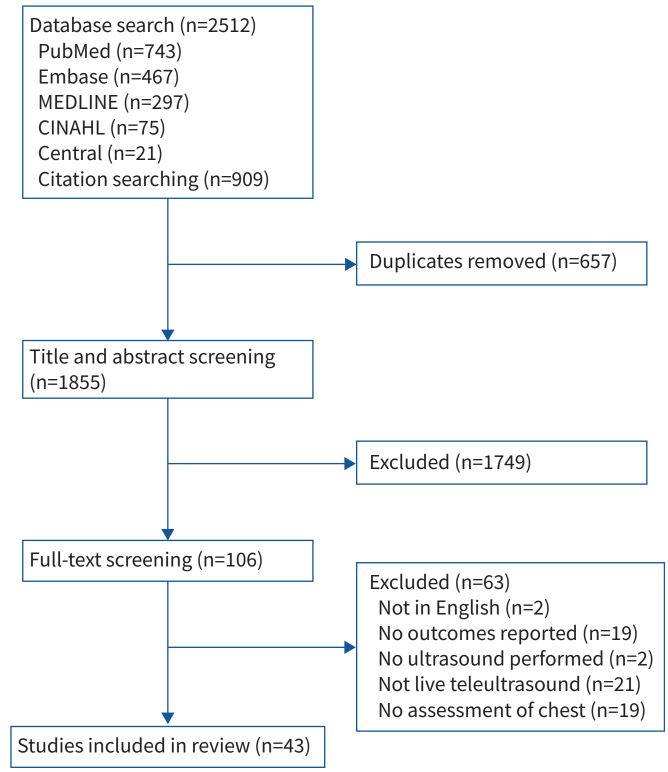

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analysis flowchart of article screening and selection.

Study design and methodology

Study design and methodology were highly variable (table 2). Many studies did not assess ultrasound of the chest in isolation, and hence reported conclusions were for live teleultrasound in the capacity examined in the specific study.

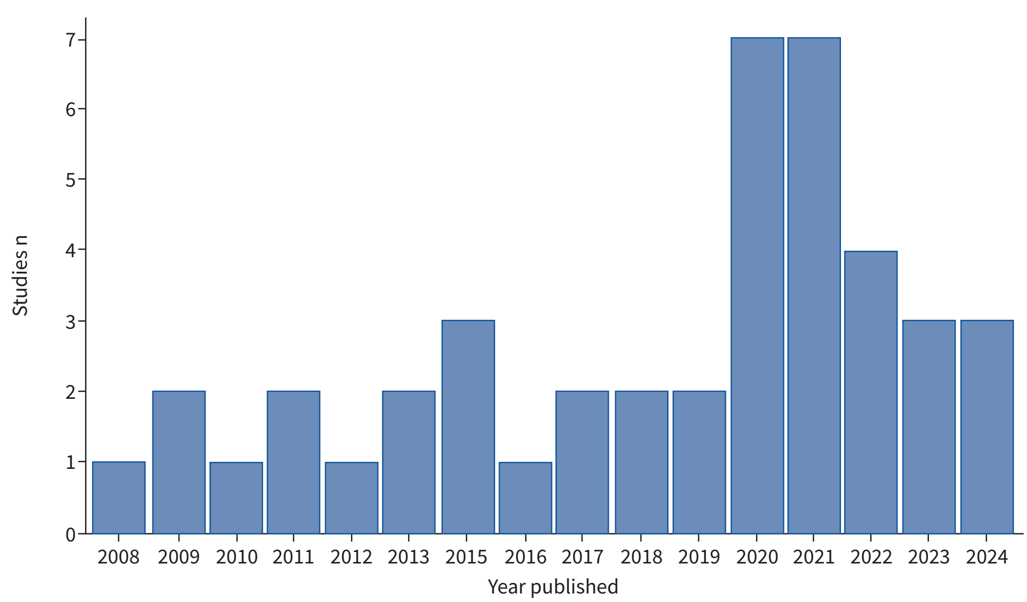

FIGURE 2 Live teleultrasound studies of the chest by year of publication (n=43).

TABLE 2 Study characteristics

First author, year [reference]	Study design	Main outcomes	Sample size n	Dedicated TUS	Ultrasound operator	Reported TUS findings	Summary of conclusions
Hospital studies							
Accorsi, 2022 [26]	Feasibility	Key image acquisition, interpretation and examination time	11	No	NEHP	B-lines	1) Untrained general practitioners may be correctly guided by telemedicine specialists to perform multiorgan POCUS 2) Telemedicine-guided ultrasound is feasible and can be performed rapidly
Al-Kadi, 2009 [27]	User survey	User perceptions of teleultrasound system for acute trauma cases	23	No	NEHP	NA	Most respondents were satisfied or very satisfied with the telemedicine interaction and agreed or strongly agreed that the technology could benefit trauma patients in rural areas
Becker, 2017 [28]	Case series	NA	2	No	NEHP	B-lines Pleural effusion Pleural thickening Effusion septations	Tele-intensivists can supervise and guide providers with no or partial ultrasound training
Biegler, 2012 [29]	Case report	NA	1	Yes	NEHP	Lung sliding Seashore sign	A nurse with no prior experience in ultrasound was remotely mentored to detect a subtle diagnosis of pneumothorax
Biegler, 2013 [30]	Feasibility	Ability of nonphysician caregiver to identify pneumothorax *via* real-time telementored ultrasound	13	Yes	NEHP	Lung sliding Lung point Seashore sign	Experienced ultrasonographers are able to direct remote examinations wherever internet connectivity is available
Duan, 2021 [31]	Feasibility	Diagnostic performance of robot-assisted teleultrasound compared to bedside ultrasound, image quality	32	No	Robot	Pleural effusion	The robot-assisted teleultrasound system was associated with ease of operation, simple process, clear images, high levels of safety, reduced infection risk and comparable results to bedside diagnostic examination
Dyer, 2008 [32]	Pilot	Technical challenges, completion of scan protocols, identification of critical anatomical features, diagnoses made, operator attitudes	23	No	NEHP	Lung sliding	1) Remote acute resuscitative ultrasound to augment real-time videoconferencing during acute trauma was found to be technically and clinically feasible 2) Remote experts were able to identify salient anatomic features of both the FAST and EFAST examination in nearly all instances 3) Education of less experienced users was supported 4) Important clinical management decisions were occasionally aided by teleultrasound
Grubic, 2022 [33]	Pre-test–post-test	Improvements in POCUS image quality following remote guidance, operator attitudes	Unclear	No	NEHP	NA	1) A 3-week virtual training programme with remote expert guidance resulted in improvements in the acquisition and interpretation of POCUS images 2) Participants found tele-POCUS useful for training and clinical integration

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TABLE 2 Continued

First author, year [reference]	Study design	Main outcomes	Sample size n	Dedicated TUS	Ultrasound operator	Reported TUS findings	Summary of conclusions
Jensen, 2019 [34]	Feasibility	Technical feasibility of teleultrasound in the emergency department, operator attitudes and acceptability	45	No	NEHP	NA	Remote supervision is operational for both junior doctors and supervisors when applied to lung and cardiac POCUS scans of hospitalised inpatients
König Klever, 2024 [35]	Diagnostic accuracy	Diagnostic concordance of telementored ultrasound in detecting pulmonary oedema *versus* POCUS	23	No	NEHP	Lung sliding A-lines B-lines Consolidation	For COPD and pulmonary oedema, remote examination can support healthcare teams, suggesting that RTMUS has the potential to be a substitute for POCUS
Lin, 2020 [36]	Case series	NA	2	No	NEHP	Lung sliding A-lines B-lines Consolidation	The application of remote ultrasound can timely monitor the changes of pulmonary findings, cardiac condition, volume state and other organ systems
Olivieri, 2020 [37]	Diagnostic accuracy	Diagnostic concordance between real-time telementored ultrasound and POCUS	20	No	NEHP	Lung sliding B-lines Seashore sign Pleural effusion Consolidation	1) Very good concordance between RTMUS and POCUS for the cardiopulmonary evaluation of patients admitted to an ICU with acute respiratory insufficiency and/or shock for most parameters 2) Reasonable concordance for the presence and location of lung consolidation
Robertson, 2017 [38]	Feasibility	Quality and clinical utility of images obtained; ease and efficiency of remote tele-mentored ultrasound image acquisition	1	No	NEHP	NA	Affordable, commercially available video-chat software can be used to connect low- and middle-income country institutions to providers in high-income countries, allowing for real-time mentored acquisition and interpretation of high-quality ultrasound images that are clinically useful
Wang, 2021 [39]	Case report	NA	1	No	Robot	B-lines Pleural effusion Irregular pleura Consolidation	Demonstration of the feasibility of using a robotic tele-echography system to examine patients with COVID-19
Wu, 2020 [40]	Pilot	Descriptive	4	Yes	Robot	A-lines B-lines Pleural effusion Pleural thickening Irregular pleura Consolidation	The clinical practice of the four cases of robot-assisted teleultrasound provides the possibility of solving the problem of early imaging of patients with confirmed or suspected COVID-19 in the isolation ward
Ye, 2021 [41]	Feasibility	Descriptive, safety	23	Yes	Robot	Lung sliding A-lines B-lines Pleural effusion Pleural thickening Irregular pleura Consolidation	The use of 5G-based robot-assisted remote ultrasound system is feasible and effectively obtains ultrasound characteristics for cardiopulmonary assessment of patients with COVID-19

Continued

TABLE 2 Continued

First author, year [reference]	Study design	Main outcomes	Sample size n	Dedicated TUS	Ultrasound operator	Reported TUS findings	Summary of conclusions
Yu, 2020 [42]	Case series	NA	2	Yes	Robot	B-lines Pleural thickening Consolidation	Two cases of patients with SARS-CoV-2 infection evaluated by 5G-powered remote robotic ultrasound; article details advantages of this method and the possibility of popularising it for diagnosis and monitoring of COVID-19 cases in clinical practice
Zaidi, 2015 [43]	Feasibility	Concordance of ultrasound findings by bedside intensivist ultrasound *versus* tele-ICU physician	18	No	Expert	B-lines Pleural effusion Consolidation	A tele-intensivist can accurately interpret POCUS images in critically ill patients
Field studies							
Balasubramanian, 2024 [44]	Case report	NA	1	Yes	NEHP	Lung sliding A-lines	This case highlights a unique opportunity to expand the use of telemedicine and ultrasound in community paramedicine
Eadie, 2018 [45]	Feasibility/ simulation	Expert rating of diagnostic utility of images, time taken to achieve diagnostic image	10	No	NEHP	Seashore sign (healthy volunteers)	Remotely supported pre-hospital ultrasound could facilitate early diagnosis and streamline care pathways for patients, particularly in areas with poor communication infrastructure and long transport times to centres of care
Otto, 2009 [46]	Feasibility	Function of equipment in hypobaric environment, ability of guided nonexperts to use ultrasound to assess respiratory status on Mount Everest	2	Yes	Non-HP	Lung sliding Comet tails	Ultrasound devices functioned in cold, hypobaric conditions; portable ultrasound with remote expert guidance provides robust diagnostic capability in austere conditions
Hermann, 2022 [47]	Feasibility	Quality of live stream and quality of communication	24	No	Expert	NA	Remote real-time supervision of POCUS in a physician-based pre-hospital emergency service is feasible with excellent imaging and communication quality
Kirkpatrick, 2021 [48]	Case report/ simulation	NA	1	Yes	Non-HP	NA	Drone-delivered telemedicine with teleultrasound capability could be used to enhance point-of-care diagnostic accuracy in catastrophic emergencies, and allow diagnostic capabilities to be delivered to vulnerable populations in remote locations
McBeth, 2010 [49]	Case report/ simulation	NA	1	No	Expert	Lung sliding Doppler	In any location where internet is available, advanced ultrasound diagnoses can be aided by remote experts
McBeth, 2011 [50]	Feasibility/ simulation	Completeness of examination, quality of video and connectivity	10	No	NEHP	Lung sliding	The emergent exclusion of apnoea and pneumothorax can be immediately accomplished by a remote expert economically linked to almost any responder over cellular networks
McBeth, 2013 [51]	Feasibility/ simulation	Image quality, participant feedback	1	No	NEHP	Lung sliding	The RTMUS enables the remote expert to obtain and interpret basic yet critical ultrasound anatomy from wherever there is an internet connection

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TABLE 2 Continued

First author, year [reference]	Study design	Main outcomes	Sample size n	Dedicated TUS	Ultrasound operator	Reported TUS findings	Summary of conclusions
Vatsvåg, 2020 [52]	Feasibility	Image quality and scanning time	37	No	NEHP	Lung sliding Seashore sign	Telementored ultrasound using existing communication and network infrastructure at offshore oil and gas installations in the North Sea is feasible and allows real-time sharing of ultrasound cineloops and images
Home studies							
DeFilippo, 2023 [53]	Pilot	Identification of sonographic features of heart failure and changes in medical management; provider attitudes	19	Yes	NEHP	B-lines Pleural effusion	Tele-lung ultrasound to guide remote management of heart failure patients at home is feasible and acceptable when performed by community paramedics with interpretation in real-time by emergency physicians *via* telemedicine
Elmi, 2024 [54]	Feasibility	Whether nonclinical patients are able to self-perform lung ultrasound and obtain images that are interpretable and clinically useful	18	Yes	Patient	NA	This study demonstrates that nonclinical patients can obtain interpretable lung ultrasound images at home
Kimura, 2022 [55]	Diagnostic accuracy	Prevalence and associations of B-lines in outpatients with SARS-CoV-2; diagnostic accuracy of telehealth-guided B-line detection compared to bedside physician imaging	50	Yes	Patient	B-lines	1) The ultrasound lung finding of B-lines was common within 1 week of mild-to-moderate SARS-CoV-2 infection in high-risk outpatients 2) Patients can perform a simplified lung ultrasound examination on themselves over telehealth
Kirkpatrick, 2021 [56]	Case series	NA	2	Yes	Patient	Lung sliding Seashore sign	These initial experiences present a paradigm for home monitoring of patients expected to become infected with SARS-CoV-2 and who threaten to overwhelm resources if they must all be assessed in person by at-risk care providers
Kirkpatrick, 2022 [57]	Feasibility	Subject able to reach anatomic position, image quality for interpretation and diagnosis, participant rating of scan difficulty	27	Yes	Patient	Lung sliding B-lines	Home self-performed telementored lung ultrasonography may be a useful method to provide surveillance of at-risk populations
Pivetta, 2020 [58]	Case report	NA	1	Yes	Patient	Lung sliding B-lines Pleural thickening Irregular pleura Consolidation	Teleguidance improved the image quality of the lung ultrasonography performed by the patient by guiding her to follow a standard imaging protocol
Pivetta, 2022 [59]	Feasibility	Quality assessment of patient self-performed lung ultrasound scan, intra- and inter-rater agreement	21	Yes	Patient	B-lines Irregular pleural line	The use of lung ultrasound performed by patients themselves remotely overseen by expert providers seems to be a feasible and reliable telemedicine tool useful in treating COVID-19 patients
Pratzer, 2023 [60]	Feasibility	Visibility of pleural line/rib interspace visibility of A- and B-lines; assessment of appropriately optimised image	8	Yes	Patient	A-lines B-lines	Patient-performed remote lung ultrasound is feasible, with >90% of exams being diagnostically valid

Continued

TABLE 2 Continued

First author, year [reference]	Study design	Main outcomes	Sample size n	Dedicated TUS	Ultrasound operator	Reported TUS findings	Summary of conclusions
Unspecified setting or training/testing centre							
Ahn, 2011 [61]	Feasibility	Technical adequacy of cardiac limited ultrasound exam	27	No	NEHP	B-lines	A novice can perform cardiac limited ultrasound exam when guided live by an expert *via* wireless transmission
Crawford, 2011 [62]	Case series	NA	Unclear	Yes	Not specified	Lung sliding Doppler	Remote experts in developed nations could increasingly assist with education and clinical care delivery using affordable technologies
Dufurrena, 2020 [63]	Feasibility/ simulation	Technical and diagnostic adequacy of images	Unclear	No	Non-HP	NA	Remotely guided novices are able to carry out cardiac and pulmonary POCUS examinations as well as, if not better than, trained physicians
Levine, 2015 [64]	Feasibility	Quality of ultrasound images	Unclear	No	NEHP	NA	High-quality, clinically relevant images can be captured using commercially available video chat software in resource limited countries
Levine, 2015 [65]	Pilot/ simulation	Image quality and suitability in guiding clinical decisions	11	No	NEHP	NA	With minimal training, bedside nonphysicians can be mentored to obtain high-quality and clinically relevant images that are transmitted without any quality degradation
Levine, 2016 [66]	Pilot/ simulation	Image quality and suitability in guiding clinical decisions	11	No	NEHP	NA	1) Commercially available chat software can transmit high-quality, clinically useful ultrasound images 2) In almost every anatomic location, images obtained with this method were noninferior to images obtained directly from the ultrasound machine
Ramsingh, 2019 [67]	Pilot/ simulation	Frequency of obtaining adequate image quality, satisfaction survey of novice users	1	No	Non-HP	Lung sliding	This project demonstrated the utility of a novel teleultrasound system to guide nonmedically trained adults to successfully acquire ultrasound images for acute cardiac, pulmonary and abdominal assessments
Tsumura, 2021 [68]	Feasibility/ simulation	Operational safety, image quality	3	Yes	Robot	Lung sliding, A-lines	Our preliminary results indicate that the proposed platform has the potential to be applied to COVID-19 and other infectious diseases

TUS: thoracic ultrasound; NEHP: nonexpert healthcare professional; POCUS: point-of-care ultrasound; NA: not applicable; FAST: focused assessment with sonography for trauma; EFAST: extended focused assessment with sonography for trauma; RTMUS: real-time telementored ultrasound; ICU: intensive care unit; COVID-19: coronavirus disease 2019; SARS-CoV-2: severe acute respiratory syndrome coronavirus 2; HP: healthcare professional.

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Critical appraisal

Diagnostic test accuracy studies

Studies evaluated with the Diagnostic Test Accuracy Checklist were of mostly low-to-medium quality (tables 3–6). Many items in the checklists were not applicable to multiple studies. No items were applicable to Ramsingh *et al.* [67] and Robertson *et al.* [38], as both studies used simulated (volunteer) subjects. There was no other tool to assess these studies.

Only three studies [26, 45, 55] clearly stated that participants were enrolled in a consecutive or random fashion. 10 studies blinded investigators when interpreting results of teleultrasound [30, 32, 35, 37, 43, 55, 63, 65, 66, 68], and of these, diagnostic criteria were pre-specified in six studies [37, 55, 61, 63, 65, 66]. Only seven studies provided sufficient information to reliably assess that there were no inappropriate exclusions [26, 31, 32, 35, 52, 55, 60]. Most studies did not use a diagnostic reference standard [26, 38, 40, 41, 45–47, 50–54, 59, 60, 64, 67].

The three studies that performed favourably on the quality assessment [35, 37, 55] were designed as diagnostic accuracy studies. Apart from Zaidi *et al.* [43] with only three missing items, the conference abstracts [53, 61, 64] performed poorly in the appraisal due to lack of clear information, such as details of participant recruitment and whether all data were included.

Case series

Studies evaluated with this checklist were of generally low quality. Notable deficiencies across all studies included unclear inclusion criteria, nonconsecutive inclusion of participants and noncomplete inclusion of participants.

Case reports

Three studies scored highly on the checklist, providing complete information on the presented cases with clear takeaway messages [39, 44, 58]. Two studies reported minimal clinical detail on the cases [48, 62].

Qualitative research

All studies evaluated with this checklist generally performed well [27, 33, 34, 57]. Item 7 (an acknowledgement of the influence of the research on the researcher, and *vice versa*) was deemed to not apply to any of the assessed studies.

Study findings

Novice-performed teleultrasound

The majority of studies evaluated outcomes relating to chest ultrasound performed by an operator with limited or no prior experience in ultrasound, with guidance on image acquisition provided by a remotely located expert [26–30, 32–38, 44–46, 48, 50–60, 61, 64–67]. The operator was most commonly a healthcare worker without ultrasound experience [26–30, 32–38, 44, 45, 50–53, 61, 64–66]. These studies were usually carried out in the hospital environment or pre-hospital setting. In three of the studies, the ultrasound operator was not a healthcare professional [46, 48, 67]. There were multiple home-based studies where the patient was guided to perform ultrasound on themselves [54–60]. 20 studies provided detail on how the novice operators were guided to perform the ultrasound examination [28, 33–35, 37, 38, 44–46, 54–60, 64–67]. 11 studies stated that novice operators were provided with training on the use of ultrasound prior to the study [28, 33–35, 37, 38, 45, 55, 64–66]. The remainder did not refer to any training provided prior to commencement of ultrasound use [44, 46, 54, 56–60, 67]. In their study involving self-scanning patients, Kirkpatrick *et al.* [57] supplied participants with an introductory video which described basic anatomical terms. Otto *et al.* [46] used a cue card demonstrating standard probe positions and anatomic positions. Ramsingh *et al.* [67] provided a handout which only showed an image of correct probe placement on the body as well as examples of ideal ultrasound images. In their case report of patient-performed lung ultrasound, Kirkpatrick *et al.* [56] simply provided real-time verbal instruction on image acquisition, without the use of formal terminology. In all studies, the live teleultrasound arrangement was described in enough detail such that the remote expert was probably able to view the operator's hands, facilitating direct feedback on probe positioning.

Five studies used augmented reality to assist in real-time instruction [44, 54, 58–60]. This was enabled by proprietary software provided by the ultrasound manufacturer (Butterfly TeleGuidance), which allows the remote expert to virtually draw on the patient's chest, with additional functions to demonstrate basic probe movements such as slide, rotate and tilt.

TABLE 3 Critical appraisal: diagnostic test accuracy studies

First author, year [reference]	Q1 Random/ consecutive sampling	Q2 Avoidance of case–control design	Q3 No inappropriate exclusions	Q4 Blinded interpretation of index test	Q5 Pre-specified threshold	Q6 Appropriate reference test	Q7 Blinded interpretation of reference	Q8 Minimal time delay between tests	Q9 Common reference standard used	Q10 All patients analysed
Kimura, 2022 [55]	Y	Y	Y	Y	Y	Y	Y	U	Y	Y
Levine, 2015 [65]	NA	Y	NA	Y	Y	Y	Y	Y	Y	Y
König Klever, 2024 [35]	U	Y	Y	Y	NA	Y	Y	Y	Y	Y
Dufurrena, 2020 [63]	N	Y	NA	Y	Y	Y	Y	Y	Y	Y
Olivieri, 2020 [37]	U	Y	U	Y	Y	Y	Y	Y	Y	Y
Tsumura, 2021 [68]	NA	Y	NA	Y	NA	Y	Y	Y	Y	Y
Levine, 2016 [66]	N	Y	NA	Y	Y	Y	Y	Y	Y	NA
Biegler, 2013 [30]	N	Y	N	Y	NA	Y	Y	Y	Y	Y
Dyer, 2008 [32]	U	Y	Y	Y	NA	Y	Y	Y	N	Y
Zaidi, 2015 [43]	U	Y	U	Y	NA	Y	Y	Y	Y	Y
Accorsi, 2022 [26]	Y	Y	Y	NA	NA	NA	NA	NA	NA	Y
Eadie, 2018 [45]	Y	Y	NA	NA	NA	NA	NA	NA	NA	Y
Pratzer, 2023 [60]	U	Y	Y	NA	NA	NA	NA	NA	NA	Y
Vatsvåg, 2020 [52]	N	Y	Y	NA	NA	NA	NA	NA	NA	Y
Duan, 2021 [31]	U	Y	Y	NA	NA	Y	N	N	Y	N
Otto, 2009 [46]	NA	Y	NA	NA	NA	NA	NA	NA	NA	Y
McBeth, 2011 [50]	N	Y	NA	NA	NA	NA	NA	NA	NA	Y
Ahn, 2011 [61]	U	Y	U	U	Y	Y	U	U	Y	U
DeFilippo, 2023 [53]	U	Y	U	NA	NA	NA	NA	NA	NA	Y
Hermann, 2022 [47]	U	Y	U	NA	NA	NA	NA	NA	NA	Y

Continued

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TABLE 3 Continued

First author, year [reference]	Q1 Random/ consecutive sampling	Q2 Avoidance of case–control design	Q3 No inappropriate exclusions	Q4 Blinded interpretation of index test	Q5 Pre-specified threshold	Q6 Appropriate reference test	Q7 Blinded interpretation of reference	Q8 Minimal time delay between tests	Q9 Common reference standard used	Q10 All patients analysed
McBeth, 2013 [51]	NA	NA	NA	NA	NA	NA	NA	NA	NA	Y
Wu, 2020 [40]	N	Y	U	NA	NA	NA	NA	NA	NA	Y
Ye, 2021 [41]	N	Y	U	NA	NA	NA	NA	NA	NA	Y
Levine, 2015 [64]	U	Y	U	NA	NA	NA	NA	NA	NA	U
Pivetta, 2022 [59]	N	Y	U	NA	NA	NA	NA	NA	NA	U
Elmi, 2024 [54]	N	Y	U	NA	NA	NA	NA	NA	NA	N
Ramsingh, 2019 [67]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Robertson, 2017 [38]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Results of critical appraisal using JBI Critical Appraisal Tool for Diagnostic Test Accuracy Studies. Studies are listed in order from highest score to lowest score. Y: yes; U: unclear; NA: not applicable; N: no.

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TABLE 4 Critical appraisal: case series

First author, year [reference]	Q1 Clear inclusion criteria	Q2 Condition measured in reliable way	Q3 Valid methods for identification of condition	Q4 Consecutive inclusion of participants	Q5 Complete inclusion of participants	Q6 Clear reporting of participant demographics	Q7 Clear reporting of clinical information	Q8 Outcomes or follow-up clearly reported	Q9 Clear reporting of study site demographics	Q10 Appropriate statistical analysis
Becker, 2017 [28]	N	NA	Y	N	NA	Y	Y	Y	Y	NA
Yu, 2020 [42]	N	Y	Y	N	N	Y	Y	N	Y	NA
Kirkpatrick, 2021 [56]	N	Y	Y	N	N	N	N	Y	Y	NA
Lin, 2020 [36]	N	Y	Y	N	N	N	N	Y	N	NA

Results of critical appraisal using JBI Critical Appraisal Tool for Case Series. Studies are listed in order from highest score to lowest score. N: no; NA: not applicable; Y: yes.

TABLE 5 Critical appraisal: case reports

First author, year [reference]	Q1 Patient demographics clearly described	Q2 Patient history clearly described	Q3 Presentation condition clearly described	Q4 Tests, assessment and results clearly described	Q5 Intervention or treatment clearly described	Q6 Post-intervention condition clearly described	Q7 Adverse events identified and described	Q8 Takeaway lesson provided
Balasubramanian, 2024 [44]	Y	Y	Y	Y	Y	Y	Y	Y
Pivetta, 2020 [58]	Y	Y	Y	Y	Y	Y	NA	Y
Wang, 2021 [39]	Y	Y	Y	Y	Y	Y	NA	Y
McBeth, 2010 [49]	NA	NA	NA	Y	Y	NA	N	Y
Biegler, 2012 [29]	NA	NA	Y	Y	Y	N	N	Y
Kirkpatrick, 2021 [48]	N	N	N	Y	Y	N	Y	Y
Crawford, 2011 [62]	N	N	N	N	N	N	N	Y

Results of critical appraisal using JBI Critical Appraisal Tool for Case Reports. Studies are listed in order from highest score to lowest score. Y: yes; NA: not applicable; N: no.

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TABLE 6 Critical appraisal: qualitative research

First author, year [reference]	Q1 Congruity between philosophical perspective and research methodology	Q2 Congruity between research methodology and research question	Q3 Congruity between research methodology and methods to collect data	Q4 Congruity between research methodology and data analysis	Q5 Congruity between research methodology and results interpretation	Q6 Statement locating the researcher culturally or theoretically	Q7 Influence of research on the researcher and *vice versa* addressed	Q8 Participants and their voices adequately represented	Q9 Research is ethical according to current criteria	Q10 Conclusions congruent with analysis and interpretation of data
Jensen, 2019 [34]	Y	Y	Y	Y	Y	Y	NA	Y	Y	Y
Kirkpatrick, 2022 [57]	Y	Y	Y	Y	Y	Y	NA	Y	Y	Y
Al-Kadi, 2009 [27]	N	Y	Y	Y	Y	NA	NA	Y	Y	Y
Grubic, 2022 [33]	Y	Y	Y	Y	Y	NA	NA	Y	Y	Y

Results of critical appraisal using JBI Critical Appraisal Tool for Qualitative Research. Studies are listed in order from highest score to lowest score. Y: yes; NA: not applicable; N: no.

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Not enough information was provided to meaningfully compare the results of different approaches to remote instruction.

Feasibility

In total, 27 feasibility or pilot studies were included [26, 30–32, 34, 38, 40, 41, 43, 45–47, 50–54, 57, 59, 60, 61, 63–68]. The assessment of feasibility varied widely between reports with often multiple aspects examined; however, almost all reported broadly on the ability of the ultrasound operator to obtain images that were of sufficient quality or interpretable by the remote expert [26, 30, 31, 38, 41, 45–47, 50–54, 57, 59, 60, 61, 63–68]. Where image quality or clinical decision-making capability was rated, scores were consistently high [31, 38, 47, 51, 52, 54, 57, 59, 61, 63–68]. Jensen *et al.* [34] did not report diagnostic quality of obtained images, but instead focused on technical image quality and qualitative outcomes. Levine *et al.* [65, 66] conducted two similar studies using the same number of nonexpert scanners and a volunteer patient; one evaluated the effectiveness of an education session on scanners' ability to produce quality images, while the other tested the ability of commercially available software (Apple FaceTime) to display these images.

Biegler *et al.* [30] assessed diagnostic capability of nurse practitioner-performed teleultrasound for the identification of pneumothorax, obtaining a sensitivity of 66% and specificity of 100% compared to the gold standard of chest radiography. Duan *et al.* [31] reported on the diagnostic accuracy of robotic-assisted teleultrasound compared to bedside ultrasound, and found 100% concordance in the detection of pleural effusion. A similar diagnostic accuracy comparison between expert-performed bedside ultrasound *versus* expert-performed teleultrasound was performed by Zaidi *et al.* [43], who found 100% concordance in the detection of B-lines, consolidation and pleural effusions. Along with image quality, Otto *et al.* [46] in their small study confirmed the functionality of ultrasound equipment in hypobaric conditions on Mount Everest.

Time to complete live teleultrasound examination was reported in multiple studies [26, 31, 45, 52, 54, 63, 65, 67]. Although chest ultrasound was not the only focus of many investigations, five of the studies reported time to perform the lung scan separately [45, 52, 63, 65, 67]. Medical students in Eadie *et al.* [45] required a mean time of 3.8 min for a remote expert to determine that pneumothorax was ruled out in a healthy volunteer. Vatsvåg *et al.* [52] reported a time of 32 s for a novice nurse guided by an offsite expert to achieve the same conclusion, again in a healthy volunteer. It was not clear if the scanning protocols differed, limiting direct comparison. Levine *et al.* [65] reported mean time to demonstrate lung sliding at four different anatomic sites. Mean time to acquire an optimal image of the right lung base was 75.6 s, while all other areas ranged between 30.8 to 43.1 s. The ultrasound operators reported in Ramsingh *et al.* [67] required a mean time of 1.6 min for remote experts to rule out pneumothorax in a healthy person. Pivetta *et al.* [59] evaluated the ability of participants infected with COVID-19 to perform a comprehensive lung scan involving 12 different anatomic locations. Mean time to complete the examination was 13 min. Notably, 47.6% of individuals needed assistance from a relative or cohabitant at least once during the study period. Elmi *et al.* [54] performed a similar study with patient self-performed ultrasound in COVID-19, with 10 lung zones to scan. The average time taken to complete the scan was 8.9 min at the first ultrasound session, decreasing to 4.2 min after 2 weeks of regular scanning. Two studies compared examination time between novice and expert scanners [45, 63]. In Eadie *et al.* [45], the novice scanners (medical students) required almost quadruple the amount of time (3.8 min *versus* 1 min) as an expert scanner (emergency medicine specialist) to exclude pneumothorax in a healthy volunteer. Dufurrena *et al.* [63] in their comparison of pulmonary and cardiac scans obtained by teleultrasound-guided novices to that acquired *via* POCUS by ultrasound-trained physicians, reported time taken for the overall scanning protocol only (including cardiac component). The median scan time was 641.5 s for novices, compared to 256 s for the trained operators.

A total of 15 feasibility studies involving novice operators incorporated thoracic ultrasound into a wider scanning protocol [26, 32, 34, 38, 43, 45, 50–52, 61, 63–67]. Image acquisition time and expert-rated image quality were used as surrogates for technical difficulty in scanning different body systems. Studies that included cardiac examination all reported this component to be more time-consuming than the lung component and with sometimes poorer image quality [26, 38, 52, 61, 63, 65–67]. Abdominal structures such as the bladder generally were identified quicker and with higher image quality than lung [38, 65, 66], whereas identifying lung sliding and abdominal free fluid or abdominal structures were largely equivalent in terms of difficulty [32, 45, 51, 67]. None of the studies offered further technical comments to account for the difference in scan time and image quality between different body systems. Four studies did not compare difficulty between different scans [34, 43, 50, 64].

Ultrasound findings

Collectively, the studies reported the array of ultrasound findings typical for chest examinations. These included lung sliding [29, 30, 32, 35–37, 41, 44, 46, 49–52, 56, 57, 59, 62, 65, 67, 68] comet tails [30, 46], A-lines [35, 36, 40, 41, 44, 60, 68], B-lines [26, 28, 35–37, 39–43, 53, 55, 57–60, 61], consolidation [35–37, 39–43, 58], pleural effusion [28, 31, 37, 39–41, 43, 53], pleural thickening [28, 40, 41, 58] and irregular pleural line [39–41, 58, 59]. Only one case report described intrapleural septations [28]. Three studies used M-mode to document a normal "seashore" pattern [29, 37, 45], while one identified a lung point in a person with pneumothorax [30]. Three studies demonstrated the use of advanced ultrasound features such as Doppler [30, 49, 62].

Diagnostic accuracy

Three diagnostic accuracy studies were included. Olivieri *et al.* [37] investigated the diagnostic performance of live teleultrasound in the evaluation of patients with acute respiratory failure and/or shock, compared to bedside ultrasound in 20 participants in an intensive care unit (ICU). The ultrasound operators were nurses who performed teleultrasound guided remotely, in real time, by an intensivist. The gold standard used was POCUS performed by a critical care fellow. Concordance between teleultrasound and POCUS ranged from 90% to 100% for lung sliding, pleural effusion and interstitial syndrome. The lowest concordance was in the identification of consolidation, which had 80% concordance.

Kimura *et al.* [55] evaluated self-performed teleultrasound in the pulmonary assessment of participants with early COVID-19 infection. This study had the largest sample size of all identified studies, with 50 participants. The outcome of interest was detection of ultrasound lung comet, otherwise known as B-lines, *via* live teleultrasound, compared to the gold standard of bedside expert ultrasound. The accuracy of detecting B-lines *via* live teleultrasound was 50% for any presence of B-lines (unilateral or bilateral); however, when the B-lines were bilateral, accuracy was reported at 100%.

König Klever *et al.* [35] reported a study assessing the accuracy of teleultrasound in detecting various lung profiles in 23 patients admitted to the ICU with respiratory failure or shock using the BLUE protocol, as compared to POCUS as the gold standard. The authors reported that live teleultrasound had a 100% sensitivity in detecting pulmonary oedema and 100% specificity in diagnosing COPD. Pneumonia was the condition in which live teleultrasound performed the least well, with reported accuracy of 65.2% and a high number of false negatives. The authors attributed this to the complexity of diagnosing pneumonia in the setting of various other respiratory conditions which may mimic the appearance of pneumonia sonographically.

Qualitative outcomes

User attitudes and perception towards live teleultrasound was assessed as an outcome in nine studies [27, 32–34, 51, 53, 54, 57, 67]. One study reportedly solely on this outcome: Al-Kadi *et al.* [27] surveyed 18 clinical users of a pilot teleultrasound system between the emergency departments of a rural hospital and tertiary trauma centre in Canada, performing FAST and E-FAST scans. They reported that 93% of respondents were either satisfied or very satisfied with the live teleultrasound interaction and agreed or strongly agreed that the programme would benefit injured patients. Additionally, it was reported that 71% of respondents believed that their ultrasound skills had improved as a result of the experience.

Grubic *et al.* [33] reported on a pre–post study examining outcomes of an education programme for cardiac and lung POCUS delivered *via* live teleultrasound. Participants were surveyed at the conclusion of the programme for ease of use, clinical relevance, utilisation and continued use of POCUS after completion of the education. Mean scores ranged from 4.03 to 4.72 (on a 1–5 Likert scale). The instructors were also surveyed on efficiency, comfort and ease of instruction. Mean scores ranged from 4.39 to 4.57 out of 5.

In their study of telementored, self-performed ultrasound to monitor progression of mild COVID-19 illness, Kirkpatrick *et al.* [57] reported on survey responses of their 27 participants. They were asked to rate the difficulty of performing various lung ultrasound protocols including the E-FAST, BLUE protocol, Soldati COVID examination, International Consensus Conference on Lung Ultrasound exam and lower lung fields protocol. Participants rated the protocols as being "easy" or "very easy" to perform.

Elmi *et al.* [54], as part of assessing interpretability of patient self-performed live teleultrasound, conducted a satisfaction survey of 11 participants. Responses included ease of ultrasound operation and reassurance from having immediate access to a physician. All participants reported being likely to use ultrasound at home if recommended, and all believed that home diagnostic methods could prevent an in-person visit to hospital or urgent care centre.

The remainder of the studies interrogating operator attitudes to live teleultrasound [32, 34, 51, 53, 67] all reported that it was acceptable and well-received by users. Jensen *et al.* [34] incorporated a large qualitative component into their feasibility study of teleultrasound in the emergency department. Junior doctors performing ultrasound guided by a remote expert were interviewed, with responses summarised into four domains: technical solution, learning perspective, patient–doctor communication and supervisor–doctor communication. Positive themes included that the ultrasound setup was operational and the novice scanners appreciated real-time discussion of ultrasound findings. There were negative themes such as the impression from junior doctors that having two simultaneous people to communicate with affected the direct patient–doctor relationship. Scanners and supervisors also described the lack of nonverbal communication cues as a limitation, and the requirement for a higher degree of patience from both parties when compared to live supervision. Correct terminology in guiding probe positioning was identified as paramount to achieving quality images.

Technical aspects

Several studies discussed bandwidth requirements, data transmission rates or other technical issues when performing live teleultrasound [27, 31, 32, 38–40, 45–48, 50, 52]. Kirkpatrick *et al.* [48] noted that bidirectional video-audio sharing *via* Zoom software required bandwidths of 1.25–1.95 Mbps, which was not supported by their local 4G cellular network. To preserve the 720p video signal from the patient side, the mentor disabled their video stream. Robertson *et al.* [38] used Apple FaceTime on a 4G network and did not report signal issues, although they did not comment on video resolution. McBeth *et al.* [50] reported excellent connection and image quality using Skype on 3G network coverage, documenting average download speeds of 600–1400 kbps and upload speed of 500–800 kbps. The resolution of the transmitted video was not specified.

To simulate a satellite link, Al-Kadi *et al.* [27] deliberately limited bandwidth to 2 Mbps and introduced a 270-ms delay to transmission. User perceptions were favourable and no technical issues were reported. Similarly, Dyer *et al.* [32] limited bandwidth and introduced delay in their pilot study of teleultrasound during trauma, with 20 acute E-FAST scans performed. Technical issues reported included initiation of audio and video communications, image freezing and ultrasound transmission delays. These issues were reportedly overcome in subsequent scans. Otto *et al.* [46] used satellite for their teleultrasound study and reported an average bandwidth use per session of 25 Mb, with no reported technical issues.

In their feasibility study of teleultrasound in pre-hospital emergency scenarios, Hermann *et al.* [47] used a 4G cellular network; however, they did not provide details on data requirements. One teleultrasound examination could not be performed due to connectivity issues. Other reported issues included lack of sound (n=3), log-in disconnection (n=3) and weak internet connection (n=2).

In their study of teleultrasound at different locations in the Scottish Highlands, Eadie *et al.* [45] utilised a combination of 2G, 3G and satellite coverage. Reported data transmission rates ranged from 22 to 1900 kbps. One planned examination was abandoned due to the lack of adequate cell signal. The authors reported that data transmission rate was inversely associated with time to achieve diagnostic image, with the strongest association seen with the lung scan. Cellular communications quality was given a mean score of 2 out of 5 on a Likert scale by reviewers, but 4 out of 5 for adequacy for diagnosis. The two examinations carried out using satellite coverage were rated 3.5 out of 5 for communication quality and 3 out of 5 for diagnostic quality. It was not clear whether the remote expert was sharing video information.

Robot-assisted teleultrasound studies performed by Wang *et al.* [39], Duan *et al.* [31] and Wu *et al.* [40] all used 5G cellular networks, with no issues reported. Vatsvåg *et al.* [52] did not report transmission issues using a fibreoptic internet line.

Other outcomes

No studies were identified that reported on the costs of using teleultrasound. No adverse events were reported in any of the studies.

Case reports and series

There were 11 case reports or case series identified where live teleultrasound was used successfully [28, 29, 36, 39, 42, 44, 48, 49, 56, 58, 62]. Settings ranged from hospital studies, home studies and field simulations. In a novel application, Kirkpatrick *et al.* [48] used a drone to deliver an ultrasound device with built-in telehealth capability to an ultrasound-naïve volunteer in a rural town in Canada, who subsequently was mentored to perform an E-FAST and BLUE protocol examination on himself, using the existing cellular network. McBeth *et al.* [49] conducted a proof-of-concept case study whereby an E-FAST teleultrasound examination was conducted at a ski resort in the Rocky Mountains, USA. It was noted that the remote examiner was better able to view the images than the onsite operator, given the environmental conditions at the scanning location.

Robot-assisted ultrasound

The majority of studies on teleultrasound involved mentoring of a novice operator by a remotely located expert. However, there were six studies involving expert-controlled robotic equipment [31, 39–42, 68]. These investigations were prompted by the COVID-19 pandemic and a desire to minimise transmission risk to clinicians. Robot-assisted ultrasound was described in case studies [39, 42], pilot/feasibility studies [31, 40, 41] and one simulation [68]. Duan *et al.* [31] performed a feasibility study assessing diagnostic performance of robot-assisted teleultrasound of the chest and abdomen compared to bedside ultrasound in the ICU. They reported no difference in diagnostic performance between the two techniques. All studies reported robotic-assisted teleultrasound to be safe.

Discussion

This systematic review has demonstrated that the available published data support the feasibility of live teleultrasound in a range of healthcare settings with few reported technical barriers and generally acceptable image quality. These conclusions are unfortunately tempered by the overall low quality of included studies, with the majority of those retrieved being case reports/series or feasibility studies, and most demonstrating a high risk of bias. While there is a need for further evaluation of this new technology, the consistent findings across the breadth of available studies does suggest a potential role for this imaging approach to improve access to expert ultrasound utilisation and interpretation in scenarios where there may be constraints on the availability of local expertise.

It is encouraging that all identified pilot or feasibility studies concluded that live teleultrasound was feasible. While the risk of publication bias is real, these conclusions are consistent with anecdotal experience with this technology. Included studies consistently reported that health professionals without prior ultrasound experience can perform live teleultrasound to an acceptable level of quality, which was defined as either the identification of common imaging findings in a simulation scenario, or clinically useful findings in a real-life setting. Ultrasound of the chest did not seem to be significantly more challenging for novices than scans of other body systems and was demonstrated to be largely equivalent in difficulty to abdominal scans, and less difficult than cardiac scans. There were few technical issues or communication failures reported. Bandwidth capacity as low as that provided by 3G cellular networks was reported to facilitate live teleultrasound of the chest to acceptable diagnostic standards. This is consistent with a previous study on live obstetric teleultrasound, which found that a connection speed of $\geqslant$384 kbps could facilitate real-time teleultrasound consultations [22]. Many studies included qualitative aspects of live teleultrasound use, with high levels of satisfaction reported by both ultrasound operators and remote experts. In totality, these data should provide clinicians and researchers with a degree of confidence that teleultrasound of the chest can be applied successfully in most settings with sufficient technical infrastructure.

While this review has provided evidence that live teleultrasound can be successfully implemented in a clinical setting, it remains unclear whether the accuracy of live teleultrasound in the diagnosis of chest pathologies is equivalent to POCUS by an expert user. Only three well-designed studies assessing diagnostic accuracy were identified, all evaluating live teleultrasound with POCUS in the diagnosis of the interstitial syndrome. Sample sizes were small, and the results are unable to be interpreted in combination as they were conducted in different settings with different ultrasound operators. Future studies should be designed to address diagnostic accuracy, through recruitment of larger samples, blinding of all participants and focusing on the detection of a single primary chest pathology or clinical scenario. Diagnoses should be independently verified by clinicians not directly involved in ultrasound examinations.

Other systematic reviews on teleultrasound have been published, with most arriving at similar conclusions. Marsh-Feiley *et al.* [69] and Britton *et al.* [20] both concluded that teleultrasound was feasible and of value in clinical practice, in emergency medicine and resource-limited settings, respectively. The low overall quality of evidence was acknowledged in both studies. Lipsitz *et al.* [70] evaluated the technology in the context of education, reporting that teleultrasound education was useful in a variety of different education models, modalities and settings. In contrast to these, Duarte *et al.* [71] in their narrative review of teleultrasound concluded that no studies were of sufficient methodological quality to demonstrate its effectiveness. This systematic review is the first to report specifically on chest ultrasound, while also including literature often excluded in systematic reviews, such as case reports and conference abstracts.

Limitations

There were several limitations of this review. Given the nature of the studies, many were not fully assessable even with the most suitable quality appraisal checklist. It is acknowledged that similar reviews on teleultrasound have used modified tools such as the Risk of Bias in Non-randomized Studies - of Interventions (ROBINS-I) [72] or QUADAS-2 [73]; however, the broad inclusion criteria and heterogeneity of the retrieved studies precluded the use of these tools. Most included studies did not evaluate chest teleultrasound alone and instead performed chest examinations in the context of a systematic scan, such as the E-FAST scan. Therefore, individual study conclusions often referred to the overall ultrasound examination and did not provide specific results related to the chest examination. As mentioned previously, all retrieved studies reported positive results for teleultrasound, suggesting a high likelihood of publication bias. Finally, there were no studies that reported on the financial costs of teleultrasound and the associated models of care, a critical component to consider when determining feasibility in clinical settings. Encouragingly, cost modelling analyses have been performed in other settings, particularly for obstetrics and abdominal teleultrasound [22, 74]. These concluded that live teleultrasound was more cost effective than in-person attendance for ultrasound in scenarios where travel between regional and metropolitan areas was required.

Conclusion

There is an increasing volume of predominantly low-quality evidence that demonstrates live teleultrasound is a useful tool to improve access to chest ultrasound. Despite the risk of bias within the studies identified in this systematic review, technical issues with live teleultrasound were infrequent, operators rated it highly and there did not appear to be any issue with diagnostic accuracy for common lung pathologies in comparison to bedside ultrasound. While further well-designed studies would help to confirm the limitations and diagnostic performance of live teleultrasound, the existing evidence supports a cautious optimism that this technology can improve access to chest ultrasound across a range of different healthcare settings.

Points for clinical practice

- Teleultrasound is a rapidly developing field of telemedicine. This systematic review demonstrates that using live teleultrasound to image the chest is feasible. The technology may be particularly useful where local expertise is not available, improving access to diagnostic ultrasound for pulmonary and pleural pathology.

Questions for future research

- The diagnostic accuracy of live teleultrasound compared to expert-performed ultrasound at the point of care requires further evaluation in the context of specific pulmonary and pleural conditions.

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